

FINAL REPORT

Loading Rates and Impacts of Substrate Delivery for Enhanced Anaerobic Bioremediation

ESTCP Project ER-0627

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Parsons

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EXECUTIVE SUMMARY

This *Technology Demonstration Report for Loading Rates and Impacts of Substrate Delivery for Enhanced Anaerobic Bioremediation* evaluates differing approaches to determining substrate loading rates and the impacts of substrate delivery for enhanced *in situ* anaerobic bioremediation. This demonstration report describes 1) the selection and evaluation of case study sites, 2) the methods that are used to compare and evaluate substrate loading rates, 3) the results achieved by these approaches, 4) methods and tools available for determining substrate requirements and substrate loading rates, 5) an assessment of differing approaches and the cost impact of design modifications, and 6) recommendations for estimating substrate requirements and for designing substrate amendments.

Problem Statement

Enhanced *in situ* anaerobic bioremediation involves the delivery of organic substrates into the subsurface to stimulate anaerobic degradation of contaminants in groundwater. Effective application of the technology depends primarily on the delivery of appropriate levels of organic substrate in the subsurface and the development of optimal geochemical and oxidation-reduction (redox) conditions for anaerobic biodegradation processes to occur.

Substrate loading rates are defined as the volume, concentration, and frequency of injection of organic substrates for in situ anaerobic bioremediation. Insufficient substrate loading rates or non-uniform delivery and mixing may result in areas of the aquifer that are not sufficiently reducing for complete dechlorination to occur, thereby increasing the potential for accumulation of regulated intermediate degradation products. For example, the potential accumulation of dechlorination products *cis*-1,2-dichloroethene (DCE), vinyl chloride (VC), or chloroethane (CA).

The presence of excessive substrate may result in uncontrolled fermentation reactions (e.g., lowering of pH and formation of undesirable fermentation products such as ketones), degradation of secondary water quality (e.g., mobilization of metals and inorganics), and poor utilization of substrate for anaerobic degradation of the contaminants of concern. The ability for aquifer systems to recover to pre-injection redox conditions and the long-term impacts on groundwater quality after enhanced bioremediation are not well documented.

Given these effects, many enhanced anaerobic bioremediation applications fail to achieve performance expectations or develop unanticipated long-term compliance problems. The cost associated with poor performance (e.g., a need for longer term operation) or with compliance issues such as degradation of secondary water quality (typically requiring additional monitoring or system modifications) may greatly increase the life-cycle costs of full-scale enhanced bioremediation applications. Therefore, determining an appropriate substrate loading rate and an effective distribution method for the various substrate types commonly applied is a critical design and operational objective.

Objectives

The objectives of this study are to:

- 1) Better understand the effects that substrate amendment loading rates (volume, concentration, and frequency of injection) have on substrate persistence (maintenance of the reaction zone) and distribution (mixing and radius of influence);
- 2) Determine how control of substrate loading rates affects amendment utilization and development of optimal geochemical and redox conditions for anaerobic biodegradation;
- 3) Identify substrate loading rates that have adverse impacts on secondary water quality;
- 4) Evaluate the effect that differing substrate types or loading rates may have on hydraulic conductivity based on physical/chemical or biological (biomass) effects of the substrate amendment; and
- 5) Use this information to develop practical guidelines for designing and optimizing substrate loading rates and injection scenarios for differing substrate types and for differing geochemical and hydrogeologic conditions.

To achieve these objectives, fifteen (15) case studies with varying methods to determine substrate loading rates were evaluated regarding system operation and performance. Quantitative and qualitative performance objectives used to evaluate the case studies are summarized in the table below, and were used to identify limiting factors for enhanced *in situ* bioremediation.

Summary of Limiting Factors for Enhanced *In Situ* Bioremediation

A number of limiting factors commonly impact the effectiveness of enhanced *in situ* bioremediation applications. These limiting factors and the best practices to mitigate them include the following:

Insufficient Substrate Distribution. The ability to effectively distribute substrate is often impacted by site-specific lithology (low or high permeability, heterogeneity) and groundwater hydraulics (low or high rates of groundwater flow). In some cases the quantity of substrate that can be injected is limited by a low aquifer buffering capacity and adverse lowering of pH. This reinforces the need to, and benefits of, conducting adequate site characterization prior to design and implementation of substrate addition. In most cases these conditions can be mitigated by modifying the injection mixture and substrate loading rate (for example more frequent and less concentrated substrate solutions, or adding a buffering amendment), or selecting an appropriate delivery technique (for example closer spaced injection points and larger injection volumes).

Adverse Geochemical Conditions. The most common geochemical condition was an adverse excursion (lowering) of pH, resulting from a combination of low buffering capacity of the aquifer and high concentrations of dissolved organic carbon (DOC). Control of the substrate loading rate is critical when treating aquifers with low buffering capacity. Mitigation measures include careful screening of the site to determine whether a buffering compound should be added to the injection protocol, and selecting substrate delivery techniques that provide for more uniform distribution of substrate without excessive “spikes” in DOC.

Performance Objectives

Performance Objective	Data Requirements	Success Criteria
Quantitative Performance Objectives		
Determine ability to uniformly distribute substrate	Post-injection concentrations of soluble organic carbon in groundwater.	Achieving the concentration of substrate targeted in the design at all monitoring locations within the reaction zone is considered successful.
Determine if optimal geochemical conditions were achieved	Pre- and post-injection concentrations of geochemical indicator parameters in groundwater.	Achieving highly reducing conditions with ORP less than -200 mV throughout the reaction zone is considered successful.
Determine remediation effectiveness	Pre- and post-treatment contaminant concentrations in groundwater.	- A greater than 99 percent reduction in compound-specific concentrations is considered successful. - A greater than 90 percent reduction in total molar concentration of CAHs is considered successful.
Determine impacts to secondary water quality	Post-treatment concentrations of secondary water quality parameters (e.g., dissolved metals such as iron and manganese).	Maintaining concentrations of secondary water quality parameters below applicable regulatory criteria downgradient of the reaction zone is considered successful.
Determine impacts on hydraulic conductivity	Pre- and post-treatment measurements of hydraulic conductivity.	A less than 50 percent decrease in hydraulic conductivity is considered successful.
Determine substrate persistence and long-term effectiveness	Post-treatment concentrations of contaminants and soluble organic carbon at the end of the intended design life of the application.	A rebound in concentrations of less than 1.0 percent of the initial contaminant concentration after the application has been completed is considered successful.
Qualitative Performance Objectives		
Determine need for and cost of additional injections or monitoring	Actual work performed will be compared to the application design plan. The cost of additional work will be calculated when data are available, or a qualitative assessment will be made when cost data are not available.	An application that does not require additional injections or monitoring beyond that in the original design is considered successful.
Application in difficult hydrogeological conditions	Site geology (permeability, heterogeneity) and groundwater hydraulics (hydraulic conductivity, hydraulic gradient, and rate of groundwater flow).	An application where permeability, heterogeneity, or the rate of groundwater flow do not limit effectiveness is considered successful. Guidelines on these parameters are developed from examples where they impacted the effectiveness of the application.

Loss of Hydraulic Conductivity or Biofouling of Injection Wells. A decrease in hydraulic conductivity (permeability) may result in bypass of contaminated groundwater around the reaction zone or uneven distribution of substrate during subsequent injections. One option to mitigate the potential for loss of hydraulic conductivity is to conservatively design the reaction zone to extend beyond the limits of contaminated groundwater to be treated. For example, a biobarrier may be installed an additional 20 to 50 feet beyond the edge of the groundwater contaminant plume to avoid potential for bypass around the ends of the reaction zone. It may also be beneficial to provide a degree of overlap (perhaps 20 to 30 percent) in radius of influence for injection wells to compensate for reductions in the ability to distribute substrate during subsequent injections.

Substrate Persistence and Longevity. Concentrations of DOC typically need to be sustained above 50 to 100 milligrams per liter (mg/L) over the design life of the application. Buildup of biomass may sustain the reaction zone and limit the amount of rebound that may occur after the initial substrate is depleted. Rebound of concentrations in the treatment zone will depend on whether a residual source of contaminant mass remains upgradient of the treatment zone, or in low permeability sediments within the treatment zone.

Difficult Hydrogeological Conditions. Rates of groundwater flow less than 0.1 feet per day (ft/day) (37 feet per year [ft/yr]) or greater than 2.7 ft/day (1,000 ft/yr) require special design considerations. Low rates of groundwater flow may require closer injection point spacing because the distribution of organic acids by dispersion will be limited. High rates of groundwater flow will require more frequent and higher concentration injections as the substrate is dispersed over a large volume of the aquifer. In the case of emulsified vegetable oil (EVO) products, the retention of the oil droplets is a critical parameter to sustain adequate substrate concentrations in the reaction zone. Oil retention in coarse grained sediments, combined with a high rate of groundwater flow, may not be sufficient without additional injections. In addition, as the degree of aquifer heterogeneity increases, so may the need for closer injection well spacing or for “targeted” injections within lower permeability sediments.

The variety of substrates and configurations that can be used for enhanced *in situ* bioremediation allows the practitioner to design around these limiting factors. Careful site screening and evaluation of each of these limiting factors will lead to higher rates of success and greater effectiveness of the remedy.

Substrate Estimating Tool

A substrate estimating tool was developed to assist the practitioner in evaluating a site for an enhanced *in situ* bioremediation application. The primary objectives of this tool are to:

- Evaluate the site-specific conditions regarding hydrogeology and geochemistry in regards to the demand exerted by both natural and anthropogenic electron acceptors,
- Screen for site conditions that require special consideration, such as excursion of pH outside of a range optimal for dechlorinating microorganisms, and
- Evaluate and compare the concentrations of differing substrate types necessary to meet the electron acceptor demand.

This tool was used during the case study evaluations to compare the substrate amendment designs and actual quantities used to the substrate requirements calculated by the tool using site-

specific electron acceptor demand. A description of how the tool works and guidance on using it for site screening purposes is included in Appendix B.

The variability in the relative percentage of electron acceptor demand for common electron accepting processes reflects the variability in site conditions that may be encountered. Sulfate reduction and methanogenesis have the greatest potential to dominate electron acceptor demand and to increase substrate requirements. This is due to the magnitude of sulfate concentrations that may occur (up to several thousand milligrams per liter), and to the high utilization rate of hydrogen by methanogenesis. In source areas, the electron acceptor demand from chlorinated solvents may predominate.

The substrate estimating tool is useful to screen site conditions that will impact substrate delivery and utilization. The tool provides an estimate of **total** substrate required over the design life of the application, given a user specified design factor. The tool calculates a time-weighted average concentration of substrate by dividing the total volume of groundwater treated by the total substrate quantity.

The substrate estimating tool is also useful to understand how the substrate will be utilized and to screen for potential adverse geochemical conditions. For example, high manganese and iron sites may require monitoring to ensure secondary water quality is not impacted downgradient of the treatment zone. pH and alkalinity are included in the tool to screen for sites with low buffering capacity.

The quantities and time weighted average substrate concentrations can be used for comparison to proposed or planned bioremediation applications as a check on the quantities of substrate being proposed or the performance targets for DOC. This should assist in avoiding application of either too little substrate or generating excessive substrate levels. Design tools are often provided by substrate vendors, and the estimated substrate quantity should always be compared to recommendations by the provider or with case studies in the literature.

Recommendations

The primary objective when selecting a substrate loading rate is to achieve a uniform distribution of substrate over time and space. Design tools that assist the practitioner with the configuration (well spacing) and injection volumes are being developed and should be incorporated into the design exercise. Examples include the Edible Oil Substrate tool being developed under ESTCP Project ER-0626 (Borden *et al.*, 2008; available at the ESTCP on-line library at <http://docs.serdp-estcp.org/>).

For slow release substrates injected in a one-time event, a conservative design factor on the order of 3- to 7-times the estimated substrate requirement should be suitable for limiting the potential for insufficient substrate. For soluble substrates, lower design factors on the order of 2- to 3-times the estimated substrate requirement are beneficial to avoid over-stimulating the aquifer and driving pH downward. Substrate quantities can be increased if initial loading rates are insufficient to create suitable reducing conditions throughout the treatment zone. The delivery methods for soluble substrates should target uniform substrate concentrations without excessive “spikes” in concentration.

The use of very high substrate concentrations to enhanced dissolution of dense non-aqueous phase liquids (DNAPL) into the aqueous phase is an exception to typical substrate loading rates.

Solutions with concentrations of lactate as high as 6 percent by weight, whey as high as 10 percent by weight, and molasses as high as 1 to 2 percent by weight have been used for this purpose. These applications require special consideration of the buffering capacity of the aquifer and the system configuration. For example, it may be acceptable to induce adverse geochemical conditions in the source zone to mobilize chlorinated solvent mass if a suitable downgradient reaction zone for biodegradation and geochemical recovery is established. In most all cases, these types of injections are typically performed in pulses of every 4 to 12 weeks to allow the aquifer geochemistry to stabilize between injections.

Six of the fifteen case study sites exhibited issues with pH excursion. For all these sites, initial background pH values were below 6.5 and alkalinity was below 150 mg/L. For screening purposes, a combination of pH below 6.0 to 6.5 and alkalinity below 300 mg/L indicates that modifications to buffer and control pH are necessary. Sodium bicarbonate was the most common buffering compound used, typically at concentrations in excess of 10,000 mg/L. Sodium bicarbonate is a relatively weak buffering compound and may be most suitable for applications using frequent injections of soluble substrates. The use of stronger and more persistent buffering compounds (e.g., magnesium hydroxide or sodium phosphates) may be necessary for applications using slow release substrates, and further research and product development will be beneficial for sites with low buffering capacity.

In practice, the amount of site characterization data that is available or that can be economically obtained is always limited to some extent. It is not unusual to design an enhanced *in situ* bioremediation application at a “well characterized” site, only to encounter difficult hydrogeological conditions such as low permeability sediments or heterogeneity that limits effective substrate distribution. Therefore, it is useful to consider practices that mitigate the uncertainty associated with subsurface environments.

Soluble substrate systems that use frequent injections have the most flexibility in modifying injection scenarios. When using infrequent applications of slow-release substrates, potential problems such as the need to add a buffering agent should be evaluated prior to substrate addition, and buffer should be added during substrate injection as a precautionary measure when in doubt.

Inadequate or excessive distribution of substrate due to aquifer permeability and/or groundwater flow rates can be adjusted by increasing or decreasing the substrate loading rate, and/or by modifying injection frequency or well spacing. Substrate loading rates may be increased in the event of inhibitory electron acceptor demand (e.g., sulfate over 50 to 100 mg/L).

Finally, incomplete or delayed dechlorination is a common limitation resulting in accumulation of intermediate dechlorination products. Prior to considering bioaugmentation, the system should be evaluated to ensure that the proper geochemical conditions have been achieved and that a sufficient acclimation period has been allowed for ecological succession and development of appropriate microbial consortia. Bioaugmentation with commercially available culture can be implemented if it has been determined that indigenous *Dehalococcoides* species are lacking or do not exhibit the reductase enzymes that indicate a capability for complete dechlorination of VC to ethene.

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ACRONYMS AND ABBREVIATIONS

°C	degrees Celsius
°F	degrees Fahrenheit
µg/L	micrograms per liter
ρ _B	sediment bulk density
AFB	Air Force Base
AFCEE	Air Force Center for Engineering and the Environment
ATK	Alliant Techsystems Facility
bgs	below ground surface
BOD	biological oxygen demand
BUCHLORAC	Buffering of Dechlorination Acidity (geochemical model)
CA	chloroethane
CaCO ₃	calcium carbonate
CAH	chlorinated aliphatic hydrocarbon
CCAFS	Cape Canaveral Air Force Station
CEC	cation exchange capacity
cm/sec	centimeters per second
CO ₂	carbon dioxide
COD	chemical oxygen demand
DCA	dichloroethane
DCE	dichloroethene
DIC	dissolved inorganic carbon
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen
DOC	dissolved organic carbon
DoD	Department of Defense
DoE	Department of Energy
Eh	redox potential (relative to a standard hydrogen electrode)
ESTCP	Environmental Security Technology Certification Program
EVO	emulsified vegetable oil
EZVI	emulsified zero-valent iron
ft/day	feet per day
ft/yr	feet per year
gm	gram or grams
gpm	gallons per minute
GSI	Groundwater Services, Inc.
H ⁺	hydrogen ion
H ₂	molecular hydrogen
HFCS	high fructose corn syrup
HRC [®]	hydrogen release compound
INEEL	Idaho National Engineering and Environmental Laboratory
ITRC	Interstate Technology and Regulatory Council
JRW	JRW Bioremediation Products, LLC
lbs	pounds
lb/ft	pounds per foot

lb/ft ³	pounds per cubic feet
MCL	Maximum Contaminant Level
meq/L	milliequivalents per liter
meq/kg	milliequivalents per kilogram
mg/L	milligrams per liter
mV	millivolts
NAVFAC	Naval Facilities Engineering Command
NFESC	Naval Facilities Engineering Service Center
NSWC	Naval Surface Warfare Center
NTC	Naval Training Center
NWIRP	Naval Weapons Industrial Reserve Plant
O&M	operations and maintenance
ORP	oxidation reduction potential
OU	Operable Unit
Parsons	Parsons Infrastructure & Technology Group, Inc.
PCE	tetrachloroethene
PLFA	phospholipids fatty acid
POC	point of contact
PRB	permeable reactive barrier
PRG	preliminary remediation goal
redox	oxidation-reduction potential
SABRE	Source Area BioREmediation Project
SOP	standard operating procedure
SS	spill site
SWMU	solid waste management unit
TAN	Test Area North
TCA	trichloroethane
TCE	trichloroethene
TDS	total dissolved solids
TOC	total organic carbon
US	United States
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VC	vinyl chloride
VFA	volatile fatty acid
VOC	volatile organic compound
wt/wt	concentration by weight (e.g., weight substrate per weight water)
ZVI	zero-valent iron

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1. INTRODUCTION

This *Technology Demonstration Report for Loading Rates and Impacts of Substrate Delivery for Enhanced Anaerobic Bioremediation* evaluates differing approaches to determining substrate loading rates and the impacts of substrate delivery for enhanced *in situ* anaerobic bioremediation. This report was prepared by Parsons Infrastructure & Technology Group, Inc. (Parsons) for the Environmental Security and Technology Certification Program (ESTCP ER-0627), under United States Army Corps of Engineers (USACE) Contract No. W912HQ-06-C-044.

This demonstration report describes 1) the selection and evaluation of case study sites, 2) the methods that are used to determine substrate loading rates, 3) the results achieved by these approaches, 4) methods and tools available for determining substrate requirements and substrate loading rates, 5) assessment of differing approaches and the cost impact of design modifications, and 6) recommendations for determining substrate requirements and for designing substrate amendments.

1.1 PROBLEM STATEMENT

Enhanced *in situ* anaerobic bioremediation involves the delivery of organic substrates into the subsurface to stimulate anaerobic degradation of contaminants in groundwater. Effective application of the technology depends primarily on the delivery of appropriate levels of organic substrate in the subsurface and the development of optimal geochemical and oxidation-reduction (redox) conditions for anaerobic biodegradation processes to occur. This project specifically addresses anaerobic reductive dechlorination of chlorinated solvents, but the concepts of adequate substrate distribution and achieving optimal subsurface geochemical conditions apply to other contaminants amenable to anaerobic degradation processes.

Substrate loading rates are defined as the volume, concentration, and frequency of injection of organic substrates for in situ anaerobic bioremediation. Insufficient substrate loading rates or non-uniform delivery and mixing may result in areas of the aquifer that are not sufficiently reducing for complete dechlorination to occur, thereby increasing the potential for accumulation of regulated intermediate degradation products (e.g., the potential accumulation of dechlorination products *cis*-1,2-dichloroethene [DCE], vinyl chloride [VC], or chloroethane [CA]). Little is known regarding the minimum or threshold concentrations of substrates that are required to sustain reductive dechlorination at sites with a history of substrate addition and mature microbial populations.

The presence of excessive substrate may result in uncontrolled fermentation reactions (e.g., lowering of pH and formation of undesirable fermentation products such as ketones), degradation of secondary water quality (e.g., mobilization of metals and inorganics), and poor utilization of substrate for anaerobic degradation of the contaminants of concern. The ability for aquifer systems to recover to pre-injection redox conditions and the long-term impacts on groundwater quality after enhanced bioremediation are not well understood.

Furthermore, the physical presence of some substrate types (e.g., vegetable oils) and the often exponential growth of biomass may adversely impact the hydraulic conductivity of the aquifer and groundwater flow. This could potentially result in contaminant bypass, unexpected deviation in plume migration patterns, or non-uniform delivery of subsequent substrate injections.

Given these effects, many enhanced anaerobic bioremediation applications fail to achieve performance expectations or develop unanticipated long-term compliance problems. The cost associated with poor performance (e.g., a need for longer term operation) or with compliance issues such as degradation of secondary water quality (typically requiring additional monitoring or system modifications) may greatly increase the life-cycle costs of full-scale enhanced bioremediation applications. Therefore, determining an appropriate substrate loading rate (the engineered delivery of substrate volume, concentration, and frequency) and an effective distribution method (accounting for radius of influence and mixing with groundwater) for the various substrate types commonly applied is a critical design and operational objective. This technology demonstration is intended to evaluate various substrate emplacement strategies to optimize the performance of enhanced *in situ* anaerobic bioremediation applications.

1.2 OBJECTIVES

ESTCP has initiated a program to determine the effectiveness of enhanced *in situ* bioremediation to remediate chlorinated solvents (e.g., CU-9920), perchlorate (e.g., CU-0219), and explosives (e.g., CU-0110) in groundwater. In addition, the *Principles and Practices of Enhanced Anaerobic Bioremediation of Chlorinated Solvents* (Air Force Center for Engineering and the Environment [AFCEE] *et al.*, 2004) guidance document has been published (CU-0125) describing the process. While a number of demonstration projects have been implemented for enhanced anaerobic bioremediation, there is still a lack of definitive guidance for determining appropriate loading rates and delivery methods based on site-specific conditions. This study is intended to supplement guidance developed to date by ESTCP for enhanced *in situ* anaerobic bioremediation.

The objectives of this study are to:

- 1) Better understand the effects that substrate amendment loading rates (volume, concentration, and frequency of injection) have on substrate persistence (maintenance of the reaction zone) and distribution (mixing and radius of influence);
- 2) Determine how control of substrate loading rates affects amendment utilization or reactivity and the development of optimal geochemical and redox conditions for anaerobic biodegradation;
- 3) Identify substrate loading rates that have adverse impacts on secondary water quality;
- 4) Evaluate the effect that differing substrate types or loading rates may have on hydraulic conductivity based on physical/chemical or biological (biomass) effects of the substrate amendment; and
- 5) Use this information to develop practical guidelines for designing and optimizing substrate loading rates and injection scenarios for differing substrate types and for differing geochemical and hydrogeologic conditions.

This technology demonstration report describes the results of the case study evaluations and the implications on system design and performance.

1.3 REGULATORY DRIVERS AND STAKEHOLDER BENEFITS

Enhanced *in situ* anaerobic bioremediation has gained wide spread acceptance as a remedy for contaminants in groundwater, including chlorinated solvents and other compounds subject to anaerobic degradation processes. While it is widely applied, regulatory concerns with performance of the technology persist. A review of state policies on enhanced bioremediation conducted by the Interstate Technology and Regulatory Council (ITRC, 1998) identified generation of VC in the reaction zone as a typical regulatory concern. Degradation of secondary drinking water quality or production of noxious gases are also concerns where potential exposure pathways exist. These issues are typically addressed through additional monitoring, which raises the cost of the remedy. Therefore, any methods that reduce the potential for production of toxic intermediate degradation byproducts, degradation of secondary drinking water quality, or production of noxious gases will lead to increased regulatory confidence and will limit costs associated with additional injections or extended monitoring.

The benefits of the proposed research to stakeholders and end-users are performance and financial based. Failure to meet remedial objectives or potential adverse impacts to secondary water quality affect the ability of the Department of Defense (DoD) to protect human health and the environment. By improving remedy performance, the potential exists to save hundreds of thousands to millions of dollars by reducing long-term operational and monitoring costs. ***For many applications, the cost to operate, modify, or to monitor system performance over periods of years is often greater than the cost to design and install the system.***

1.4 DEMONSTRATION REPORT ORGANIZATION

This technology demonstration report is organized into eleven sections and four appendices as follows:

- Section 1 includes this introduction to the demonstration project.
- Section 2 provides a technology description.
- Section 3 describes the performance objectives that are used to evaluate the case study sites.
- Section 4 describes the site selection process and the sites that were selected for this study.
- Section 5 provides the methods used for the Phase I and Phase II evaluations that were performed, with a discussion of the relevant observations from each site.
- Section 6 provides an summary evaluation of the demonstration performance objectives, and a discussion of the factors that impact the performance and cost of enhanced *in situ* bioremediation applications.
- Section 7 contains a discussion of the current methods used for design of substrate amendments.

- Section 8 contains a discussion and evaluation of controlling pH using groundwater buffering amendments.
- Section 9 provides a cost assessment of differing bioremediation approaches and of the cost impacts of modifications to system designs.
- Section 10 provides recommendations for design of substrate loading rates and amendments.
- Section 11 contains references cited in this document.
- Appendix A provides a table of contact information for the project team.
- Appendix B provides a description and guidance for the substrate estimating tool developed for this demonstration.
- Appendix C contains Phase I summary evaluations for each of the case studies.
- Appendix D contains a technical memorandum that summarizes the field and laboratory data collected for Phase II evaluation at the DP98 Site at Elmendorf Air Force Base (AFB), Alaska.

2. TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

Enhanced *in situ* anaerobic bioremediation can be an effective method of degrading various chlorinated solvents dissolved in groundwater. Many different substrate types have been used to stimulate the *in situ* anaerobic bioremediation of chlorinated solvents in groundwater. This creates an anaerobic treatment zone within and downgradient of the zone of injection (Figure 2.1). Creating and sustaining the appropriate anaerobic geochemical conditions is essential to an effective application of the technology.

Enhanced in situ anaerobic bioremediation involves the delivery of an organic substrate into the subsurface to stimulate microbial growth and development, creating an anaerobic groundwater treatment zone and generating hydrogen through fermentation reactions. This creates conditions conducive to anaerobic biodegradation of chlorinated solvents dissolved in groundwater.

Common substrate types include soluble substrates (lactate, molasses), slow-release substrates (vegetable oil, emulsified vegetable oil [EVO], Hydrogen Release Compound [HRC[®]]), and solid substrates (mulch and compost). Other amendments also may need to be delivered with the substrate, including pH buffering agents, nutrients, or bioaugmentation cultures. The substrates used for enhanced bioremediation each have differing physical, chemical, and biodegradation characteristics. Therefore, the approach used to design an enhanced bioremediation application and to determine substrate requirements varies between the different substrates.

2.2 TECHNOLOGY DEVELOPMENT

Determining substrate requirements is not an exact science, and the degree of uncertainty in the methods currently employed is considerable. Two general approaches have been used to estimate substrate requirements and to derive a substrate loading rate. One approach is to target an empirical concentration of substrate in the reaction zone that is based upon previous experience and experimentation at sites with similar hydrogeology, geochemistry, and contaminant distribution.

The other approach is to calculate a substrate (electron donor) requirement based on estimates of native and contaminant electron acceptor mass and mass flux through the contaminant treatment zone. The rate at which the substrate is applied (amount and frequency) is equally as important as determining a total substrate requirement. To undertake a calculation of this kind may infer an understanding of the biological and geochemical processes that is greater than the current state of the science. To make the process work a substantial engineering design factor is frequently applied, casting some doubt on the value of the calculation.

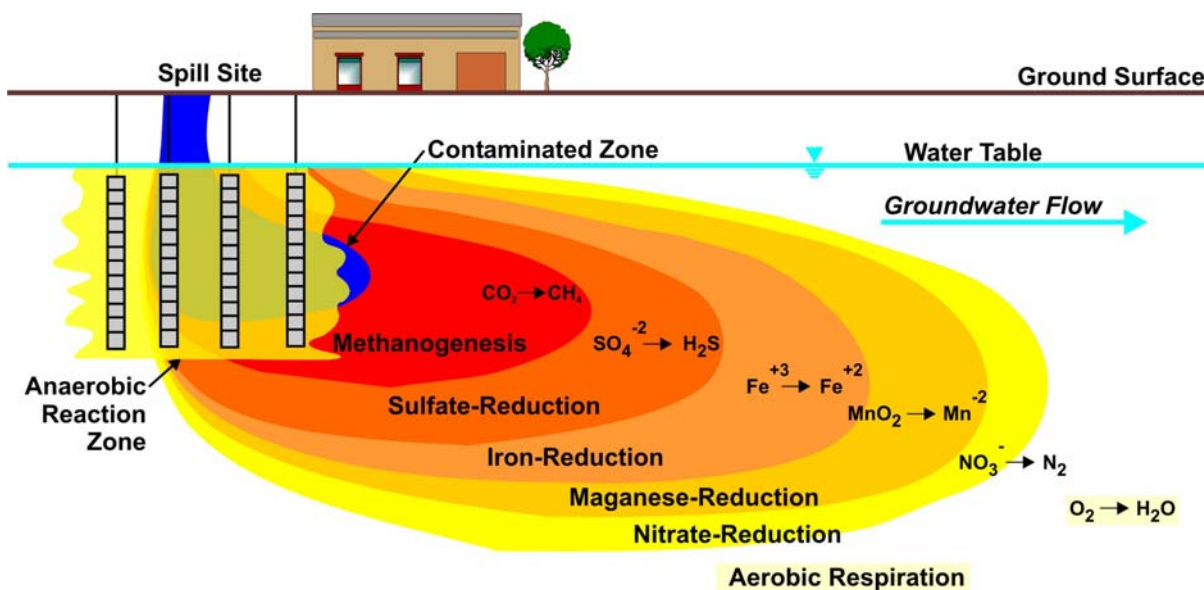


Figure 2.1 Reducing Zones Established Downgradient of Substrate Injection (from AFCEE *et al.*, 2004)

Users of soluble substrates typically use an empirically-based approach because they are able to modify the substrate loading rate on a more frequent basis until the desired geochemical conditions are achieved (for example Suthersan *et al.*, 2002). In these cases the substrate loading rate is commonly based on experience, field observations, or practical engineering considerations. Conversely, users or vendors of slow-release substrates (e.g., HRC[®] and EVO) typically rely on calculated substrate requirements because the product is usually applied in a single event (e.g., see Appendix G of AFCEE, 2007).

More recently, users of EVO products have realized that the retention of oil droplets in the aquifer is highly dependent on the physical and chemical properties of the EVO product (e.g., the ionic strength of the emulsifiers) and of the aquifer matrix (e.g., percent clay and organic material in the aquifer matrix). This study evaluates the methods used to determine oil retention, including the approach used in the design tool being developed under ESTCP project ER-0626.

Formulating substrate amendments to stimulate biogeochemical transformation processes has not been developed in the literature. However, the stoichiometry for the production of reduced iron mono-sulfides is relatively straight forward (AFCEE, 2002; Kennedy and Everett, 2003), and the potential for formation of reactive metal sulfides based on native geochemical conditions is included in this study as a supplementary calculation in evaluating substrate requirements. For sites where soil data for iron and groundwater data for sulfate are available, it should be possible to evaluate whether the formation of reactive metal sulfides is limited by the availability of iron or the availability of sulfide produced by sulfate reduction. Sites where iron or sulfate have been intentionally added are evaluated to determine the effectiveness of adding these amendments.

2.3 ADVANTAGES AND DISADVANTAGES

2.3.1 Advantages of Enhanced *In Situ* Bioremediation

Enhanced *in situ* bioremediation may in some cases offer the following advantages:

- **Lower Capital and Maintenance Costs:** Lower capital costs often are realized because substrate addition can be easily accomplished using conventional well installations or by use of direct-push technology. Systems used to mix and inject substrates can be readily designed and installed by environmental engineers, and operation and maintenance (O&M) is generally routine.
- **Destruction of Contaminants *In Situ*:** Chlorinated solvents have the potential of being completely mineralized or destroyed. Destruction of contaminants *in situ* is highly beneficial because contaminant mass is not transferred to another phase, there is no secondary waste stream to treat, potential risks related to exposure during remediation are limited, and there is minimal impact on site infrastructure.
- **Interphase Mass Transfer:** Enhanced anaerobic processes may increase the rate of dense non-aqueous phase liquid (DNAPL) source zone dissolution. This has sparked interest in enhanced bioremediation as a more efficient and expeditious method for remediating chlorinated solvent source areas (ITRC, 2008a and 2008b).
- **Potential Application to a Variety of Contaminants:** In addition to chlorinated solvents, the technology may be applicable to a variety of other contaminants including perchlorate and energetics. Enhanced *in situ* bioremediation has the potential to treat any contaminant that can be made less toxic or less mobile through reduction reactions.

2.3.2 Potential Limitations of Enhanced *In Situ* Bioremediation

Injection of an organic substrate causes profound changes to the subsurface environment, and the effectiveness of the technology may be subject to hydrogeological, geochemical, and biological limitations. Some of these limitations also affect other *in situ* remedial techniques. Potential issues that should be considered when applying enhanced *in situ* bioremediation include the following:

- **Site-Specific Limitations.** Site-specific limitations may include low permeability or a high degree of heterogeneity that limits the ability to effectively distribute the substrate throughout the aquifer. Other site-specific limitations may include high levels or influx of competing electron acceptors (e.g., sulfate), inhibitory geochemical conditions (e.g., pH), or lack of appropriate microbial communities or species. As a result, degradation may be limited.
- **Timeframe for Remediation.** Enhanced *in situ* bioremediation is not an instantaneous or rapid process. The time required to develop the appropriate environmental conditions and to grow a microbial population capable of complete degradation is on the order of several months to years. Therefore, the technology may require prolonged operation and monitoring.
- **Remediation of DNAPL Sources.** While the technology has been shown to be a viable remedial approach for dissolved contaminant mass and for limiting mass flux from DNAPL source zones, it is not yet a proven technology for reducing large volumes (pools) of DNAPL.
- **Incomplete Degradation Pathways and Accumulation of *cis*-DCE.** Microbial populations capable of anaerobic dechlorination of the highly chlorinated compounds

(e.g., tetrachloroethene [PCE] and trichloroethene [TCE] to *cis*-DCE) are thought to be more or less ubiquitous in the subsurface environment. However, the ability of these dechlorinators to compete with other native microbial populations or to complete the degradation of chlorinated compounds to innocuous end products may be an issue at some sites.

- **Secondary Degradation of Water Quality.** Secondary degradation of groundwater quality may occur under the highly anaerobic conditions resulting from substrate addition. Degradation reactions or excessive changes in groundwater pH and redox conditions may lead to solubilization of metals (e.g., iron, manganese, and potentially arsenic), formation of undesirable fermentation products (e.g., aldehydes and ketones), and other potential impacts to secondary water quality (e.g., total dissolved solids). Many of these changes are not easily reversed, and in the case of a slow-release carbon source it may take many years for the effects of the substrate addition to diminish.
- **Generation of Volatile Byproducts and Noxious Gases.** Stimulating biodegradation also may enhance generation of volatile byproducts and noxious gases (e.g., VC, methane, or hydrogen sulfide) that may degrade groundwater quality and/or accumulate in the vadose zone.

While these concerns and potential limitations should be considered when evaluating enhanced anaerobic bioremediation, many of them can be mitigated or compensated for by understanding the biogeochemical and hydrogeologic conditions of the aquifer system and using an appropriate design and substrate loading strategy.

2.4 FACTORS AFFECTING COST AND PERFORMANCE

The uncertainty in determining appropriate substrate loading rates and distribution methods often leads to either insufficient substrate or an excess of substrate to meet design and remedial objectives. Inadequate application of substrate can usually be corrected with additional or modified injections, with an associated cost. Application of excessive substrate cannot be easily corrected, usually requiring a period of extended monitoring (again at a cost) while aquifer redox conditions recover to appropriate levels.

In summary, determining an optimal substrate loading rate and an effective distribution method are critical design and operational objectives. Guidance is limited for determining optimal substrate amendment strategies. This study of enhanced bioremediation applications (1) compares techniques used to calculate or design substrate loading rates, (2) evaluates performance monitoring efforts to determine optimal injection scenarios, (3) provides a substrate estimating tool for site screening, and (4) provides recommendations for design of substrate amendments. The effectiveness and cost of these methods to achieve remedial objectives provides the DoD with a useful tool for designing appropriate substrate loading rates and implementing effective amendment strategies.

3. PERFORMANCE OBJECTIVES

The objectives (Section 1.2) of this study are addressed by comparative evaluations for three broad categories of substrates: soluble (dissolved), slowly soluble (low viscosity or viscous fluids), and solid (e.g., mulch) substrates. Fifteen (15) case studies were evaluated, primarily consisting of DoD and Department of Energy (DoE) applications. Additional field sampling and analysis were performed for two select sites to obtain additional data to support evaluation of the project objectives. Quantitative and qualitative performance objectives have been developed to evaluate and measure the success of the demonstration sites. These objectives are listed in Table 3.1, and a description of the performance objectives is included in the following subsections. Results of evaluating these project objectives are presented in Section 6.

3.1 PERFORMANCE OBJECTIVE NO. 1: ABILITY TO UNIFORMLY DISTRIBUTE SUBSTRATE

The ability to uniformly distribute organic substrate is a primary operational objective when applying enhanced *in situ* bioremediation. The distribution of substrate is evaluated using concentrations of soluble organic carbon measured within the intended reaction zone. Concentrations achieved are compared to target concentrations described in the application design (i.e., work plans). This data is used to better understand the effects that substrate amendment loading rates (volume, concentration, and frequency of injection) have on substrate distribution (mixing and radius of influence).

An application is considered successful when the targeted concentrations of soluble organic carbon are achieved in all monitoring locations within the intended reaction zone. Design calculations and site-specific conditions (e.g., aquifer heterogeneity) are reviewed if uniform distribution of substrate is not achieved to evaluate causes for poor distribution.

3.2 PERFORMANCE OBJECTIVE NO. 2: ACHIEVING OPTIMAL GEOCHEMICAL CONDITIONS

Achieving optimal geochemical conditions in groundwater for anaerobic degradation of chlorinated solvents is another primary objective of enhanced *in situ* bioremediation. Achieving optimal geochemical conditions is evaluated by analyzing indicator parameters of anaerobic conditions such as dissolved oxygen (DO), oxidation-reduction potential (ORP), nitrate, manganese, ferrous iron, sulfate, and methane.

For example, successful geochemical conditions for stimulating anaerobic degradation of chlorinated solvents is when the groundwater environment is highly anaerobic with DO less than 0.5 milligrams per liter (mg/L), ORP is less than -200 millivolts (mV), sulfate is reduced by more than 50 percent relative to background conditions, and methane is greater than 1.0 mg/L.

These criteria may not apply in all cases. For example, a recirculation system using a bioaugmentation culture may attempt to control the substrate loading rate to limit the production of soluble ferrous iron, manganese, and methane. Applications for contaminants such as perchlorate or nitroaromatic compounds may require less reducing conditions.

Table 3.1
Performance Objectives

Performance Objective	Data Requirements	Success Criteria
Quantitative Performance Objectives		
Determine ability to uniformly distribute substrate	Post-injection concentrations of soluble organic carbon in groundwater.	Achieving the concentration of substrate targeted in the design at all monitoring locations within the reaction zone is considered successful.
Determine if optimal geochemical conditions were achieved	Pre- and post-injection concentrations of geochemical indicator parameters in groundwater.	Achieving highly reducing conditions with ORP less than -200 mV throughout the reaction zone is considered successful.
Determine remediation effectiveness	Pre- and post-treatment contaminant concentrations in groundwater.	- A greater than 99 percent reduction in compound-specific concentrations is considered successful. - A greater than 90 percent reduction in total molar concentration of CAHs is considered successful.
Determine impacts to secondary water quality	Post-treatment concentrations of secondary water quality parameters (e.g., dissolved metals such as iron and manganese).	Maintaining concentrations of secondary water quality parameters below applicable regulatory criteria downgradient of the reaction zone is considered successful.
Determine impacts on hydraulic conductivity	Pre- and post-treatment measurements of hydraulic conductivity.	A less than 50 percent decrease in hydraulic conductivity is considered successful.
Determine substrate persistence and long-term effectiveness	Post-treatment concentrations of contaminants and soluble organic carbon at the end of the intended design life of the application.	A rebound in concentrations of less than 1.0 percent of the initial contaminant concentration after the application has been completed is considered successful.
Qualitative Performance Objectives		
Determine need for and cost of additional injections or monitoring	Actual work performed will be compared to the application design plan. The cost of additional work will be calculated when data are available, or a qualitative assessment will be made when cost data are not available.	An application that does not require additional injections or monitoring beyond that in the original design is considered successful.
Application in difficult hydrogeological conditions	Site geology (permeability, heterogeneity) and groundwater hydraulics (hydraulic conductivity, hydraulic gradient, and rate of groundwater flow).	An application where permeability, heterogeneity, or the rate of groundwater do not limit effectiveness is considered successful. Guidelines on these parameters are developed from examples where they impacted the effectiveness of the application

3.3 PERFORMANCE OBJECTIVE NO. 3: REMEDIATION EFFECTIVENESS

Pre- and post-treatment concentrations of the targeted contaminants are evaluated to determine the effectiveness of the remedy. The success of the application is evaluated by comparing concentrations to site-specific performance criteria, if established. Otherwise, a reduction in contaminant concentration of 99 percent or greater (over two orders of magnitude) is considered successful. For chlorinated aliphatic hydrocarbons (CAHs, or chlorinated solvents) where production of regulated intermediate dechlorination products may occur, a reduction in the total molar concentration of CAHs of greater than 90 percent is considered to be a success.

3.4 PERFORMANCE OBJECTIVE NO. 4: IMPACTS TO SECONDARY WATER QUALITY

Creating an anaerobic groundwater environment may lead to degradation of water quality. The term “secondary water quality” is used in this document to refer to water-quality issues or concerns, apart from the primary contaminants being treated, that result from substrate addition. For example, degradation of secondary water quality can occur as a result of mobilization of formerly insoluble forms of metals that occur naturally in the aquifer matrix, or from production of sulfides that affect taste and odor. Secondary water quality parameters that are evaluated include pH, chloride or salinity, total dissolved solids (TDS), sulfide, and dissolved metals or semi-metals (i.e., ferrous iron, manganese, arsenic, and selenium).

Exceeding secondary water quality standards within the reaction zone may be acceptable if water quality downgradient of the reaction zone is maintained. If concentrations of secondary water quality parameters are maintained below applicable regulatory standards downgradient of the reaction zone, then the application is considered successful in limiting or mitigating any potential adverse impacts.

3.5 PERFORMANCE OBJECTIVE NO. 5: IMPACTS TO HYDRAULIC CONDUCTIVITY

The hydraulic conductivity of the aquifer may be impacted by physical, chemical or biological processes. For example, the growth of biomass or the presence of non-soluble substrate (e.g., vegetable oil) in the pore space of the aquifer matrix may significantly reduce hydraulic conductivity. Pre- and post-treatment of hydraulic conductivity (typically from slug tests) are evaluated to determine the degree to which hydraulic conductivity within the reaction zone may have been reduced. Because hydraulic conductivity of most sediments ranges over several orders of magnitude, a reduction of less than 50 percent in the average hydraulic conductivity within the reaction zone is considered to be acceptable. A reduction in hydraulic conductivity greater than 50 percent may potentially result in contaminant bypass, unexpected deviation in plume migration patterns, or non-uniform delivery of subsequent substrate injections.

3.6 PERFORMANCE OBJECTIVE NO. 6: SUBSTRATE PERSISTENCE AND LONG-TERM EFFECTIVENESS

Effective enhanced *in situ* bioremediation applications must sustain the reaction zone over the design life of the application. Substrate persistence and long-term effectiveness are evaluated using concentrations of soluble substrate and contaminants over the design life of the application. The depletion of organic substrate may result in less effective degradation of the targeted contaminants, and when this is observed an attempt has been made to determine an approximate

“threshold” concentration of soluble organic carbon that must be maintained for that particular site.

A rebound in contaminant concentrations may also occur after the remedy is halted. A rebound in contaminant concentrations of less than applicable regulatory standards, or less than 1.0 percent of the initial concentration before treatment, is considered as a successful endpoint to the bioremediation remedy.

3.7 PERFORMANCE OBJECTIVE NO. 7: NEED FOR AND COST OF ADDITIONAL INJECTIONS OR MONITORING

The cost associated with poor performance or compliance issues may significantly increase the life-cycle costs of full-scale enhanced *in situ* bioremediation applications. For example, poor performance may result in a need for longer-term operation. Compliance issues such as degradation of secondary water quality typically require additional monitoring or system modifications, also increasing the cost of the application.

Actual work performed is compared to the application design or work plan to determine whether additional work was required. An application is considered successful if additional injections or monitoring beyond that in the initial design are not required. When sufficient cost data are not available to quantify the cost for additional work, a qualitative assessment is made of the relative effort required to conduct the additional work.

3.8 PERFORMANCE OBJECTIVE NO. 8: APPLICATION IN DIFFICULT HYDROGEOLOGICAL CONDITIONS

There are limits to the hydrogeological conditions under which enhanced *in situ* bioremediation may be applied. Section 3 of AFCEE *et al.*, (2004) provides a description of some limiting factors associated with site lithology and groundwater hydraulics. A qualitative assessment is made to determine whether performance is related to adverse site conditions such as low permeability sediments, a high degree of heterogeneity, or high rates of groundwater flow. This information is used to develop practical guidelines for site screening, and for designing and optimizing substrate loading rates and injection scenarios for differing substrate types and for differing geochemical and hydrogeologic conditions.

4. DEMONSTRATION SITE SELECTION

Fifteen (15) sites were selected for evaluation of soluble, slow-release viscous fluids, and solid phase substrate types to ensure that a representative number of sites were included and to develop a valid spreadsheet calculator (Appendix B) to calculate stoichiometric substrate requirements. The following summarizes site selection criteria and provides a list of the demonstration sites selected for Phase I and Phase II evaluations.

4.1 SITE SELECTION CRITERIA

The hydrogeology, contaminant distribution, geochemical conditions, and enhanced bioremediation technical approach of each site was reviewed to determine if it was suitable and appropriate for this study. Site screening criteria for this demonstration are summarized in Table 4.1. Desired site characteristics for the demonstration sites include the following:

- Readily available work plans and results reports that describe how the system was designed and operated. Adequate site characterization, description of design criteria, and documentation of system performance are required.
- Adequate monitoring networks and multiple monitoring events. Monitoring over periods of at least 2 years when determining substrate depletion or recovery in aquifer redox conditions after substrate depletion. Concentrations should be sufficient to detect and measure enhanced rates of biodegradation. The presence of co-contaminants subject to anaerobic degradation processes may also be useful.
- A representative number of sites for each of the substrate categories.
- Differing injection methods including direct injection, recirculation, and biowall trenches.
- Differing injection scenarios including one time injection of slow release substrates and multiple injection (greater than 10 events) of soluble substrates.
- A point of contact (POC) with access to data and reports. Site access was necessary for the Phase II evaluations.
- Well characterized distribution of contaminants. Both vertical and horizontal delineation is preferred.
- Diverse hydrogeology to include permeable (sandy), high flow aquifers and low permeability (clays and silts), low flow sites.
- Diverse groundwater conditions. Including both low and high sulfate sites, and low and high iron and manganese sites.

Table 4.1
Summary of Site Selection Criteria

Parameter	Preferred Value(s)	Relative Importance	Comment
Design	Final Work Plan	1	Adequate description of design criteria.
Monitoring and Reporting	Final Report <i>or</i> Current Monitoring Results	2	Adequate documentation.
Representative Substrates	Minimum two sites for each substrate type.	3	To include vegetable oil, HRC [®] , molasses, lactate, and mulch biowalls.
Point of Contact (POC)	DoD POC with access to data and site access.	4	Beneficial to obtain work plans and data, required for Phase II evaluations.
Diverse injection scenarios	Differing injection methods including direct injection, recirculation, and biowall trenches. One time and multiple injection events.	5	Beneficial to evaluate substrate distribution and persistence between different amendment approaches.
Adequate site characterization	Well defined distribution of contaminants.	6	Adequate characterization of hydrogeology, stratigraphy, and groundwater geochemistry also desired.
Diverse hydrogeology and geochemistry	Varied low and high permeability sites, low and high rates of groundwater flow, low and high electron acceptor demand.	7	Determination of substrate loading rates should be sensitive to varied site conditions.

Not all selection criteria could be satisfied for every site. For example, not all substrates have well documented cases studies and some sites had not completed their designed treatment period. Site summary evaluations are included in Appendix C.

4.2 PHASE I SITES

In all, 15 sites were selected for the Phase I evaluation. The breakdown by substrate type includes three sites using vegetable oil or EVO, two sites using a combination of EVO and sodium lactate, two sites using HRC[®], one site using whey, two sites using molasses, one site using ethanol, two sites using sodium lactate, and two sites using mulch and compost (one of which has been replenished with EVO). Sites selected for the Phase I evaluation are listed in Table 4.2. Site summary sheets are included in Appendix C, and relevant observations for each site are provided in Section 5.3.

Table 4.2
Summary of Sites Selected for Evaluation of Substrate Loading Rates

	Site/Facility	Agency/Contractor	Notes	Usefulness
	Vegetable Oil			
1	Hangar K, CCAFS, FL	Air Force/Parsons	DNAPL source area, neat oil injection, over 5 years of monitoring data	Document long-term impacts of groundwater quality
2	Area C, Alliant Tech Systems, Elkton, MD	ESTCP/Solutions IES	Perchlorate and 1,1,1-trichloroethane (1,1-TCA)	Substrate distribution and depletion, co-contaminants (1,1,1-TCA and perchlorate)
3	SA17, NTC Orlando, FL	Navy/AGVIQ-CH2M Hill, Solutions IES	Temporary recirculation for injection. Low pH, low alkalinity, high sulfate.	Distribution of EVO substrate using recirculation techniques, pH excursion requiring buffering
	Vegetable Oil/Lactate Mix			
4	DP98, Elmendorf AFB, AK	Air Force/Parsons	High iron and manganese, low groundwater temperature, dechlorination stalled at <i>cis</i> -DCE.	Used stoichiometric approach in design. Lack of <i>Dehalococcoides</i> .
5	Kenney Avenue Plume, Elmendorf AFB, AK	Air Force/Parsons	High iron and manganese, low groundwater temperature, high rate of groundwater flow, dechlorination stalled at <i>cis</i> -DCE.	Required modification to the injection amendment to achieve sufficient reducing conditions. Lack of <i>Dehalococcoides</i> .
	HRC® Products			
6	Contemporary Cleaners, Orlando, FL	Florida Department of Environmental Protection/IT Corporation	Required additional injection, difficult hydrogeology and geochemistry.	Application methodology for HRC® products, revised injection plans.
7	Springdale Cleaners, Portland, OR	Oregon Department of Environmental Quality	Inferred DNAPL site, use of extended release HRC-X™ formulation.	Application methodology for HRC® products
	Whey			
8	East Gate Disposal Yard, Fort Lewis Logistics Center, WA	USACE, ESTCP/ North Wind, CDM	Compared low and high concentration electron donor solutions to enhance DNAPL bioavailability	Application methodology for whey using high electron donor solutions

Table 4.2
Summary of Sites Selected for Evaluation of Substrate Loading Rates

	Site/Facility	Agency/Contractor	Notes	Usefulness
	Molasses			
9	Site 1, Hanscom AFB, MA	Air Force/ARCADIS	Required multiple injections and revisions to injection design.	Application method for molasses.
10	Demonstration Site, Vandenberg AFB, CA	Air Force/ARCADIS	Required multiple injections and revisions to injection design.	Application method for molasses, required buffering for pH control.
	Ethanol			
11	Aerojet Facility, CA	Aerojet/ESTCP/GeoSyntec	Treatment of TCE, 1,2-dichloroethane (1,2—DCA), and perchlorate (SERDP CU 1164)	Used stoichiometric calculations for design to limit sulfate reduction and production of dissolved metals.
	Lactate			
12	Test Area North, INEEL, ID	DOE/North Wind	Multiple injection scenarios during optimization, DNAPL application.	Evaluate multiple injection scenarios and enhanced dissolution of DNAPL.
13	Building 1419, Indian Head NSWC, MD	Army/Shaw Group	Perchlorate application in low pH environment.	Required buffering to raise pH for effective degradation of perchlorate.
	Mulch Biowalls			
14	Area E, S, M, and F, NWIRP McGregor, TX	Navy/CH2M Hill	Recharge is part of long-term O&M	Recharge is based on substrate depletion and select geochemical indicator parameters
15	Building 301, Offutt AFB, NE	Air Force/GSI and URS Corporation	Over 6 years of data for evaluation of long-term sustainability	Sustainability of mulch biowalls

4.3 PHASE II SITES

Two DoD facilities were selected for collection of additional data to provide further evaluation and demonstration of the principles of determining substrate loading rates that are described in this study. Three sites were sampled at NTC Orlando, Florida, including SA17, OU-4, and OU-2. Two sites were sampled at Elmendorf AFB, Alaska, including the DP98 Site and the Kenney Avenue Plume. Details for sampling at the NTC Orlando sites and the Elmendorf AFB sites are included in the Demonstration Plan (Parsons, 2008).

The SA-17, OU-2, and OU-4 sites at NTC Orlando, Florida involved additional injections of EVO in the Fall of 2008. Past performance issues have tentatively been tied to inefficient substrate distribution or insufficient oil retention. These site offered an opportunity to sample soil before injection to determine oil retention characteristics. Soil analytical protocols for the NTC Orlando sites are listed and described in the Demonstration Plan (Parsons, 2008). Parameters analyzed as an indication of residual vegetable oil included total organic carbon (TOC), oil and grease with hexane extraction, and vegetable oil phospholipid fatty acids (PLFAs). Maximum oil retention was evaluated using a permeameter test method developed by Dr. Robert Borden under ESTCP Project ER-0626.

The DP98 and Kenney Avenue Plume sites at Elmendorf AFB, Alaska also were selected for Phase II evaluations to determine whether incomplete dechlorination is a result of geochemical conditions and/or microbiology. Dechlorination at both sites appears to stall at *cis*-DCE and VC. Microcosm studies indicate that acclimation of dechlorinating bacteria proceeds very slowly in the cold groundwater at these sites. Therefore, groundwater sampling (including molecular screening for *Dehalococcoides* reductase genes) was conducted at the older DP98 site, while only molecular screening was conducted at the younger Kenney plume Avenue Site. Analytical protocols for the DP98 Site and the Kenney Avenue Plume are listed and described in the Demonstration Plan (Parsons, 2008).

5. CASE STUDY EVALUATIONS

5.1 EVALUATION METHODS

This demonstration consisted of two phases of performance evaluation for the selected sites. Phase I involved an evaluation of sites based on work plans and results reports (Appendix C). Phase II involved collection of additional data (field mobilizations) to further investigate substrate distribution, methods used to determine substrate requirements, or to fill data gaps necessary to evaluate performance. The following subsections provide a description of the two evaluation phases, and a description of the field sampling and analyses that were performed.

5.1.1 Phase I Evaluations

Phase I evaluations consisted of a comparison of substrate loading rates and delivery methods. The objective of this evaluation is to better understand how substrate loading rates are currently estimated, and to evaluate how different substrate amendment scenarios affect substrate distribution, geochemical conditions, and groundwater hydraulics. Phase I evaluations for the 15 sites included the following:

1. How substrate loading rates were calculated or designed for each application (work plan review).
2. Evaluate distribution (using existing monitoring networks) and trends in concentrations of substrate (soluble organic carbon and volatile fatty acids [VFAs]) over time.
3. Evaluate what modifications to the substrate amendment protocol were required (e.g., concentration and frequency for soluble substrates; and depletion and additional injection of slow-release substrate types such as HRC[®] and EVO).
4. Evaluate the impact on life-cycle cost to implement modifications to injection protocols.
5. Evaluate efficiency in removal of chlorinated solvents based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Attempt to determine “threshold” concentrations of dissolved organic carbon (DOC) that represent the minimum levels required to sustain complete reductive dechlorination.
6. Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.
7. Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.
8. Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

The performance objectives listed in Table 3.1 were used to measure the relative success of the Phase I demonstration sites. Stoichiometric hydrogen demand is compared to guidelines and

methods used by various practitioners, since these methods are often based on the practitioners experience at tens to perhaps a hundred or more sites.

5.1.2 Phase II Evaluations

Phase II consisted of select field evaluations to evaluate the following:

1. For EVO, methods to calculate the amount of substrate needed are based in large part on the retention of oil within the soil matrix (AFCEE, 2007). Values used for oil retention are currently based on limited laboratory bench tests conducted by Dr. Robert Borden at North Carolina State University. The calculation method was tested for samples from Naval Training Center (NTC) Orlando.
2. Sampling was conducted to determine the persistence of substrate and longevity of an application at the DP98 Site, and causes for incomplete dechlorination at the DP98 and Kenney Avenue Plume sites, at Elmendorf AFB, Alaska.

Sampling activities at NTC Orlando are summarized in the case study evaluation in Appendix C. Sampling focused on determining the oil retention capacity of soils at SA-17, OU-4, and OU-2. Pre-injection samples were collected and evaluated for oil retention using the permeameter method described in the design tool for ER-0626. These results may be used to build a database for comparing soil properties (grain size distribution, bulk density, fraction organic carbon, and clay content) to oil retention.

Sampling activities and locations for the DP98 Site at Elmendorf AFB, Alaska are described in Appendix D. In addition, sampling for *Dehalococcoides* species and reductase genes was conducted at the Kenney Avenue Plume, where a rigorous biogeochemical sample protocol was implemented by the Air Force.

5.2 SUBSTRATE ESTIMATING TOOL

A substrate estimating tool (**Appendix B**) was developed to assist the practitioner in evaluating a site for an enhanced *in situ* bioremediation application. The primary objectives of this tool are to:

- Evaluate the site-specific conditions regarding hydrogeology and geochemistry in regards to the demand exerted by both natural and anthropogenic electron acceptors,
- Screen for site conditions that require special consideration, such as excursion of pH outside of a range optimal for dechlorinating microorganisms, and
- Evaluate and compare the concentrations of differing substrate types necessary to meet the electron acceptor demand.

This tool was used during the case study evaluations to compare the substrate amendment designs and actual quantities used to the substrate requirements calculated by the tool using site-specific electron acceptor demand. A description of how the tool works and guidance on using it for site screening purposes is included in Appendix B.

5.3 CASE STUDY EVALUATIONS

Individual case study summaries are included in Appendix C. The following subsections describe the notable characteristics of each case study and the observations that are relevant to the evaluation of the performance objectives described in Section 3. Individual performance objectives are evaluated in greater detail in Section 6.

5.3.1 Vegetable Oil Applications

Three sites were selected for evaluation of vegetable oil substrates (Table 4.2) and include Hangar K, Cape Canaveral Air Force Station (CCAFS), Florida; SA17 at NTC Orlando, Florida; and Area C at the Alliant Techsystems Facility in Elkton, Maryland. Two additional sites were selected which used a mixed vegetable oil/lactate substrate amendment. These include the DP98 Site and the Kenney Avenue Plume at Elmendorf AFB, Alaska.

5.3.1.1 Hangar K, CCAFS, Florida

Data from the Hangar K site are used to evaluate the ability of a single injection to sustain the reaction zone over a period of over 5 years, including the impact on groundwater quality and the ability of the aquifer to rebound to natural conditions after the substrate was depleted. An empirical approach was used to determine the loading rate for neat vegetable oil at this site, based in part on a pilot “push-pull” test. The expanded pilot test used an injection of 55 gallons neat oil per injection point with 10-foot screens, followed by 200 gallons of native groundwater to push the oil into the formation and result in a saturation that was sufficiently low enough to limit mobility of the oil.

Concentrations of TCE within the treatment zone were reduced from baseline concentrations of greater than 100,000 micrograms per liter ($\mu\text{g/L}$) to below the United States Environmental Protection Agency (USEPA) Maximum Contaminant Level (MCL) of 5.0 $\mu\text{g/L}$ for TCE within three years of the Phase II injection. This represents a reduction in concentrations of TCE of over four orders of magnitude (>99 percent). During the same period, concentrations of *cis*-1,2-DCE and VC showed variable trends, generally peaking at approximately 7 to 21 months post injection, then declining. During the April 2006 sampling event, *cis*-1,2-DCE and VC concentrations were below USEPA MCLs at 7 of 11 locations sampled and 6 of 11 locations sampled, respectively. While VC has apparently accumulated at a few locations within the treatment zone, the observed increases in ethene concentrations indicate that VC is being dechlorinated. Of the eight well locations sampled for both the baseline (July 2000) and final sampling events (April 2006), reductions in total molar concentrations of chlorinated ranged from approximately 96 percent for one location to over 99 percent for the other seven well locations sampled. Therefore, the remedial effectiveness of the demonstration is considered successful.

Overall, monitoring data indicate that the effective life span of the application is on the order of 4 to 5 years. It is difficult to determine a “threshold” concentration of TOC necessary to sustain dechlorination at this site. But it appears that concentrations of chlorinated ethenes did not exhibit any rebound until TOC dropped below approximately 20 mg/L, and only at the upgradient fringe of the treatment zone where highly contaminated groundwater enters the reaction zone. The application at the Hangar K Site benefited from 1) high permeability that aided injection of neat vegetable oil, 2) low hydraulic gradient and rate of groundwater flow that

limited contaminant and native electron acceptor flux, and 3) calcareous sand that limited pH excursion.

An evaluation of secondary water quality indicates that concentrations of total manganese and ferrous iron were elevated within and downgradient of the reaction zone. Total manganese was measured as high as 17 mg/L and ferrous iron was measured as high 29 mg/L. Concentrations of total manganese and ferrous iron remained elevated in April 2006 (63 months post-injection), even after concentrations of TOC were depleted. This indicates that the groundwater geochemistry at the site will be slow to rebound to natural background conditions. The shallow groundwater at the Hangar K Site is not a drinking water source, and the magnitude of the increase in concentrations of total manganese and ferrous iron does not appear to be an issue at this site.

5.3.1.2 Area C, Alliant Techsystems Facility, Elkton, Maryland

The Area C application at the Alliant Techsystems facility (ATK) in Maryland was an ESTCP Demonstration Site (ER-0221), which is also being modeled for an EVO substrate distribution optimization tool (ER-0626). Evaluation under this study furthers the understanding of how substrate loading rates impact groundwater geochemistry and the maintenance and sustainability of the reaction zone. The amount of EOS[®] emulsified oil product to inject was based on two methods including 1) the oil required for biodegradation (stoichiometric demand and organic carbon released), and 2) the oil retention by the aquifer sediment. The application had an effective life span of 2.5 to 3.5 years based on depletion of TOC, versus the design life of 3 years.

Perchlorate concentrations in the injection wells were reduced to below detection (<4 µg/L) within 5 days of injection, but increased to an average of 89 µg/L at 68 days post injection and remained above that level for the duration of the pilot test. However, removal efficiencies in the injection wells remained above 80 percent through 36 months of post-injection monitoring. Better overall reductions were observed in the downgradient wells, ranging from 97.1 to 99.9 percent from 1 to 42 months post injection. Maximum efficiencies were observed during both the first 4 months and during a period between year 2 and 3 when groundwater flow velocity slowed due to shutdown of a downgradient groundwater extraction system. After 3.5 years post-injection, residual TOC was limited and the resumption of pump and treat system operation resulted in a drop in perchlorate removal efficiency.

The pilot test was also effective in enhancing reductive dechlorination of 1,1,1-trichlorethane (1,1,1-TCA), PCE, and TCE. Increases in the concentration of daughter products (1,1-dichlorethane [1,1-DCA], CA, *cis*-DCE, VC and ethene) were observed. Dechlorination efficiency reached a maximum between year 2 and 3, when groundwater flow velocity slowed and contact time in the biobarrier increased. Concentrations of chlorinated solvents did not approach regulatory drinking water criteria, although that was not a primary performance measure for the demonstration.

5.3.1.3 SA-17, NTC Orlando, Florida

The SA-17 site at NTC Orlando reflects more recent methods employed to determine a substrate loading rate for EVO, and the SA-17 application employed a recirculation technique to enhance

substrate distribution. However, EVO recirculation was less effective in certain locations because groundwater recovery and injection rates were lower than rates from aquifer testing (i.e., recirculation was difficult to perform). In addition, subsurface heterogeneity (silt and clay lenses) limited substrate distribution. Follow-up injections using direct-push techniques were planned to enhance substrate distribution.

This site was also selected for Phase II sampling to determine site-specific characteristics for oil retention. The Naval Facilities Engineering Command (NAVFAC) conducted field sampling, while this ESTCP demonstration provided soil and oil retention analytical services. Additional samples were collected from the OU-2 and OU-4 sites at NTC Orlando to supplement the data at SA-17. The soil analytical data are summarized in the SA-17 case study in Appendix C.

5.3.1.4 DP98, Elmendorf AFB, Alaska

The DP98 Site used a stoichiometric approach to determine substrate requirements, including both sodium lactate to rapidly induce anaerobic conditions and EVO to sustain the reaction zone. This site was also sampled for a Phase II evaluation (Appendix D), which demonstrated that substrate levels remained elevated at 35 months post-injection. However, performance was compromised by low groundwater temperatures and a high electron acceptor demand exerted by manganese and iron.

Dechlorination of TCE to *cis*-DCE was only observed after methanogenesis was induced, and further dechlorination to VC and ethene was limited. While concentrations of TCE were reduced to below detection within the injection zone, concentrations of *cis*-DCE remained elevated and concentrations of VC were observed to increase in June 2008 (approximately 3 years post-injection). As a result of incomplete dechlorination, substantial reductions in total molar concentrations of chlorinated ethenes were not observed. Phase II sampling demonstrated that that only very low concentrations (close to or below detection limits) of *Dehalococcoides* are present in groundwater at the site.

5.3.1.5 Kenney Avenue Plume, Elmendorf AFB, Alaska

The Kenney Avenue Plume at Elmendorf AFB also used a stoichiometric approach to determine substrate requirements. Three injections were conducted because groundwater flow rates are in excess of 800 feet per year (ft/yr). Sulfate was also added to stimulate production of reduced iron sulfides. This data is used to evaluate the relationship between stoichiometric calculations and achieving optimal geochemical conditions.

Application of enhanced *in situ* bioremediation at the Kenney Avenue Plume is limited by site-specific conditions. Conditions that contribute to the limited effectiveness of the treatability study include 1) high rates of groundwater flow that disperse the substrate and limit the ability to sustain highly reducing conditions, 2) low populations of microbes (*Dehalococcoides*) capable of sequential dechlorination of TCE all the way to ethene, and 3) slow rates of microbial activity due to low groundwater temperatures (less than 10 degrees Celsius [°C]).

The high groundwater flow rate (888 ft/yr) is close to an upper limit suitable for applying enhanced *in situ* bioremediation. The high rate of groundwater flow was a primary reason for having to modify the substrate to a form (coarse field-mixed EVO) that does not readily disperse.

5.3.2 Hydrogen Release Compounds (HRC[®] and HRC-X[™])

Two sites were selected for evaluation of HRC[®] and HRC-X[™] (extended release formula), including the Contemporary Cleaners site in Orlando, Florida and the Springdale Cleaners site in Portland, Oregon. These applications are used to evaluate software used by the vendor to determine the application rate for HRC[®] and HRC-X[™].

5.3.2.1 Contemporary Cleaners, Orlando, Florida

HRC[®] was applied to an upper and lower zone during two mobilizations at the Springdale Cleaners site in Orlando, Florida. Substrate loading rates were based on recommendations from Regenesi Bioremediation Products, specified in pounds of product per vertical foot with specification of injection point spacing. The HRC[®] product released elevated levels of organic acids, although the distribution was not uniform or consistent from one monitoring event to another. The effective duration of the HRC application in the upper surficial aquifer was in the range of 7 to 27 months, while substrate persisted for at minimum of 12 months in the lower aquifer zone. This is attributed to site-specific conditions including aquifer heterogeneity and slow rates of groundwater flow that limited dispersion of organic acids released from the HRC[®] product.

Kean *et al.* (2003) attributed a stall in dechlorination of *cis*-DCE to excessive methanogenesis. They report a correlation between the accumulation of *cis*-DCE and methanogenesis, such that dechlorination of *cis*-DCE began to occur after methanogenesis subsided. This suggested to the authors that methanogens were out-competing the halo-respiring bacteria. An alternative explanation may be that pH was less than optimal, with pH of less than 5.0 in many locations shortly after injection.

5.3.2.2 Springdale Cleaners, Portland, Oregon

HRC-X[™] was applied to a potential DNAPL source zone at the Springdale Cleaners site, and the standard HRC[®] product was applied to a dissolved portion of the contaminant plume. This site is used to evaluate the relationship between stoichiometric calculations and design factors, achieving optimal geochemical conditions, and substrate persistence and longevity.

The HRC[®] product in the dissolved plume was able to maintain elevated concentrations of total organic acids for a minimum period of 18 months (1.5 years). The HRC-X[™] product applied in the source zone was able to maintain a total organic acid concentrations of 64 to 4,230 mg/L at 1,247 days, an effective period of 3.4 years (at a minimum).

While the Springdale Cleaners application was effective at reducing the concentrations of PCE in groundwater at the site, site-specific performance objectives for all chlorinated compounds were not achieved due to the accumulation of *cis*-DCE and VC. The threshold concentration to stimulate effective dechlorination was reported to be from 80 to 100 mg/L. Therefore, additional injections and longer term operation and monitoring are likely required to meet all the site-specific remedial objectives.

5.3.3 Whey (East Gate Disposal Yard, Fort Lewis, Washington)

This ESTCP demonstration site (ER-0218) was selected because varying amounts of the product were applied to evaluate the impact of enhanced mass transfer using a high dosage rate in a DNAPL source area. Because the objective of this demonstration was to evaluate enhanced mass transfer from a DNAPL to a soluble phase, stoichiometric calculations were not used for this demonstration.

Laboratory studies demonstrated that whey solutions increased effective solubility of TCE as a linear function of the dissolved organic matter concentration in the range from 0% to 6% by weight (Macbeth *et al.*, 2006; Macbeth, 2008). From 6% to 10% whey powder concentrations, the solubility of TCE increases at a slower rate. It was expected that at low concentrations of whey powder (1% by weight), enhanced mass transfer would be due primarily to mechanisms associated with biological anaerobic dechlorination. At a high whey powder concentration (10% by weight), it was thought that mass transfer of TCE from DNAPL would be enhanced to a greater extent due to physiochemical interactions between the electron donor solution and TCE mass occurring as DNAPL or sorbed to the aquifer matrix.

Significant biological inhibition of dechlorination of *cis*-DCE and VC occurred during the initial periods of low pH. While dechlorination was initially incomplete, this was useful for maintaining a mass balance to evaluate enhanced dissolution. Monitoring towards the end of the demonstration showed that in seven of eight downgradient wells, mass flux based on total chloroethene concentrations had decreased by a factor of 94 to 99% in May 2006. This indicates that anaerobic degradation of volatile organic compounds (VOCs) was stimulated, and was sufficient to degrade a large proportion of VOC mass that was transferred to the aqueous phase.

5.3.4 Molasses

Two sites were evaluated for application of dissolved molasses (Table 4.2), which include Site 1 at Hanscom AFB, Massachusetts and the Demonstration Site at Vandenberg AFB, California. Data from these sites are used to evaluate the methods described in the ESTCP/AFCEE protocol document for applying soluble carbohydrate substrates (Suthersan *et al.*, 2002).

5.3.4.1 Site 1, Hanscom AFB, Massachusetts

A demonstration of molasses injection was conducted at Site 1 at Hanscom AFB, Massachusetts as part of ESTCP Project ER-9920. The substrate loading rate for the Hanscom AFB demonstration was based on empirical methods, with the initial dosing anticipated to be 40 to 80 pounds (lbs) of carbohydrates (molasses) per injection well per week. The dosing objectives were to achieve concentrations of TOC from 500 to 5,000 mg/L in the injection well, and greater than 50 mg/L TOC in the downgradient monitoring wells. It was anticipated that the dosing rate and frequency would be adjusted based on field observations, and determining the optimal strength and frequency of reagent delivery was a primary objective of the demonstration.

Substrate (molasses) dosing was variable during the demonstration, as was the use of a water chase to disperse the substrate. The substrate loading for each injection event was based field observations to limit pH excursion in the injection well, while trying to maximize target concentrations of TOC in downgradient wells. The ability to inject substrate mixtures of higher

concentration to achieve a broader distribution at target concentrations was limited by pH excursion at the injection well. A buffering agent had to be used to achieve target TOC concentrations near the injection well.

The biggest factor inhibiting bioremediation performance was an adverse excursion in pH due to the low buffering capacity of the aquifer. The amount of substrate injected had to be limited until a buffering agent was added to the injection solution. This initially resulted in limited distribution of substrate and poor initial results. Once the buffering agent was added, higher strength substrate solutions could be injected and degradation results improved.

5.3.4.2 Demonstration Site, Vandenberg AFB, California

A second demonstration of molasses injection was conducted at Site 35 at Vandenberg AFB, California as part of ESTCP Project ER-9920. The substrate loading for each injection event was based field observations to limit pH excursion in the injection wells, while trying to maximize target concentrations of TOC in downgradient wells. The site exhibited low buffering capacity, and pH was initially controlled by limiting the substrate dose, reducing the frequency of injection, and injection of an occasional clean water “push” to disperse dissolved substrate away from the immediate vicinity of the injection wells. This revised dosing regime was necessary to avoid further drops in pH, but negatively affected the consistency of the TOC level in the injection and downgradient monitoring wells and resulted in a limited reaction zone.

Sodium bicarbonate was added to the injection regimen at 20 months after injections started in an attempt to control pH excursion. This allowed for a nearly four-fold increase in the molasses loading rate and helped to expand the reaction zone. Stabilization and mild recovery of pH was observed at most downgradient monitoring wells following the addition of a buffering agent.

5.3.5 Ethanol and Lactate

Three sites were selected for evaluation of ethanol and lactate (Table 4.2), and include 1) Area 20, Aerojet Facility, Rancho Cordova, California; 2) Test Area North (TAN), Idaho National Engineering and Environmental Laboratory (INEEL), Idaho; and 3) Building 1419, Indian Head Division, Naval Surface Warfare Center (NSWC), Maryland.

5.3.5.1 Area 20, Aerojet Facility, California

The application at Area 20, Aerojet Facility, Rancho Cordova, California used ethanol and a stoichiometric approach to limit degradation of secondary water quality (e.g., mobilization of metals). Bioaugmentation was used to stimulate complete reductive dechlorination of TCE under moderately reducing conditions. Ethanol was a highly effective and efficient electron donor for reduction of perchlorate, nitrate and TCE. At a concentration of 50 mg/L (a 3:1 donor to acceptor ratio), the degree of reductions in perchlorate and TCE indicates that little substrate was wasted on non-required microbial processes. Ethanol was rapidly metabolized to acetate and propionate, which were subsequently used as secondary electron donors and depleted within 100 feet of the re-injection well.

The electron acceptor calculations did not account for iron reduction, manganese reduction, or methanogenesis. Furthermore, the calculations were based on balanced redox reactions directly

with ethanol, versus calculations based on fermentation of ethanol to produce molecular hydrogen (H₂). While these conventions may underestimate the substrate requirement, the use of three times the calculated electron acceptor demand resulted in highly efficient transformation of perchlorate and TCE without significant production of methane.

5.3.5.2 Test Area North, INEEL, Idaho

The TAN INEEL site is a source area application in a deep, fractured rock. An area approximately 200 feet (60 meters) in diameter is being treated, primarily focused on the upper 100 feet (30 meters) of the aquifer. Both field and laboratory data have demonstrated that injection of high concentration solutions of sodium lactate and whey have enhanced depletion of source mass (DNAPL) by enhancing mass transfer into the aqueous phase.

The TAN INEEL application used an experimental approach to optimize injections of sodium lactate and whey for distribution of substrate and maintenance of the reaction zone over a large area from just a few injection wells. The initial treatment cell consisted of a 500-foot long aquifer zone, with a single injection well (TSF-05) and 14 monitoring wells throughout the treatment cell (including multiple depths in two wells). An additional injection well was added at a later date to create a larger reaction zone.

Enhanced bioremediation field activities were initiated at TAN in 1998 and have been ongoing since. Over the first four years, the remedy went through several phases to test and optimize injections of sodium lactate. The volume, concentration, and frequency of injection were varied to evaluate the optimal injection strategy. In general, a high volume, relatively low concentration injection every 8 weeks was found to be highly effective.

Following the first four years of injections and optimization studies, the system was expanded with additional injection and monitoring wells, and tests using whey were conducted. For example, the initial whey injection design called for 12,000 gallons of a 10% by weight (wt/wt) whey solution at 40 gallons per minute (gpm), followed by a 2,000 gallon water push. Testing at this site indicates that biodegradation rates remain faster than the mass transfer kinetics resulting from injection of high concentration lactate and whey solutions. This has led to an optimization strategy devoted to accelerating mass transfer rates. This case study illustrates many of the optimization measures that can be used for enhanced *in situ* bioremediation applications.

5.3.5.3 Building 1419, Indian Head Division, NSWC, Maryland

The Building 1419 site at Indian Head NSWC, Maryland was for a demonstration perchlorate reduction using a recirculation system, where perchlorate biodegradation was observed to be pH sensitive. The application used a stoichiometric approach validated with laboratory studies, and included a buffering compound to maintain pH.

Microcosm studies indicated that perchlorate reduction did not occur at an ambient pH of approximately 4.3, but perchlorate was reduced by native microorganisms when pH was raised to 7.0 with a pH modifier (sodium carbonate). Additional microcosms demonstrated that perchlorate reduction could be achieved using sodium lactate as the organic substrate and by raising the pH to 7.0 to 7.3. The microcosm study used approximately 250 mg/L of sodium lactate. For the initial design, 380 mg/L of lactate was chosen to provide a reasonable excess of

electron donor based on average concentrations of DO, nitrate, and perchlorate. There was no intent to stimulate sulfate reduction or methanogenesis, which were not desired to achieve effective perchlorate reduction.

Titration studies were performed using sediment and groundwater samples from the site and various mixtures of sodium carbonate and sodium bicarbonate. Based on the titration results and consideration of the ability to control the increase of pH, a concentrated stock solution (6.67%) of 80% bicarbonate and 20% carbonate was initially chosen for the concentrated buffer solution.

Concentrations of perchlorate throughout the test plot showed an overall decline during the 140 day demonstration. The average perchlorate concentration was 174 mg/L at 7 days prior to startup. By the end of the 20-week demonstration, the reduction in perchlorate levels in four wells was in excess of 99%, and over 95% in two other wells. One well only showed a reduction in concentration of perchlorate of 43%, ending at approximately 90 mg/L after 140 days. This well consistently had the lowest concentration of lactate during the demonstration.

5.3.6 Permeable Mulch Biowalls

Two permeable mulch biowall applications (AFCEE, 2008) were evaluated (Table 4.2), and include Areas E, F, M, and S, Naval Weapons Industrial Reserve Plant (NWIRP) McGregor, McGregor, Texas and Building 301, Offutt AFB, Nebraska.

5.3.6.1 Areas E, F, M, and S, NWIRP McGregor, Texas

Areas E, F, M, and S at NWIRP McGregor were selected primarily because an O&M plan was developed (EnSafe, Inc., 2005) to evaluate the need for biowall rejuvenation. The monitoring protocol developed to evaluate the need for rejuvenation was based on an optimization study (EnSafe, Inc., 2005). Parameters deemed the most useful for this evaluation (in addition to perchlorate) included TOC, nitrate, and methane. DO and ORP are primarily monitored as well purging parameters, but are also included in the evaluation.

Three methods were evaluated to determine substrate loading rates for biowall rejuvenation. The first method was based on a recommendation from the emulsified oil vendor (EOS Remediation) to use a ratio of 0.1 to 0.4% EOS product by weight of the mass of solid media in the biowall. The second method used the EOS Remediation design spreadsheet and was based on electron acceptor demand and groundwater specific discharge through the biowall. The third method used an assumption initially used when the biowalls were installed. The first method yielded the lowest of the three calculated substrate requirements, and was selected based on economic considerations.

For Areas E, F, and M, the biowalls are operating as designed, meeting performance expectations, and no replenishment was required as of 2008. The sampling ports for biowalls at Area S were mostly dry in 2008, with perchlorate below detection in the few that were sampled. Several biowalls at Area S were replenished in June 2008. Overall the biowalls are performing to expectation, with occasional injection of EVO substrate required.

5.3.6.2 Building 301, Offutt AFB, Nebraska

The Building 301 biowall at Offutt AFB, Nebraska was used to evaluate long-term performance of a mulch biowall without substrate replenishment, for comparison to replenishment options at the NWIRP McGregor biowall systems. The full-scale application has an effective life span of at least 5 years based on monitoring in August 2006. Over the first 31 months of operation, the pilot biowall was found to remove 75 percent of TCE and 64 percent of the total chlorinated ethenes in groundwater passing through the pilot biowall. Biotic reductive dechlorination was responsible for some of the removal as evidenced by the production of dechlorination products (e.g., *cis*-DCE), but molar conservation of TCE to DCE to VC and ethene was not observed. Therefore, other degradation processes are thought to account for the extent of TCE removal (Parsons, 2010).

Greater reductions in concentrations of TCE have been observed in the full-scale biowall system. In the north section of the full-scale biowall, removal of up to 95 percent of TCE and 80 percent of total CAHs was observed through 2003 (Groundwater Services, Inc. [GSI], 2004). The B301 biowalls remain very effective at reducing concentrations of TCE and *cis*-DCE in August 2006, five years after installation of the full-scale biowall. Concentrations of TCE in August 2006 are reduced by over 99 percent within the downgradient pilot biowall relative to upgradient concentrations, to concentrations below 1.0 µg/L. Reductions in the concentration of *cis*-DCE are less pronounced in the full-scale biowall, but a reduction in *cis*-DCE is observed in the pilot biowall without an accumulation of VC. Concentrations of *trans*-DCE have increased over time within the biowalls, and this may indicate that the biowalls are losing their effectiveness to completely transform TCE to innocuous end products.

TOC measured within the biowalls in August 2006 was at concentrations less than 5.0 mg/L. Historically, the highest concentration of TOC at the B301 Site was 11.8 mg/L at location MW24S in July 2001. This well is located downgradient of the full-scale biowall. These are relatively low concentrations of TOC for stimulating *in situ* anaerobic bioremediation. Given the evidence for sulfate reduction and methanogenesis within the biowalls, it appears that TOC or DOC are not good indicators of the degree to which the biowalls can stimulate and sustain anaerobic biodegradation processes (Parsons, 2010). The mulch media is an excellent growth substrate. Microbes may be growing as a film on the surface of the mulch and utilizing the mulch by hydrolysis of complex organics without release or accumulation of organic carbon in the soluble phase. Therefore, biowalls may require a “multiple lines of evidence approach” to evaluate substrate depletion, similar to that employed for the NWIRP McGregor biowalls.

6. SUMMARY OF CASE STUDY EVALUATIONS

6.1 SUMMARY OF CASE STUDY PERFORMANCE CRITERIA

The following evaluation of the demonstration case study sites focuses on the performance criteria listed in Table 3.1. These criteria are intended to identify specific performance issues. The ability to modify the system design to overcome these issues is included in the evaluation. Table 6.1 presents a summary evaluation of the success of each site to meet each performance criteria, which are discussed in more detail in the following sections.

6.1.1 Ability to Uniformly Distribute Substrate

The distribution of substrate was evaluated using concentrations of soluble organic carbon (TOC, DOC, or VFAs) measured within the reaction zone. This data is typically monitored to understand the effects that substrate amendment loading rates have on substrate distribution. Overall, 10 of the 15 case study sites were able to effectively distribute substrate without modifications to the substrate delivery design (Table 6.1, Appendix C). The other five sites had limited success due to site conditions, and several required modifications to the injection protocol.

Injection of EVO using a recirculation configuration was used at the SA-17 Site at NTC Orlando, Florida. Low yield from the extraction wells and moderate aquifer heterogeneity limited the distribution of substrate (Hudson *et al.*, 2009). Additional injections using direct-push techniques have been used to obtain better substrate distribution

A commercial EVO product was readily injected at the Kenney Avenue Plume at Elmendorf AFB, Alaska. However, the coarse grained nature of the aquifer and a high rate of groundwater flow (over 800 ft/yr) resulted in the substrate being dispersed over a broad area and a highly reducing reaction zone could not be sustained (USAF, 2009). This was corrected by modification of the substrate mixture to a coarse, field-mixed emulsion of larger droplet size. Greater entrapment of the oil droplets in the reaction zone resulted in appropriate reducing conditions being achieved and sustained over a minimum period of 9 months.

Injection of HRC[®] products in the upper and lower surficial aquifers at the Contemporary Cleaners site in Florida generally resulted in reducing (methanogenic) conditions and degradation of TCE (Kean *et al.*, 2000 and 2003). However, a review of data for organic acids indicates that the presence and persistence of organic acids in both the upper and lower surficial aquifers was highly variable. For example, in three wells in the upper surficial aquifer, total organic acids ranged from below detection to as high as 410 mg/L over a period of 27 months following injection (Appendix C). The slow rate of groundwater flow at this site (estimated to be 16 ft/yr in the upper surficial aquifer and 2.6 ft/yr in the lower surficial aquifer) may have limited the dispersion of organic acids.

Table 6.1
Summary of Achieving Performance Objectives

Performance Criteria (from Table 3.1)								
Site	1. Substrate Distribution	2. Optimal Geochemical Conditions	3. Remediation Effectiveness	4. Impacts on Secondary Water Quality	5. Impacts on Hydraulic Conductivity	6. Substrate Persistence/ Longevity	7. Need for Additional Injections or Monitoring	8. Difficult Hydrogeological Conditions
Hangar K, CCAFS, FL	Successful	Successful	Successful	Potential – elevated levels of manganese and iron	Successful (no apparent impact)	Successful (4 to 5 year lifespan)	Successful (no additional injections)	None encountered
Area C, Alliant Techsystems, Inc., Elkton, MD	Successful	Successful	Moderately successful for perchlorate, less successful for chlorinated solvents. Greater removal efficiencies could have been achieved with longer contact time.	Potential – elevated levels of manganese and iron. Fouling of downgradient extraction/air stripping system occurred until substrate levels began to decrease.	Moderately successful. A moderate decrease in hydraulic conductivity was observed, but did not impact overall effectiveness.	Successful (2.5 to 3.5 year lifespan)	None for pilot test. Long-term operation of a biobarrier may need additional injections for operation over periods of 3 years or more.	Higher rates of groundwater flow were encountered after injection due to a downgradient extraction trench. This limited the extent of degradation.
SA-17, NTC Orlando, FL	Initial recirculation was limited by low yield and aquifer heterogeneity	Low pH	To be determined – follow up injections performed	To be determined	To be determined	To be determined	Follow up injections using direct-push techniques	Low yield and heterogeneity limited the effectiveness of a recirculation approach
DP98, Elmendorf AFB, AK	Successful	Successful	Limited – Incomplete dechlorination to <i>cis</i> -DCE (lack of <i>Dehalococcoides</i>)	Potential – High levels of manganese and iron, but background above criteria	Moderately successful. A moderate decrease in hydraulic conductivity was observed, but did not impact overall effectiveness.	Successful (minimum 3 year lifespan)	Successful (no additional injections)	None encountered
Kenney Avenue Plume, Elmendorf AFB, AK	Successful only after modifications	Successful with modifications	Limited – Incomplete dechlorination to <i>cis</i> -DCE (lack of <i>Dehalococcoides</i>)	Potential – High levels of manganese, but background above criteria	Moderately successful. A moderate decrease in hydraulic conductivity was observed, but did not impact overall effectiveness.	Successful only after modifications	Required Modifications – last injection met longevity objectives	High rate of groundwater flow limited ability to achieve reducing conditions
Contemporary Cleaners, Orlando, FL	Limited success – Uneven distribution in of organic acids in space and time	Highly reducing with methanogenesis, but low pH (often less than 5.0 su)	Limited – Rapid removal of PCE but accumulation of <i>cis</i> -DCE in lower aquifer	Potential – High levels of iron, but background above criteria	Successful (no observed impact)	Moderately successful – Organic acids elevated for periods of 7 to 27 months	Successful (no additional injections)	Low rates of groundwater flow may have limited dispersion of organic acids
Springdale Cleaners Site, Portland, OR	Appears successful – Limited monitoring data	Successful	Limited – Rapid removal of PCE and TCE but accumulation and limited degradation of <i>cis</i> -DCE and VC	Potential – High levels of manganese and iron, but background above criteria	Successful (no observed impact)	Successful – Effective for minimum 1.5 years in dissolved plume and 3.4 years in source zone	Successful (no additional injections)	None encountered

Table 6.1
Summary of Achieving Performance Objectives

Performance Criteria (from Table 3.1)								
Site	1. Substrate Distribution	2. Optimal Geochemical Conditions	3. Remediation Effectiveness	4. Impacts on Secondary Water Quality	5. Impacts on Hydraulic Conductivity	6. Substrate Persistence/ Longevity	7. Need for Additional Injections or Monitoring	8. Difficult Hydrogeological Conditions
East Gate Disposal Yard, Fort Lewis Logistics Center, WA	Successful	Successful	Successful	Potential – Low pH and elevated ferrous iron	Successful (no observed impact)	Successful (no observed rebound)	Successful (no additional injections)	A moderate degree of heterogeneity and low yield did require re-installation of extraction and injection wells.
Site 1, Hanscom AFB, MA	Limited success – pH excursion limited substrate quantities until a buffer was added	Limited success – Only achieved in immediate vicinity of injection wells	Limited success – Performance objectives achieved only in immediate vicinity of the injection zone	Potential – High levels of manganese and iron, but background above criteria	Successful (no observed impact)	Successful – No rebound observed after 17 months	Additional injections required. Fouling and compromise of injection seal reduced injection rate from 10 gpm to 1-2 gpm	Performance objectives could only be achieved after buffering agent added to the injection regimen.
Site 35, Vandenberg AFB, CA	Limited Success – pH excursion limited substrate quantities until a buffer was added	Limited– Reductions in TCE but <i>cis</i> -DCE and VC increased	Limited success – Performance objectives achieved only in immediate vicinity of the injection zone	Potential – Low pH and elevated sulfide persisted downgradient	Successful (no observed impact)	Successful – No rebound observed	Additional injections required and addition of buffer compound were required	Performance objectives could only be achieved after buffering agent added to the injection regimen
Area 20, Aerojet Facility, CA	Successful	Successful	Successful	Successful – Only limited manganese production	Successful	Not applicable – Short term pilot test	Not applicable – Short term pilot test	None, with the exception of biofouling of the injection well
Test Area North, INEEL, ID	Successful	Successful	Successful		Successful – None observed	Successful	Several successful optimization studies were conducted	None
Building 1419, Indian Head NSWC, MD	Successful	Successful	Successful	Insufficient data reported	Successful – None observed	Not applicable – Short term pilot test	Not applicable – Short term pilot test	None other than a need to account for moderate aquifer heterogeneity
Areas E,F,M, and S, NWIRP McGregor, TX	Successful	Successful	Successful	Successful – None observed	Successful – None observed	Successful with rejuvenation option	Rejuvenation with EVO is typically required every 3 to 4 years	Periods of high rates of precipitation may increase local rates of groundwater flow, and biowall performance could be impacted during these periods.
Building 301, Offutt AFB, NE	Successful	Successful	Successful	Potential – Slightly elevated levels of manganese and iron, but background above criteria	Biowall conductivity has decreased to slightly below that of the surrounding formation.	Successful – Continues to be effective 5 years after installation	May require replenishment within a couple years	None encountered

Distribution of dissolved molasses at Hanscom AFB, Massachusetts and at Vandenberg AFB, California was impacted by adverse excursion in pH, where both aquifers exhibit low buffering capacity. The substrate loading for each injection event was based field observations to limit pH excursion in the injection wells, while trying to maximize target concentrations of TOC in downgradient wells. pH was initially controlled by limiting the substrate dose, reducing the frequency of injection, and injection of an occasional clean water “push” to disperse dissolved substrate away from the immediate vicinity of the injection wells. This revised dosing regime was necessary to avoid further drops in pH, but negatively affected the consistency of the TOC level in the injection and downgradient monitoring wells and resulted in a limited reaction zone. Once a buffering agent was added to the substrate mixture, higher strength substrate solutions could be injected and distribution of substrate and degradation results improved.

In the cases described above, the ability to effectively distribute substrate was impacted by site-specific lithology (low or high permeability, heterogeneity), groundwater hydraulics (low or high rates of groundwater flow), and geochemistry (low buffering capacity and pH excursion). This reinforces the need to, and benefits of, conducting adequate site characterization prior to design and implementation of substrate addition. In most cases these conditions can be mitigated by modifying the injection mixture (substrate type and buffering amendment) or delivery technique (for example closer spaced injection points).

6.1.2 Achieving Optimal Geochemical Conditions

Achieving optimal geochemical conditions was evaluated by analyzing indicator parameters of anaerobic conditions, including DO, ORP, nitrate, manganese, ferrous iron, sulfate, methane, pH, and alkalinity. Achieving optimal geochemical conditions was usually defined as when the groundwater environment is highly anaerobic with DO less than 0.5 mg/L, ORP is less than -200 mV, sulfate is reduced by more than 50 percent relative to background conditions, and methane is greater than 1.0 mg/L. These criteria may not apply in all cases, and many sites had site-specific geochemical targets to limit sulfate reduction and methanogenesis as processes not necessary for effective treatment.

For all sites, reducing conditions suitable for reductive dechlorination of CAHs or for reduction of perchlorate were achieved when sufficient substrate was present. This typically required concentrations of DOC or TOC on the order of 20 to 50 mg/L. Mulch and compost substrates are an exception to a direct correlation between DOC and reducing conditions. Concentrations of DOC measured within the biowalls at the B301 Site at Offutt AFB in August 2006 were less than 5.0 mg/L. But given evidence for sulfate reduction and methanogenesis within the biowalls, it appears that DOC alone is not a good indicator of the degree to which the biowalls can sustain anaerobic degradation processes (Parsons, 2010). Therefore, biowalls require a “multiple lines of evidence approach” to evaluate substrate depletion.

The use of recirculation allows the best control of geochemical conditions. The demonstrations at the Area 20 Site at the Aerojet Facility, California and the Building 1419 Site at Indian Head NSWC, Maryland were both able to induce geochemical conditions suitable for reduction of perchlorate without stimulating a high degree of sulfate reduction and methanogenesis. This has the added benefit of limiting the impact of substrate addition on secondary water quality.

For the molasses applications where the concentration of substrate injected was limited by pH excursion, highly reducing conditions were limited to the immediate injection area. Once a buffering compound was added to the injection mixture, the concentration of substrate injected could be increased and the distribution of substrate and zone of highly reducing conditions improved. Achieving appropriate reducing conditions is a function of substrate distribution, and geochemical conditions may vary significantly from the point of injection where concentrations of DOC organic carbon are highest to the area downgradient where substrate is depleted.

To achieve uniform reducing conditions suitable for anaerobic degradation processes, careful thought should be given to how the substrate will be distributed and how uniform the concentration of DOC can be controlled. In practice, a “range” of concentrations of DOC will occur within the aquifer. Achieving optimal geochemical conditions will depend on establishing a reaction zone that sustains an appropriate range of substrate concentration. For slow release substrate, the reaction zone is often most reducing near the point of injection (see Figure 2.1). For soluble substrate, the most reducing conditions may occur in a zone downgradient of the point of injection as illustrated in Figure 6.1.

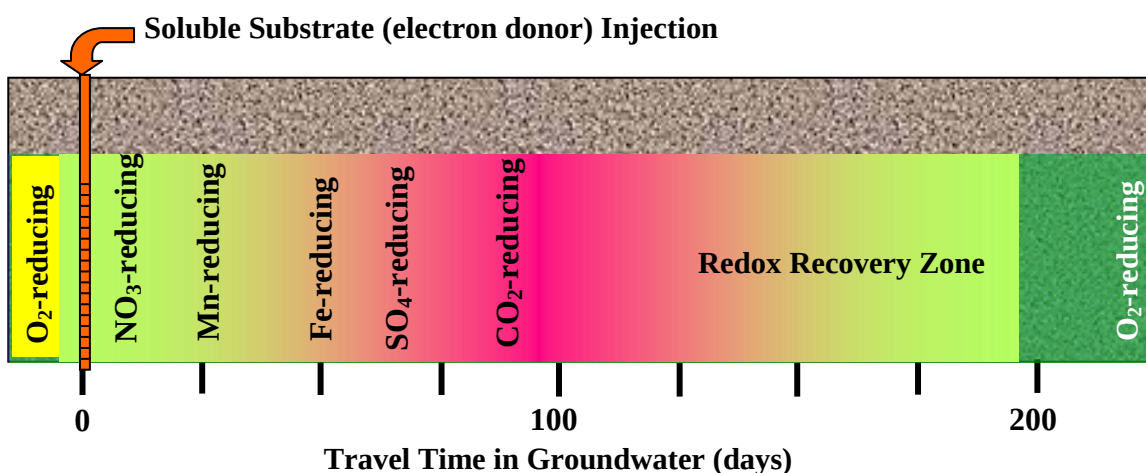


Figure 6.1 Reducing Zones Established Downgradient of Injection in a High-flow Aerobic Aquifer (Suthersan and Payne, 2003)

Lowering of pH was also a significant limitation at several sites, resulting from a combination of low buffering capacity of the aquifer and high concentrations of DOC. Control of the substrate loading rate is critical when treating aquifers with low buffering capacity. The best practices to mitigate pH excursion include careful screening of the site to determine whether a buffering compound should be added to the injection protocol, and selecting substrate delivery techniques that provide for more uniform distribution of substrate without excessive “spikes” in DOC.

6.1.3 Remediation Effectiveness

For each site, groundwater analytical data was used to determine whether performance objectives were met. Sites that exhibited incomplete dechlorination included the DP98 and Kenney Avenue Plume applications at Elmendorf AFB, Alaska; the Contemporary Cleaners Site, Florida; the Springdale Cleaners Site, Oregon; and Site 35 at Vandenberg AFB, California.

The primary factors attributed to incomplete dechlorination of chlorinated solvents include the following:

- Insufficient substrate distribution, either non-uniform distribution or low substrate concentrations.
- Inability to induce highly anaerobic conditions due to high rates of groundwater flow (e.g., initial injections at the Kenney Avenue Plume in Alaska).
- Insufficient residence time due to too small a reaction zone or high rates of groundwater flow (e.g., Area C at the ATK Facility, Maryland).
- Lack of growth or activity of *Dehalococcoides* species (e.g., DP98 and Kenney Avenue Plume sites at Elmendorf AFB, Alaska).
- Low pH that inhibits complete dechlorination (Section 8).

Similar to inducing optimal geochemical conditions, the first three factors correspond to adequate substrate distribution at appropriate substrate concentrations. The accumulation of *cis*-DCE and VC at sites such as the Contemporary Cleaners Site, the Springdale Cleaners Site, and Site 35 at Vandenberg AFB, California may also be due to non-uniform distribution of substrate and uniformly achieving highly reducing conditions. A lack of growth of appropriate strains of *Dehalococcoides* species at the Alaska sites is discussed in Appendix D, and may be due, in part, to low groundwater temperatures.

The best practices to mitigate these factors include the following:

- Selection of delivery techniques (e.g., closer spaced injection points or recirculation) that optimize uniform substrate distribution,
- Modifying the injection mixture (substrate type and buffering amendment) to limit adverse excursions in pH, and
- Bioaugmentation for sites with low populations of *Dehalococcoides* species or with species that lack the ability to transform *cis*-DCE and VC to ethene.

The Area 20 Site at the Aerojet Facility in California is an example of using recirculation to optimize substrate distribution, combined with bioaugmentation to achieve complete dechlorination of TCE. The careful control of substrate dosing and use of a bioaugmentation culture resulted in effective treatment without inducing highly anaerobic conditions (i.e., sulfate reduction and methanogenesis), limiting the potential for adverse conditions such as pH excursion and mobilization of metals.

6.1.4 Impacts to Secondary Water Quality

The term “secondary water quality” is used to refer to water-quality issues or concerns, apart from the primary contaminants being treated, that result from substrate addition. Production of

regulated intermediate degradation products of the primary contaminant (e.g., production of VC from TCE and DCE) is not considered a secondary water quality issue for this evaluation.

Table 6.2 lists common parameters monitored during enhanced *in situ* bioremediation and associated federal water quality standards. This list is not inclusive, as many USEPA regions and states enforce additional water quality standards. Generation of reduced sulfur compounds (e.g., thiols/mercaptans) that affect odor and taste, ketones (e.g., acetone and 2-butanone) or alcohols (e.g., isopropanol) may occur under extreme fermentation conditions. Several examples for USEPA Region 9 Preliminary Remediation Goals (PRGs) are included in Table 6.2 as examples. Other secondary water quality parameters that may be degraded include chemical oxygen demand (COD) and biological oxygen demand (BOD). Stimulating biodegradation also may enhance generation of volatile byproducts and noxious gases (e.g., methane and hydrogen sulfide) that may degrade groundwater quality and/or accumulate in the vadose zone.

Table 6.2
Secondary Water Quality Parameters Subject to Regulatory Compliance (modified from AFCEE *et al.*, 2004)

Compound or Element	Molecular Formula	USEPA MCL (mg/L) ^{a/}	USEPA Secondary Standard ^{b/} (mg/L)	USEPA Region 9 PRGs for Tap Water ^{c/} (mg/L)
<i>Volatile Organic Compounds</i>				
Acetone	C ₃ H ₆ O	--	--	5.5
Carbon Disulfide	CS ₂	--	--	1.0
Isobutanol	C ₄ H ₁₀ O	--	--	1.8
Methyl ethyl ketone (2-butanone)	C ₄ H ₈ O	--	--	7.0
Total trihalomethanes (includes CF)	--	0.080	--	
<i>General Water Quality Parameters</i>				
Nitrate (as nitrogen)	NO ₃ ⁻	10	--	10
Nitrite (as nitrogen)	NO ₂ ⁻	1.0	--	1.0
Sulfate	SO ₄ ⁻	--	250	--
Chloride	Cl ⁻	--	250	--
pH	--	--	<6.5, >8.5	--
Total dissolved solids (TDS)	--	--	500	--
Odor (e.g., sulfide)	--	--	3 threshold odor number	--
<i>Metals/Inorganics</i>				
Arsenic	As	0.01	--	0.045
Selenium	Se	0.05	--	0.18
Iron	Fe	--	0.3	11
Manganese	Mn	--	0.05	0.88

^{a/} USEPA MCL = USEPA Maximum Contaminant Level; mg/L = milligrams per liter.

^{b/} National secondary drinking water regulations are non-enforceable guidelines. However, states may choose to adopt them as enforceable standards.

^{c/} PRGs are USEPA Region 9 preliminary remediation goals for tap water.

Secondary water quality parameters that were evaluated for this study included VOCs resulting from fermentation reactions (e.g., acetone and methyl ethyl ketone), sulfate and sulfide, chloride, pH, total dissolved solids (TDS), and dissolved metals or inorganics (e.g., ferrous iron, manganese, arsenic, and selenium). Not all parameters were measured at each site, and often

data is only available for just a few of these parameters. Nonetheless, the evaluation provides some insight into how much of an issue secondary water quality is and what parameters typically provide the most potential to create a secondary water quality issue.

For each site, background concentrations of these parameters (as available) within and downgradient of the reaction zone were compared to background concentrations and to applicable regulatory criteria to determine whether secondary water quality has been adversely impacted. Table 6.3 summarizes this comparison for select cases studies with available data.

The most common secondary water quality issues include the following, in order of most common occurrence:

- **Dissolved Manganese.** Manganese oxides are common minerals in many aquifer sediments, and reduction of Mn^{4+} to soluble Mn^{2+} is a common occurrence. Manganese does not precipitate or sorb out of solution with as readily as ferrous iron (e.g., with sulfide), and dissolved manganese tends to persist farther downgradient within redox recovery zones. Sites with glacial sediments (e.g., Elmendorf AFB, Alaska) appear to be particularly prone to elevated concentrations of manganese, although natural levels of manganese may often be above regulatory criteria to start with.
- **Dissolved Iron.** Dissolved (ferrous) iron is also commonly observed at concentrations above its USEPA secondary water quality standard. However, dissolved iron typically precipitates or sorbs out of solution within a short distance of migrating out of the anaerobic reaction zone. Compared to manganese, dissolved iron attenuates more rapidly with distance downgradient. For sites with naturally high concentrations of dissolved iron, anaerobic bioremediation may exacerbate the condition.
- **pH.** Lowering of pH to below 6.5 is a common during enhanced anaerobic bioremediation. While low pH by itself may not by itself present a serious health hazard or nuisance issue, it may create other secondary problems. Low pH may enhance the solubility of heavy metals, enhance the potential for adverse fermentation reactions, and inhibit complete dechlorination.
- **Sulfide.** Hydrogen sulfide produced by sulfate reduction has a low odor threshold and a “rotten egg” odor is commonly observed by field technicians sampling anaerobic bioremediation sites. Sulfide typically attenuates rapidly downgradient of the anaerobic treatment zone, and rarely persists as the substrate is depleted.

Adverse impacts for dissolved arsenic and selenium appear to be less common, perhaps because minerals containing these elements are present at much lower concentrations in most aquifer sediments. However, it is prudent to evaluate whether arsenic or other heavy metal minerals may be prevalent in the aquifer matrix and what the impact of lowering the pH and redox state of the aquifer may be on their solubility.

Table 6.3
Summary of Secondary Water Quality Issues

Secondary Water Quality Parameters (Comparison Criteria)								
Site	pH (<6.5, >8.5)	TDS (500 mg/L)	Ferrous Iron (0.3 mg/L)	Manganese (0.05 mg/L)	Arsenic (0.01 mg/L)	Selenium (0.05 mg/L)	Acetone (5.5 mg/L) / 2-butanone (7.0 mg/L)	Notes
Hangar K, CCAFS, Florida	No Impact	Not Analyzed	Elevated up to 22 mg/L downgradient of reaction zone	Elevated up to 12 mg/L downgradient of reaction zone	No impact	No impact	No impact	Potential impacts only – not a drinking water supply
Area C, Alliant Techsystems, Inc., Elkton, MD	No Impact	Not Analyzed	Elevated up to 37 mg/L downgradient of reaction zone	Elevated up to 46 mg/L downgradient of reaction zone	No impact, only a few isolated detections above the criterion	Not Analyzed	Not Analyzed	Downgradient extraction system was shut down until substrate levels decreased. Downgradient concentrations of iron and manganese moderated after substrate depletion. Not a drinking water supply.
DP98, Elmendorf AFB, AK	No Impact	Not Analyzed	Elevated but background above criteria	Elevated up to 44 mg/L downgradient of reactions zone, but background above criteria	Background close to criteria and slightly elevated in treatment zone	No Impact	No Impact	Potential iron and manganese impacts, but background concentrations above criteria and not a drinking water supply
Kenney Avenue Plume, Elmendorf, AFB, AK	No Impact	Not Analyzed	Elevated but background above criteria	Elevated up to 32 mg/L downgradient of reactions zone, but background above criteria	No Impact	No Impact	No Impact	Potential manganese impact, but not a drinking water supply
Contemporary Cleaners, Orlando, FL	Low pH, typically below 5.0 after injection	Not Analyzed	Elevated but background above criteria	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed	Potential impacts only – not a drinking water supply
Springdale Cleaners, Portland, OR	Not Reported	Not Analyzed	Elevated but background above criteria	Elevated but background above criteria	Not Analyzed	Not Analyzed	Not Analyzed	Potential impacts only – not a drinking water supply
East Gate Disposal Yard, Fort Lewis, WA	Low pH, typically below 6.0 after injection	Not Analyzed	Elevated with concentrations > 3.3 in of reaction zone	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed	Potential impacts only – not a drinking water supply
Site 1, Hanscom AFB, MA	Low pH – did not persist downgradient	Not Analyzed	Elevated but background above criteria	Elevated but background above criteria	Not Analyzed	Not Analyzed	Not Analyzed	Sulfide, biological oxygen demand, and chemical oxygen demand all elevated in treatment zone but impacts did not persist downgradient. Not a drinking water supply.
Area 20, Aerojet Facility, CA	No Impact	Not Analyzed	No Impact	Elevated downgradient at 1 to 2 mg/L	No Impact	No Impact	Not Analyzed	The sole groundwater impact appears to be the mobilization and persistence of low levels (1 to 2 mg/L) of dissolved manganese.
Building 301, Offutt AFB, NE	No Impact	No Impact	Elevated but background above criteria	Slightly elevated downgradient at 0.66 mg/L	No Impact	No Impact	No Impact	Potential manganese impact, but appears to decrease with distance downgradient

Fermentation products such as acetone and methyl ethyl ketone (2-butanone) are often observed under highly reducing conditions. However, they are rarely observed downgradient of the immediate treatment zone as reducing conditions diminish. Therefore, these compounds do not pose a significant impact on groundwater quality.

Best practices to mitigate these secondary water quality issues include the following:

- Site screening to identify site-specific potential for secondary water issues. Examples may include characterizing the iron, manganese, and heavy metal content of aquifer sediments; and evaluating the buffering capacity of the aquifer (pH and alkalinity).
- Establishing natural concentrations of secondary water quality and determining the beneficial use of the impacted groundwater. Groundwater at many sites is not used for drinking water and secondary water quality criteria may not apply.
- Providing more a more uniform distribution of substrate without “spikes” of highly concentrated substrate solutions.
- Adding a buffering amendment to control pH.
- Providing for an adequate redox recovery zone downgradient of the treatment zone.

In many cases providing a sufficient redox recovery zone is sufficient. This is readily accomplished at many large DoD facilities, but may be more difficult to incorporate at small industrial or commercial sites.

6.1.5 Impacts on Hydraulic Conductivity

A loss of hydraulic conductivity was only observed for a few sites, primarily based on data collected from single well slug tests. Table 6.4 is summary of observations regarding impacts on hydraulic conductivity. Sites where there appears to be an impact on hydraulic conductivity include the following:

- Area C, ATK, Maryland. The average hydraulic conductivity in the biobarrier decreased from 40 feet per day (ft/day) pre-injection to 8.5 ft/day at 18 months post-injection, then stabilized with an average hydraulic conductivity of 11 ft/day at 42 months post-injection. This represents a decrease of 72 percent from pre-injection to 42 months post-injection. Similarly, the average hydraulic conductivity in the downgradient monitoring wells decreased from 32 ft/day pre-injection to 17 ft/day at 18 months post-injection, then increased with an average hydraulic conductivity of 24 ft/day at 42 months post-injection. This represents a decrease of 24 percent from pre-injection to 42 months post-injection. Although hydraulic conductivity in the injection wells decreased by greater than 50%, the average hydraulic conductivity downgradient of the biobarrier was typically higher than both the upgradient and injection wells. In general, hydraulic conductivity and groundwater flow was not thought to be adversely affected by injection of EVO.

Table 6.4
Impacts of Enhanced *In Situ* Bioremediation on Hydraulic Conductivity

Site ID	Background Hydraulic Conductivity	Treatment Zone Hydraulic Conductivity	Percent Reduction	Potential Impact
Hangar K, CCAFS, Florida	Not measured	3.4 to 17 ft/day (1.2E-03 to 6.2E-03 cm/sec)	Not measured	No adverse impacts were noted, likely due to the limited distribution of substrate away from the well screen.
Area C, Alliant Techsystems Facility, Elkton, MD	Up to 8.8 ft/day outside of treatment zone	Decreased from 40 ft/day pre-injection to 8.5 ft/day at 18 months post-injection	A decrease of 72 percent from pre-injection to 42 months post-injection	Although hydraulic conductivity in the injection wells decreased by greater than 50%, the average hydraulic conductivity downgradient of the biobarrier was typically higher than both the upgradient and injection wells. In general, hydraulic conductivity and groundwater flow was not adversely affected by injection of the emulsified oil.
DP98, Elmendorf AFB, Alaska	0.09 to 1.7 ft/day	Decreased from 1.7 to 1.0 ft/day at DP98INJ-02	Approximately 30 percent for injection well DP98INJ-02	The hydraulic conductivity measured for injection well DP98INJ-02 decreased by approximately 30 percent over time from July 2005 to October 2006. However, the hydraulic conductivity at DP98INJ-02 increased in June 2008, indicating any effects from the injection were not long-term. Hydraulic conductivity at downgradient well locations DP98MW-05 and DP98MW-06 remained relatively stable over time.
Kenney Avenue Plume, Elmendorf AFB, Alaska	Ranges up to 100 ft/day	Hydraulic conductivity decreased from approx. 94 to 99 ft/day in August 2006 to 55 to 74 ft/day in June 2008.	Less than 50 percent	The hydraulic conductivity at wells OU5KINJ-02 and OU5KINJ-03 appeared to decrease slightly over time, but by less than 50 percent.
Contemporary Cleaners, Orlando, FL	Not Reported	Not Reported	NA	No apparent impacts on hydraulic conductivity
Springdale Cleaners, Portland, OR	Not Reported	Not Reported	NA	No apparent impacts on hydraulic conductivity
East Gate Disposal Yard, Fort Lewis, WA	Not Reported	Not Reported	NA	No apparent impacts on hydraulic conductivity

Table 6.4
Impacts of Enhanced *In Situ* Bioremediation on Hydraulic Conductivity

Site ID	Background Hydraulic Conductivity	Treatment Zone Hydraulic Conductivity	Percent Reduction	Potential Impact
Site 1, Hanscom AFB, MA	Not Reported	Not Reported	NA	No apparent impacts on hydraulic conductivity, although biofouling of injection well limited injection rates.
Site 35, Vandenberg AFB, CA	Not Reported	Not Reported	NA	No apparent impacts on hydraulic conductivity, although biofouling of injection well limited injection rates.
Area 20, Aerojet Facility, CA	Not Reported	Not Reported	NA	No apparent impacts on hydraulic conductivity, although biofouling of injection well limited injection rates.
Teat Area North, INEEL, ID	Not Reported	Not Reported	NA	Fractured basalt with high secondary permeability, no apparent impacts on hydraulic conductivity
Building 1419, Indian Head NSWC, MD	Not Reported	Not Reported	NA	No apparent impacts on hydraulic conductivity
Areas E,F, M, and S, NWIRP McGregor, TX	Not Reported	Not Reported	NA	No apparent impacts on hydraulic conductivity
B301 Biowall, Offutt AFB, Nebraska	3.6 ft/day (1.3E-03 cm/sec) to 20 ft/day (7.1E-03 cm/sec) in August 2006	2.3 ft/day (8.1E-04 cm/sec) to 12.3 ft/day (4.3E-03 cm/sec) in August 2006	18 to 31 percent reduction was observed from 2001 to 2003 in biowall wells (GSI, 2004)	Hydraulic conductivity decreased by 18 to 31 percent within the biowalls from 2001 to 2003, and hydraulic conductivity measured in 2006 for wells within the biowalls were slightly less than in the surrounding formation.

Note: ft/day = feet per day; cm/sec = centimeters per second.

- DP98 Site, Elmendorf AFB, Alaska. The hydraulic conductivity measured for injection well DP98INJ-02 decreased by approximately 30 percent over time from July 2005 (pre-injection) to October 2006. However, the hydraulic conductivity at DP98INJ-02 increased in June 2008, indicating any impacts from the injection were not long-term. Hydraulic conductivity at downgradient well locations DP98MW-05 and DP98MW-06 remained stable over time. Therefore, groundwater flow was not thought to be adversely impacted.
- Kenney Avenue Plume, Elmendorf AFB, Alaska. Hydraulic conductivity at injection wells OU5KINJ-02 and OU5KINJ-03 decreased slightly over time. For example the hydraulic conductivity at OU5KINJ-02 was estimated to be 99 ft/day in August 2006 and 55 ft/day in June 2008, decreasing the most between September 2007 (87 ft/day) and June 2008. Similarly, the hydraulic conductivity at OU5KINJ-03 was estimated to be 94 ft/day in August 2006 and 74 ft/day in June 2008, with the lowest estimate of hydraulic conductivity occurring in September 2007 (57 ft/day). The magnitudes of these reductions are less than 50 percent.
- B301 Biowall, Offutt AFB, Nebraska. Hydraulic conductivity decreased by 18 to 31 percent within the biowalls from 2001 to 2003, and hydraulic conductivity measured in August 2006 for wells within the biowalls were slightly less than in the surrounding formation. This may be a cause for some bypass of contaminated groundwater around or underneath the biowalls.

One possible explanation for the observed decreases is biofouling of the aquifer and/or well screen due to the high concentrations of organic substrate at these injection locations. It is difficult to determine whether a loss of hydraulic conductivity observed by single well slug tests is due loss of hydraulic conductivity or due to fouling of the well screen. Biofouling of injection wells screens is not uncommon. Potential impacts on hydraulic conductivity may be better analyzed using tracer tests through the reaction zone before and after treatment.

Biowalls represent another condition where loss of hydraulic conductivity may be due to breakdown of the mulch and compost organic matter and compaction of the backfill material. These conditions are not reversible without re-installation of new material. Using a backfill mixture of greater than 50 to 60% sand or gravel may limit loss of conductivity, and the backfill material should be designed to be an order of magnitude of permeability (or more) greater than the surrounding formation. Conducting compaction tests of the backfill material by a geotechnical laboratory may be prudent for sites where utilities or roadways may be placed over the biowall trench.

It is difficult to assess the impact of a decrease in hydraulic conductivity, but it may result in bypass of contaminated groundwater around the reaction zone or uneven distribution of substrate during subsequent injections. The degree of loss of hydraulic conductivity observed above does not appear to have impacted the effectiveness of the applications. One way to address the potential for loss of hydraulic conductivity is to conservatively design the reaction zone to extend beyond the limits of contaminated groundwater to be treated. For example, a biowall may be installed an additional 30 to 50 feet beyond the edge of the groundwater contaminant plume to avoid potential for bypass around the ends of the biowall. It may also be beneficial to provide a degree of overlap (perhaps 20 percent) for injection well radius of influence to compensate for reductions in the ability to distribute substrate during subsequent injections.

6.1.6 Substrate Persistence and Long-Term Effectiveness

Effective enhanced *in situ* bioremediation applications are able to sustain the reaction zone over the design life of the application. Substrate persistence and long-term effectiveness are typically evaluated by monitoring concentrations of DOC over time. The depletion of organic substrate may result in less effective degradation of the targeted contaminants, and when this is observed an attempt has been made to determine an approximate “threshold” concentration of soluble organic carbon that must be maintained for that particular site. A rebound in contaminant concentrations may also occur after the remedy is halted. A rebound in contaminant concentrations of less than applicable regulatory standards, or less than 1.0 percent of the initial concentration before treatment, is considered as a successful endpoint to the bioremediation remedy.

Approximate threshold concentrations were estimated for the following sites:

- Hangar K, CCAFS, Florida. Concentrations of chlorinated ethenes did not exhibit any rebound until TOC dropped below approximately 20 mg/L.
- DP98, Elmendorf FB, Alaska. A rebound in concentrations of TCE at downgradient wells occurred when TOC dropped from over 90 mg/L to less than 20 mg/L, suggesting that the threshold concentration to sustain dechlorination of TCE is between 20 and 90 mg/L at this site.
- Kenney Avenue Plume, Elmendorf AFB, Alaska. Initial injections could only sustain concentrations of TOC at approximately 30 to 40 mg/L, with little evidence of dechlorination of TCE. The use of a field-mixed emulsion resulted in concentrations of TOC greater than 100 mg/L being sustained in the injection wells over a 9-month period. During this period methanogenesis was induced and dechlorination of TCE to *cis*-DCE occurred.
- Contemporary Cleaners Site, Florida. A rebound in concentrations of CAHs appears to correlate to total organic acid concentrations falling below 30 to 40 mg/L.
- Springdale Cleaners Site, Oregon. A threshold concentration of 80 to 100 mg/L total organic acids was interpreted to be required for effective dechlorination of CAHs.
- Area S, NWIRP McGregor, Texas. Depletion of TOC followed a first order rate, and the minimum range at which breakthrough of perchlorate occurred appeared to be between 5 and 10 mg/L.

Based on these observations, the minimum threshold concentrations of DOC or TOC range from 5 to 10 mg/L for perchlorate, to 20 to 100 mg/L for CAHs. While the threshold concentration to sustain dechlorination of CAHs is highly site specific, sustaining concentrations of DOC greater than 100 mg/L should be effective for most sites.

For sites with extended monitoring data, a rebound in concentrations of CAHs or perchlorate was not usually observed. The potential for a rebound in concentrations depends primarily in the presence and persistence of an upgradient source. For example, at the Hangar K Site, CCAFS, Florida, by 68 months post injection concentrations of TOC had been depleted to background levels and a rebound in the concentration of TCE was been observed at location HGRK-MP10.

This well was installed at the upgradient fringe of the treatment zone, and the rebound was due to migration of contaminated groundwater from a residual upgradient source.

Substrate longevity for the slow-release substrates was typically from 1.5 to 3.5 years (Table 6.1). Exceptions were noted, but longevity less than 1.5 years could be attributed to poor initial distribution of substrate. For the molasses sites, it was noted that dechlorination continued and even improved at some locations after injection ceased. In many cases, decaying biomass may act as a secondary substrate and sustain anaerobic degradation processes for a period of months to perhaps a year or more. The improved performance at the molasses sites (i.e., dechlorination of *cis*-DCE and VC) may be due to moderation of pH as substrate was slowly depleted.

In summary, concentrations of DOC typically need to be sustained above 50 to 100 mg/L over the design life of the application. Buildup of biomass may sustain the reaction zone and limit the amount of rebound that may occur after the initial substrate is depleted. Rebound of concentrations in the treatment zone will depend in large part on whether a residual source of contaminant mass remains.

6.1.7 Need for and Cost of Additional Injections or Monitoring

The cost associated with poor performance or compliance issues may significantly increase the life-cycle costs of full-scale enhanced *in situ* bioremediation applications. For example, poor performance typically result in a need for longer-term operation. Compliance issues such as degradation of secondary water quality may require additional monitoring or system modifications, also increasing the cost of the application. Actual work performed for the demonstration studies was compared to the application design or work plan to determine whether additional work was required.

Sites where additional injections or monitoring were performed include the following:

- Hangar K, CCAFS, Florida and Area A, ATK Facility, Maryland. Long-term follow-up monitoring at these two sites was primarily for research purposes to determine substrate longevity and the potential for rebound in contaminant concentrations.
- SA-17, NTC Orlando, Florida. Recirculation of EVO was less effective in certain areas because rates of groundwater extraction and injection were lower than estimated from aquifer tests (Hudson *et al.*, 2009). Additional testing was conducted and optimization efforts included conducting oil retention tests, targeting the most permeable zones, increasing injection volumes, and using direct-push injection techniques.
- Kenney Avenue Plume, Elmendorf AFB, Alaska. Greater quantities of substrate and a switch to a field-mixed emulsion were required to achieve appropriate reducing conditions. Additional substrate requirements increased from a proposed cost of \$14,900 to a final cost of \$62,600, a difference of \$47,700.
- Site 1, Hanscom AFB, Massachusetts. A total of 32 weekly injections were planned, while a total of 47 injections were conducted over a 2-year period. Cost impacts occurred from increasing the injection frequency from weekly to twice weekly, increased time for each injection due to rates of injection that were reduced from approximately 10 gpm down to 1-2 gpm due to biofouling and compromise of the injection well seal, and the cost of additional substrate and the buffering amendment.

- Site 35, Vandenberg AFB, California. A total of 27 weekly injections were initially planned, while a total of 31 injections were conducted over a 27-month period. Additional substrate and a buffering amendment were also required.
- TAN INEEL, Idaho. Modifications to the injection protocol were primarily for optimization of long-term operations.
- Area S, NWIRP McGregor, Texas. Biowall rejuvenation was anticipated as part of long-term operations, and two rounds of EVO injections have been performed.

A qualitative assessment of these cost impacts is included in Section 9. Several of the activities were anticipated or were conducted for research or optimization purposes, and do not represent a cost impact. But these observations do point out that additional monitoring or testing are often required to optimize system performance.

6.1.8 Application in Difficult Hydrogeological Conditions

There are limits to the hydrogeological conditions under which enhanced *in situ* bioremediation may be applied. Section 3 of AFCEE *et al.*, (2004) provides a description of some limiting factors associated with site lithology and groundwater hydraulics. Difficult hydrogeological conditions may include low permeability sediments, a high degree of heterogeneity, or high rates of groundwater flow. Demonstration sites that exhibited difficult hydrogeological conditions include the following:

- Variable and high rates of groundwater flow at Area C, ATK, Maryland. The maximum efficiency of perchlorate removal was observed during the first 4 months of operation when concentrations of TOC were high, and during a period between 2 and 3 years post-injection when groundwater flow velocity slowed due to shutdown of the downgradient groundwater extraction system. When the groundwater extraction system was in operation, the contact time in the reaction zone was less than anticipated and resulted in a drop in perchlorate removal efficiency.
- Low yield and heterogeneity at the SA-17 Site at NTC Orlando, Florida. Low yield and heterogeneity limited the effectiveness of a recirculation approach at this site, resulting in non-uniform substrate distribution.
- High rate of groundwater flow at the Kenney Avenue Plume, Elmendorf AFB, Alaska. The ability to induce highly reducing conditions at this site were limited by high rates of groundwater flow that dispersed the substrate over a broad area at less than suitable concentrations. The high rate of groundwater flow (888 ft/yr) is close to an upper limit of the rate of groundwater flow suitable for applying enhanced *in situ* bioremediation. The high rate of groundwater flow was mitigated to some extent by use of a coarse field-mixed emulsion that was better retained by entrapment within the aquifer matrix.
- Low rates of groundwater flow at the Contemporary Cleaners Site in Florida. Variable and non-uniform distribution of substrate is attributed to aquifer heterogeneity and slow rates of groundwater flow (less than 16 feet per year) that limited dispersion of organic acids released from the HRC[®] product.

- A moderate degree of heterogeneity at the East Gate Disposal Yard, Fort Lewis Logistics Center, Washington and at the Building 1419 Site at Indian Head NSWC, Maryland. Injection and extraction wells had to be re-installed to get uniform substrate distribution at the East Gate Disposal Yard Site. For the Building 1419 Site, substrate distribution improved over time as substrate dispersed and diffused into lower permeability sediments.

Based on these observations, rates of groundwater flow less than 0.1 ft/day (37 ft/yr) or greater than 2.7 ft/day (1,000 ft/yr) require special design considerations. Low rates of groundwater flow may require closer injection spacing, while high rates of groundwater flow will require more frequent and higher concentration injections. In the case of EVO products, the retention of the oil droplets is a critical parameter to sustain adequate substrate concentrations in the reaction zone. Similarly, as the degree of aquifer heterogeneity increases, so may the need for closer injection well spacing or for “targeted” injections within lower permeability sediments.

6.2 SUMMARY OF LIMITING FACTORS IN ENHANCED *IN SITU* BIOREMEDIATION

Based on the conditions described above, a number of limiting factors commonly impact the effectiveness of enhanced *in situ* bioremediation applications. These limiting factors and the best practices to mitigate these factors include the following:

Insufficient Substrate Distribution. The ability to effectively distribute substrate is often impacted by site-specific lithology (low or high permeability, heterogeneity) and groundwater hydraulics (low or high rates of groundwater flow). In some cases the quantity of substrate that can be injected is limited by a low aquifer buffering capacity and pH excursion. These observations reinforce the need and benefits of conducting adequate site characterization prior to design and implementation of substrate addition. In most cases these conditions can be mitigated by modifying the injection mixture and substrate loading rate (e.g., more frequent and less concentrated substrate solutions, or adding a buffering amendment) or delivery technique (e.g., closer spaced injection points and larger injection volumes).

Adverse Geochemical Conditions. The most common geochemical problem for the demonstration case studies was an adverse excursion (lowering) of pH, resulting from a combination of low buffering capacity of the aquifer and high concentrations of DOC. Control of the substrate loading rate is critical when treating aquifers with low buffering capacity. Mitigation measures include careful screening of the site to determine whether a buffering compound should be added to the injection protocol, and selecting substrate delivery techniques that provide for more uniform distribution of substrate without excessive “spikes” in DOC.

Loss of Hydraulic Conductivity or Biofouling of Injection Wells. A decrease in hydraulic conductivity (permeability) may result in bypass of contaminated groundwater around the reaction zone or uneven distribution of substrate during subsequent injections. One way to address the potential for loss of hydraulic conductivity is to conservatively design the reaction zone to extend beyond the limits of contaminated groundwater to be treated. For example, a biobarrier or biowall may be installed an additional 20 to 50 feet beyond the edge of the groundwater contaminant plume to avoid potential for bypass around the ends of the reaction zone. It may also be beneficial to provide a degree of overlap (perhaps 20 to 30 percent) for injection well radius of influence to compensate for reductions in the ability to distribute substrate during subsequent injections.

Substrate Persistence and Longevity. Concentrations of DOC typically need to be sustained above 50 to 100 mg/L over the design life of the application. Buildup of biomass may sustain the reaction zone and limit the amount of rebound that may occur after the initial substrate is depleted. Rebound of concentrations in the treatment zone will depend in large part on whether a residual source of contaminant mass remains upgradient of the treatment zone, or in low permeability sediments within the treatment zone.

Difficult Hydrogeological Conditions. Rates of groundwater flow less than 0.1 ft/day (37 ft/yr) or greater than 2.7 ft/day (1,000 ft/yr) require special design considerations. Low rates of groundwater flow may require closer injection point spacing, while high rates of groundwater flow will require more frequent and higher concentration injections. In the case of EVO products, the retention of the oil droplets is a critical parameter to sustain adequate substrate concentrations in the reaction zone. Similarly, as the degree of aquifer heterogeneity increases, so may the need for closer injection well spacing or for “targeted” injections within lower permeability sediments.

The variety of substrates and configurations that can be used for enhanced *in situ* bioremediation allows the practitioner to design around these limiting factors. Careful site screening and evaluation of each of these limiting factors will lead to higher rates of success and greater effectiveness of the remedy. The following section discusses the most common substrate types and how substrate loading rates are commonly designed.

7. DESIGN OF SUBSTRATE AMENDMENTS

This section describes how substrate loading rates are typically determined for common substrate products. The substrate products currently on the market are continually increasing in number and complexity. Table 7.1 is a list of substrate products being used for enhanced *in situ* bioremediation. This table is not inclusive, products are constantly coming on the market or being modified to improved versions. No endorsement of any substrate product is implied.

7.1 SUBSTRATE DESIGN FOR SLOW-RELEASE SUBSTRATES

A common approach with slow release substrates is to calculate a substrate (electron donor) requirement based on estimates of native and contaminant electron acceptor mass, and mass loading through the treatment zone over the design life of the application. Vendors of slow-release substrates (e.g., HRC[®] and EVO) typically rely on calculated substrate requirements because the product is usually applied in a single injection event (e.g., see Appendix G of AFCEE, 2007). Even so, some designs still focus on achieving a “target” concentration of substrate (TOC) in the treatment zone. More recently, design of EVO applications has focused on the oil retention properties of the aquifer matrix. The following sections describe design considerations for the most common slow release substrate types.

7.1.1 Vegetable Oil Products

7.1.1.1 Neat Vegetable Oil

The use of pure vegetable oil is only considered appropriate for source areas, while EVO may be used for both source area and biobarrier applications (AFCEE, 2007). The primary limitation to using pure vegetable oil is the ability to distribute the oil throughout the aquifer matrix. Studies of oil retention with pure oil (Coulibaly and Borden, 2004) suggest that the residual saturation may be 30 to 50 percent or more. The volume required to distribute the oil uniformly throughout the aquifer matrix is not practical for all but the smallest source areas. However, demonstrations using this approach have shown it is not necessary to have a completely uniform distribution of the oil, because biodegradation occurs in the aqueous phase where soluble metabolic acids are distributed by the processes of advection, dispersion, and diffusion (AFCEE, 2007).

The use of pure oil has two unique impacts. First, a large proportion of chlorinated solvent mass may be sequestered into the oil due to partitioning. This mass is slowly released back into a reactive zone which is optimal for anaerobic degradation to occur. Second, neat oil acts to reduce permeability, which slows groundwater flow and mass discharge out of the source zone.

The Hangar K Site at CCAFS, Florida is an example of injecting neat vegetable oil into a source area. An empirical approach was used to determine how much oil to inject, based in part on a pilot test “push-pull” test. During the pilot test, 110 gallons of neat oil was injected into a 1-foot long well screen, and approximately 62 gallons of neat oil was then extracted, leaving 48 gallons of residual oil in the formation. This was done to leave the oil in a residual (non-mobile) phase. The expanded pilot test used an injection of 55 gallons neat oil per injection point with 10-foot screens, followed by 200 gallons of native groundwater to push the oil into the formation at a low enough saturation to limit mobility of the oil. In this case, the volume of oil injected was less than 3 percent of the total treatment area aquifer pore space.

Table 7.1
Substrates Used for Enhanced *In Situ* Anaerobic Bioremediation

Substrate Type	Product (Vendor)	Product Description	Form of Application and Typical Delivery Techniques
Common Soluble Substrates			
Sodium Lactate	Wilclear [®] (JRW Bioremediation Products)	Lactate salts (sodium or potassium lactate) in solution typically at 60% by weight.	Diluted in water; multiple injections in dedicated wells or using a recirculation system.
	Purac [®]		
Propionate, and Butyrate	Chemical supply companies (e.g., Archer Daniels Midland)	Acids or salts in solution	Acids or salts diluted in water; multiple injections in dedicated wells or using a recirculation system.
Methanol and Ethanol	Chemical supply companies	Typically in solution at 60 to 80 percent by weight	Diluted in water.
Molasses, High Fructose Corn Syrup	Food service companies	Viscous fluid at 60 to 80 percent by weight	Dissolved in water.
Slow-Release Substrate			
Emulsified Vegetable Oil	EOS598 [®] , AquaBuf ^{pH} (EOS Remediation Products, Inc)	Oil-in-water emulsion	Diluted to concentrations of 1 to 10 percent oil in water and injected directly.
	Newmans Zone [®] (Remediation and Natural Attenuation Services, Inc.)	Oil-in-water emulsion	Diluted to concentrations of 1 to 10 percent oil in water and injected directly.
	SRS [™] (TerraSystems, Inc.)	Oil-in-water emulsion	Diluted to concentrations of 1 to 10 percent oil in water and injected directly.
	Lactoil [™] (JRW Bioremediation Products)	Emulsified oil and ethyl lactate	Typically diluted at 10 parts water to 1 part product.
	CAP-18 [™] (DBI Remediation Products)	Liquid product refined from edible oils	Straight injection of product.
HRC [®] , HRC-X [™]	Regenesis Bioremediation Products	Viscous fluid - proprietary mixtures of polylactate esters, glycerol, and other materials	Straight injection of product.

Table 7.1
Substrates Used for Enhanced *In Situ* Anaerobic Bioremediation

Substrate Type	Product (Vendor)	Product Description	Form of Application and Typical Delivery Techniques
3DME™	Regenesys Bioremediation Products	Low viscosity fluid – a complex molecule composed of lactic acid, controlled-release lactic acid (polylactate), and certain fatty acid components esterified to a carbon backbone molecule of glycerin	Diluted at a ratio of from 10:1 to 100:1 water to product.
Whey (sweet dairy whey)	Multiple suppliers (e.g., Valley Bakers)	Sold as dry or liquid product. Dry product most commonly used.	Dissolved in water or as a slurry, direct injection or injection wells.
Chitin	Chitorem® (JRW Bioremediation Products)	Food grade biopolymer derived from caustic-treated exoskeletons from crustacean shells.	Water slurry, direct injection or injection wells.
Solid Substrates			
Mulch and Compost	Waste products of landscaping and agricultural industries	Examples include ground tree mulch, mushroom compost, and cotton gin trash.	Trenches, excavations, <i>in situ</i> bioreactors, or surface amendments.
Chitin (solid)	Bulk Chitin	Sea food waste product, exoskeletons from crustacean shells	Solid amendment in trenches or excavation.
Mixed Iron and Organic Substrate Products			
Zero-valent iron (ZVI) and organic substrate	EHC® (Adventus Americas, Inc.)	Integrated carbon fiber and ZVI product in powder form	Direct injection as a slurry (e.g., with a grout pump)
	Duramend® (Adventus Americas, Inc.)	Integrated organic carbon and ZVI product in solid (pellet) form	Biowall trenches or bioreactor excavations
	Anaerobic BioChem (ABC®) Plus ZVI (Redox Tech, Inc.)	Mixture of lactates, fatty acids, and phosphate buffer, plus ZVI.	Direct injection as a slurry (e.g., with a grout pump)
Emulsified zero-valent iron	Licensed by NASA, contact license holders	Nano-scale or micro-scale iron suspended in an oil-in-water emulsion.	Direct injection.

7.1.1.2 Emulsified Vegetable Oil Products

Oil-in-water emulsions using vegetable oil (i.e., EVO) have been developed in an effort to improve the distribution of oil substrates in the subsurface. Microemulsions are traditionally defined as transparent, isotropic solutions of oil, water, and surfactant (and frequently co-surfactants) which are thermodynamically stable (Flanagan *et al.*, 2005). Microemulsions form upon simple mixing of the components, and do not require the high shear conditions generally used in the formation of commercial oil-in-water emulsions used for bioremediation applications. While not adhering to a scientific definition of a microemulsion, the manner in which the term “microemulsion” is applied to enhanced bioremediation refers to an oil-in-water emulsion with an average or mean oil droplet size that is significantly less than the average or mean pore throat size of the aquifer formation into which it is being injected (AFCEE, 2007). This allows the emulsion to be injected through the aquifer pore throats with minimal entrapment of the oil droplets within the pore spaces.

Emulsions consisting of 1 to 10% vegetable oil in water by volume are relatively low-viscosity mixtures (e.g., non-dairy creamers like Coffee Mate®), compared to neat vegetable oil. Oil droplets are immobilized by attaching to the aquifer matrix (sorption) or by entrapment in very fine pore spaces. Coarse grained aquifers (low sorption or entrapment potential) with high flow rates may require more frequent injections (e.g., annually) to sustain the reaction zone. Refined soybean oil is the most common oil used, and substrate loading typically is controlled by modifying the oil saturation in the emulsion (typically 1 to 5%). Oil saturations higher than 10 to 15% may cause a large reduction in hydraulic conductivity (AFCEE, 2007).

Several pre-mixed oil-in-water emulsions are available commercially (Table 7.1) that meet requirements for small droplet sizes and stability, and that can be readily diluted to the desired oil concentration in the field. Once injected, typical life spans for EVO products are on the order of 1 to 3 years. Life span depends on the effective emulsion saturation (retention) in the aquifer and the rate at which the oil is degraded and, to a lesser extent, on the rate of groundwater flow and native electron acceptor loading.

More recently, users of EVO products have realized that the retention of oil droplets in the aquifer is highly dependent on the physical and chemical properties of the EVO product (e.g., the ionic strength of the emulsifiers) and of the aquifer matrix (e.g., percent clay and organic material in the aquifer matrix). EVO retention test and distribution tools (described below) have been developed for ESTCP under ER-0626 that evaluate and use oil retention to determine EVO distribution in the subsurface.

7.1.1.3 EVO Design Tools

Two design tools for EVO applications have been developed by Solutions IES, Inc. and EOS Remediation Products, Inc. The first is a spreadsheet calculation tool that includes a determination of stoichiometric demand in electron equivalents. The second is a spreadsheet model developed under ETSCP ER-0626 for evaluating the delivery of EVO.

An example of the first tool is the calculations used for the ESTCP ER-0221 demonstration at the Area C Site, ATK Facility, Maryland (Appendix D and E of Solutions IES [2006]). Solutions IES determined the amount of EOS® to inject based on 1) the oil required for biodegradation

(stoichiometric demand), and 2) the oil retention by the aquifer sediment. The oil required for biodegradation based on stoichiometry was based on concentrations of native electron acceptors (DO, nitrate, sulfate), concentrations of contaminants to be treated (primarily perchlorate and 1,1,1-TCA), the expected levels of organic carbon to be released from the barrier (typically 50 to 100 mg/L TOC), and estimated concentrations of reduced compounds produced (dissolved iron, manganese, methane).

Data for the site were entered into the EOS[®] spreadsheet, and it was determined that 2 drums of EOS598 product were required for biodegradation based on a 3-year design life. The design life was limited to 3 years so that oil depletion and reduced treatment efficiency could be observed within the timeframe of the demonstration.

The second method evaluated the product requirement based on oil retention. To form a permeable biobarrier with emulsified oil, the sediments within the barrier should ideally be uniformly coated with oil. The oil retention by the sediment can be determined using the following equation (Solutions IES, 2006):

$$\text{Oil required} = x * y * z * \rho_B * \text{OR}$$

Where, x = Treatment zone length parallel to groundwater flow (feet)

y = Design width perpendicular to groundwater flow (feet)

z = Effective height (feet)

ρ_B = Sediment bulk density (lb/ft³)

OR = Effective oil retention (lb oil/lb sediment)

The pilot test barrier was designed to be 50 feet wide perpendicular to groundwater flow (y). The effective height of the barrier was estimated to be between 5 and 10 feet (z). Although they injected into a 10-foot zone, the site lithology indicated 5 feet of higher permeability material where most of the injected material would likely be distributed. The length of the barrier parallel to groundwater flow was determined based on the desired contact time. The barrier was designed to provide a contact time of 30 days. Based on groundwater velocity data for the site, a design length of 5 feet (x) was used. The sediment bulk density (ρ_B) was estimated to be 120 pounds per cubic feet (lb/ft³), and the effective oil retention was determined to be between 0.001 and 0.002 from laboratory column tests. Using these numbers, the oil required for retention by the sediment was calculated to be between 150 to 600 lbs, which is equivalent to between 1 and 3 drums of EOS[®] product.

Solutions IES also calculated to the total volume of water and emulsion that needed to be injected to create the desired treatment zone to be one pore volume of the treatment zone. Based on these calculations, two 55-gallon drums of EOS598 and 2,200 gallons total volume (water and emulsion) were injected.

7.1.1.4 Determining Oil Retention

Oil retention is a critical design parameter in the Edible Oil Design Tool (available at http://www.estcp.org/cs_upload/ER-0626-ToolKit/). A table of oil retention values presented with the Edible Oil Design Tool shows measured values of oil retention that exhibit a wide range, from 0.0004 grams oil per gram soil (gm/gm) for a coarse gravelly sand to 0.0095 gm/gm

for a laboratory blended sand with 12 percent silt and clay. Given the wide range of values, it is important to determine oil retention for site-specific soil samples. A laboratory standard operating procedure (SOP) is provided in an appendix to the Edible Oil Design Tool Manual that describes a procedure to measure oil retention (Solutions IES *et al.*, 2009; Clayton and Borden, 2009).

A slightly modified version of this procedure was used to measure oil retention for soils collected from the SA-17, OU-2, and OU-4 sites at former NTC Orlando, Florida. Results of the tests are summarized in Table 7.2. Permeameter tests were run prior to adding one pore volume of the substrate mixture (containing 5% or 12% oil by volume), and again after several pore volumes of water were passed through the permeameters.

Table 7.2
Permeability and Oil Retention Measurements for NTC Orlando, Florida

Site Location/ Sample Identification	Percent Oil Injected	Pre-injection Permeability (cm/sec)	Post-injection Permeability (cm/sec)	Percent Reduction	TOC Retained (percent by weight)
SA-17, NTC Orlando					
NTC-SA17-SB1-15-25	12%	8.1E-06	6.9E-08	99.1	3.74
NTC-SA17-SB1-15-25 (SPLIT)	5%	4.9E-07	4.8E-08	90.2	0.80
NTC-SA17-SB1-30-40	12%	1.2E-06	2.0E-10	99.99	5.45
OU-2, NTC Orlando					
NTC-OU2-SB1-22-25	12%	4.6E-08	2.8E-08	39.1	2.30
NTC-OU2-SB1-22-25 (SPLIT)	5%	1.9E-06	1.4E-07	92.6	1.67
NTC-OU2-SB1-32-35	12%	3.1E-07	1.9E-08	93.9	2.55
NTC-OU2-SB2-22-25	12%	1.5E-07	5.3E-08	64.7	1.29
NTC-OU2-SB2-32-35	12%	1.2E-05	6.4E-08	99.5	5.00
NTC-OU2-SB2-32-35 (SPLIT)	5%	2.4E-06	1.2E-07	95.0	4.57
OU-4, NTC Orlando					
NTC-OU4-SB1-9-14	12%	1.1E-04	4.7E-06	95.7	0.89
NTC-OU4-SB1-9-14 (SPLIT)	5%	4.9E-07	8.0E-08	83.7	1.25
NTC-OU4-SB1-25-30	12%	5.5E-05	2.3E-05	58.2	1.06

The range of pre-injection permeability was highly variable, ranging from 1.1E-04 to 4.6E-08 centimeters per second (cm/sec). After the EOS598 product was pumped through the permeameter and flushed with water, the percent reductions in conductivity ranged from 39 to 99.99 percent, or by up to four orders of magnitude. There was no apparent correlation between the percent reduction and percentage of silt/clay in the soil samples (Appendix C).

Concentrations of TOC (in triplicate) were measured both prior to and after injection of the EOS product in the permeameters. The difference in TOC was used to estimate the percentage of oil

retention on a weight TOC per weight soil basis. For the SA-17 site, oil retention ranged from 0.80 percent to 5.45 percent, averaging 3.33 percent. For the OU-2 site, oil retention ranged from 1.29 percent to 5.0 percent, and averaged 2.89 percent. For the OU-4 site, oil retention ranged from 0.89 percent to 1.25 percent, averaging 1.07 percent. As could be expected, oil retention was lowest in the soil samples with the least amount of silt/clay (i.e., samples from OU-4, see Appendix C).

Hydraulic conductivity for the SA-17 sites has been reported to average 4.7 ft/day (1.7 E-03 cm/sec) in the upper zone and 6.9 ft/day (2.4E-03 cm/sec) in the lower zone. It is unclear why the conductivity values measured in the laboratory were significantly lower than reported for field measurements. The reductions in permeability may have also been influenced by biodegradation and fouling of the aquifer material after injection of the substrate mixtures.

The oil retention values appear to be relatively high compared to values presented with the Edible Oil Design Tool. Values posted in the tool show measured values of oil retention that range from 0.0004 grams oil per gram soil (0.04 percent) for a coarse gravelly sand to 0.0095 gm/gm (0.95 percent) for a laboratory blended sand with 12 percent silt and clay. The higher oil retention measured in this study may be an artifact of the very low permeability measured in the permeameter tests. In addition, the target volume of post-injection water flush (five pore volumes) was not achieved for all tests.

Oil retention studies were also conducted by CH2M Hill at an in-house geotechnical laboratory for samples collected from the OU-4 site (CH2M Hill, 2008), the results of which are listed in Table 7.3. Oil retention was measured by analysis of both TOC and volatile solids. The oil retention ranged from 0.39 to 0.85 percent for samples from the shallow zone (9 to 14 feet below ground surface [bgs]), which compares to 0.89 to 1.25 percent for the measurements from this depth at OU-4 in Table 7.2.

Table 7.3
Oil Retention Values for NTC Orlando, Florida (CH2M Hill, 2008)

Sample Identification	Percent Oil Injected	Sampling Depth (feet bgs)	Retention based on TOC (percent by weight)	Retention based on Volatile Solids (percent by weight)
NTCOU4SB1-9-14' (SB1-Shallow)	12%	9 - 14	0.51	0.39
NTCOU4SB1-55-60' (SB1-Deep)	12%	55 – 60	3.77	3.39
NTCOU4SB2-9-14' (SB1-Shallow)	12%	9 -14	0.85	0.67
NTCOU4SB2-57-62' (SB1-Deep)	12%	57 - 62	0.96	0.61

It is evident that additional refinement of the laboratory protocol to evaluate oil retention may be necessary for differing soil types. Different permeameter test methods might be required for soils that are expected to have low permeability. In addition, the tests must be run over a relatively short duration (within a couple days) to avoid degradation of the oil after injection. Alternatively, the soil could be sterilized (autoclaved) to avoid biodegradation of the oil.

7.1.2 Hydrogen Release Compounds

HRC[®], HRC-X[™], and 3-D Microemulsion[™] (3DMe[™]) are bioremediation products supplied by Regenesi Bioremediation Products. These products are designed to provide a slow release of lactic acid and dissolved organic carbon to stimulate *in situ* fermentation, producing hydrogen for anaerobic dechlorination of CAHs. The slow release nature of these products is attributed to their molecular and polymeric compositions, which allow control of viscosity and donor release rates.

7.1.2.1 HRC[®] and HRC-X[™]

According to the manufacturer's product literature, various forms of these products are available, but all contain proprietary mixtures of polylactate esters, glycerol, and other materials. Application of HRC[®] is best suited for groundwater plumes where direct-push technology can be used to effectively cover large areas of a plume or to create long biobarriers. In addition, HRC[®] has been used effectively in fractured bedrock where the material is injected into borings. HRC[®] and HRC-X[™] are highly viscous and are injected using specialized, commercially-available equipment and pumps. HRC-X[™] may require heating prior to injection to reduce viscosity.

The HRC[®] products are typically injected at rates of 4 to 20 pounds per vertical foot (lb/ft) of aquifer to be treated (e.g., Norris, 2004). HRC[®] has a density of approximately 10 pounds per gallon, and the physical distribution of the substrate in a radial direction ranges from few inches to a couple of feet from actual point of injection. The rate at which dissolved lactic acid and glycerol released from the substrate product migrates from the point of injection depends on the advective groundwater flow velocity, and will be dominated by the rate of diffusion in low-permeability aquifers. Typical injection point spacing varies from 5-foot centers for low-permeability lithologies to 8- to 12-foot centers for more permeable lithologies (e.g., Case *et al.*, 2001).

The rate of application (lb/ft) of HRC[®] or HRC-X[™] is calculated using a spreadsheet-style program provided by Regenesi. The calculations take into account site-specific conditions including hydrogeology, contaminant levels, and competing (native) electron acceptors. The program also takes into account the size of the treatment area and number of injection points so that the rate of application falls within practical limits. Safety factors are applied to account for competing microbial demand and a general (non-specific) efficiency factor. Safety factors applied typically range from 2- to 4-times the stoichiometric electron acceptor demand.

The typical lifespan for the standard HRC[®] product ranges from 12 to 24 months, and depends to some extent on the rate of groundwater flow and native electron acceptor flux. It is not unusual for an additional injection of HRC[®] to be required, particularly in biobarrier configurations that typically have a design life of several years. The use of the HRC-X[™] product is gaining in frequency because a longer lifespan of 3 to 5 years is anticipated, sufficient to remediate many sites with only a single application.

7.1.2.2 3-D Microemulsion[™]

Regenesi also produces the 3DMe[™] product, which is significantly different from the HRC[®] or HRC-X[™] products. The 3DMe[™] product contains a complex molecule composed of free lactic

acid, controlled-release lactic acid (polylactate), and certain fatty acid components esterified to a carbon backbone molecule of glycerin. The 3DMe material is mixed on-site with water to easily form an emulsion. When injected into contaminated soil and groundwater, 3DMe™ produces a sequential, staged release of its electron donor components. The immediately available free lactic acid is fermented rapidly while the controlled-release lactic acid is metabolized at a more gradual rate. The fatty acids are fermented to molecular hydrogen over a mid- to long-range timeline giving 3DMe™ a long electron donor release profile. This staged fermentation of the substrate provides a controlled release supply of hydrogen (electron donor) to stimulate anaerobic degradation processes (e.g., reductive dechlorination of chlorinated solvents). This product is reported by Regenesis to differ from vegetable oil emulsions in that micelles are formed which are mobile in groundwater and may continue to disperse in the aquifer after injection.

Regenesis currently offers design support for 3DMe™ to the general public in the form of software and dedicated engineering staff. Similar to the HRC products, site-specific hydrogeology and contaminant and native electron acceptor demand are taken into account when determining the quantity of product to apply based on stoichiometric relationships. Similar to the HRC calculations, a safety factor of 2- to 4-times the stoichiometric electron acceptor demand is applied. The substrate loading requirement is then compared to a minimum desired threshold (usually in the range of 1,000 to 1,500 mg/L) for initial loading of TOC throughout the pore space of the treatment zone. The greater of the two values is used to specify the quantity of 3DMe™ product to apply.

A review of case studies provided by Regenesis (www.regenesis.com) indicates the product is typically diluted with water at a ratio of from 10:1 to 20:1 water to 3DMe™, although dilutions of up to 100:1 may be used to achieve a greater distribution of the product through out the treatment zone pore space. Due to the mobility of the micelles in the product, the product may be effectively distributed by the processes of advection and dispersion and most applications are performed at a standard dilution of 10:1. The anticipated design life of a 3DMe™ is on the order of 3 to 5 years, although case studies to support this are limited due to the recent introduction of the product.

7.1.3 Other Vegetable Oil-Based Products

Two other vegetable oil-based products on the market include Lactoil™ from JRW Bioremediation Products, LLC (JRW) and CAP-18 from DBI Remediation Products, LLC.

7.1.3.1 Lactoil™

Lactoil differs from the oil-in-water based EVO products discussed above. Lactoil is described by the vendor as a soy-based microemulsion that is a “complex mixture of solute and solution present as reversed micelles (water in oil), normal micelles (oil in water), and bi-continuous phase lamellar structures which together comprise a visually homogeneous transparent liquid.” The product has an organic content of approximately 80%, composed of 45% oleaginous compounds (refined soybean oil fatty acids), 35% ethyl lactate, and the remaining 20% water. Particle size distribution data provided by JRW indicates that the Lactoil soy microemulsion particle size is consistently smaller than 1 micron (i.e., median particle size is less than 1

micron). Benefits claimed by the supplier include longer shelf life, ease of mixing, and greater dispersal and distribution in aquifers.

JRW typically recommends that the product be diluted with water at a dilution of 10 parts water to 1 part product. This results in a substrate amendment with an approximate concentration of 80,000 mg/L of organic carbon. This is then injected at sufficient volume to achieve an overall average concentration of approximately 4,000 to 8,000 mg/L organic carbon in the pore volume of the targeted reaction zone. The product is thought to migrate within aquifer sediments as micelles, in a manner perhaps similar to that of the 3DMe™ product.

7.1.3.2 CAP-18™

CAP18™ from DBI Remediation Products, LLC is reported by the manufacturer to be a liquid product refined from edible oils, designed specifically for groundwater remediation. It is a food-grade product that is reported to minimize methanogenesis, and that does not require emulsification or blending, or injection of large volumes of water. Similar to EVO products, it can be injected with standard direct-push equipment or via monitoring wells, is purported to be immobile upon injection, and to sustain anaerobic conditions for several years.

7.1.4 Whey

There are various forms of whey, including sweet dairy whey, acid whey, and salt whey. The form most suitable for enhanced *in situ* bioremediation is sweet dairy whey, which may be purchased in raw (liquid) or dry powder form. Purchasing dry sweet dairy whey in 50-pound bags is the most practical way to procure the product for field applications. A typical composition of sweet whey is as follows:

- Lactose ($C_{12}H_{22}O_{11}$) at 70 to 75% by weight
- Protein
- Fat
- Water

The dry form is soluble in water, and the chemical composition of lactose is similar to that of other sugars such as sucrose. Whey is typically dissolved in water at concentrations of 1 to 10 percent by weight and injected on a monthly to quarterly basis.

7.1.5 Mixed Iron and Carbon Substrates

Several commercial products are now available that combine an organic substrate with zero-valent iron (ZVI). EHC® technology from Adventus Americas, Inc. is a family of remediation products used for the *in situ* treatment of groundwater and saturated soil impacted by chlorinated solvents and heavy metals. EHC® is a controlled-release, integrated carbon and ZVI product that is purported to yield redox potential (Eh) in the -500 to -650 mV range. This is significantly lower than typically achieved using only an organic substrate or by ZVI alone. The manufacturer claims that Eh potentials in this range facilitate effective degradation of normally recalcitrant chlorinated organics without the formation of intermediates such as *cis*-DCE and VC. EHC mass requirements for chlorinated solvent sites are reported by the manufacturer to typically range from 0.05% to 1% product to soil by weight (non-barrier configurations), and up

to 2% by weight product to soil mass for injected permeable reactive barriers (PRBs), and up to 10% by weight product to soil mass for trenched PRB applications.

Redox Tech, Inc. provides an oil-based product (Anaerobic Biochem, or ABC[®]), which is a patented mixture of lactates, fatty acids, and a phosphate buffer. ABC[®] contains soluble lactic acid as well as unspecified slow-release oil-based components. The phosphate buffer limits pH excursion and also provides a source of phosphate as a micronutrient (*aka* vitamin) for biological activity. Through a license agreement provided by Envirometals and Adventus Americas, Inc., Redox Tech is licensed to add ZVI to its formulation of ABC[®]. In this case, a ZVI powder (micro-scale iron) is mixed in at the time of injection and is not an “off-the-shelf” pre-mixed product.

The NASA Kennedy Space Center has commercialized the use of emulsified zero-valent iron (EZVI), which they developed for treatment of DNAPL sites. EZVI was originally developed by researchers at NASA and the University of Central Florida to treat chlorinated-solvent contamination at Launch Complex 34 at the Kennedy Space Center in Florida. NASA has since licensed EZVI to seven companies that are developing their own versions of the technology. To date, a standard off the shelf products is not available, presumably due to difficulties producing a stable EZVI product.

7.2 SUBSTRATE DESIGN FOR SOLUBLE SUBSTRATES

Advantages of using soluble substrates include the ability to readily distribute the substrate in the subsurface relative to viscous or solid substrates, and the ability to modify the rate at which the substrate is applied over time to achieve the desired biogeochemical conditions. For these reasons soluble substrates are well suited for recirculation systems and for bioaugmentation applications. The primary disadvantage of this approach is the requirement for multiple injections (higher O&M and cost) and the potential for biofouling of injections wells (GeoSyntec Consultants, 2005).

7.2.1 Sodium Lactate

Lactate is available in the form of lactate salts (sodium or potassium lactate), which disassociate and form lactic acid ($C_3H_6O_3$) in water. Lactate salts are typically mixed at a concentration of 1 to 6 percent in water by weight. For the recirculation demonstration at Building 1419, Indian Head NSWC, Maryland, groundwater was amended with 380 mg/L (0.038 percent). However, the pilot test cell was very small and for larger applications a higher dose might be necessary to effectively treat a larger volume of aquifer before the substrate is depleted.

For the TAN INEEL case study (Appendix C), sodium lactate was typically injected at concentration of 3 to 6 percent sodium lactate by weight. Enhanced dissolution of DNAPL was observed to occur at concentrations of 6 percent or more by weight. With the exception of targeting enhanced dissolution of DNAPL, most applications using lactate will base the design on site-specific calculations of stoichiometric electron acceptor demand and then optimize the injection protocol in the field to achieve a target concentration of TOC or organic acids.

7.2.2 Molasses and Fructose

Molasses is comprised primarily of sugars (sucrose), but may contain other minor constituents such as sulfur, sulfate, and metals that may be of potential concern. Higher grades of molasses or high fructose corn syrup (HFCS) may be used in situations where the addition of additional sulfur or other impurities to an aquifer is undesirable.

Molasses is comprised of approximately typically 60% fermentable carbohydrates, primarily sucrose, and typically costs from \$0.25 to \$0.50 per pound for raw molasses. Molasses is injected in a water solution of 10 percent molasses or less by volume (approximately 6,000 mg/L carbohydrates) (Suthersan *et al.*, 2002), although molasses may be injected at much higher concentrations in an effort to enhance the dissolution of chlorinated solvent DNAPL (Payne *et al.*, 2006a and 2006b; Chu *et al.*, 2004).

HFCS comprises a group of corn syrups that have undergone enzymatic processing to convert its glucose into fructose, and has then been mixed with pure corn syrup (100% glucose) to produce a desired sweetness. In the United States, HFCS is typically used as a sugar substitute and is ubiquitous in processed foods and beverages. Many confuse pure “fructose” with “high fructose corn syrup,” a sweetener that never contains fructose alone, but always in combination with a roughly equivalent amount of a second sugar (glucose from corn syrup).

The composition of HFCS is approximately 50% fructose and 50% glucose, ranging from 42% to 55% fructose with the remaining sugars being primarily glucose. The most widely used types of high-fructose corn syrup are: HFCS 55 (mostly used in soft drinks), approximately 55% fructose and 45% glucose; and HFCS 42 (used in many foods and baked goods), approximately 42% fructose and 58% glucose.

Molasses and fructose are typically injected in high concentration solutions that target a range of TOC in the treatment zone that is based on experience. For the Hanscom AFB and Vandenberg AFB demonstrations (Appendix C), the initial dosing was anticipated to be 40 to 80 lbs of carbohydrates per injection well per week. The feed solution was proposed to consist of a 10:1 mixture by volume of potable water to raw blackstrap molasses, where the total consumable carbohydrate concentration in the molasses is approximately 60% by weight. The dosing objectives were to achieve concentrations of TOC from 500 to 5,000 mg/L in the injection well, and greater than 50 mg/L TOC in the downgradient monitoring wells. It was anticipated that the dosing rate and frequency would be adjusted based on field observations.

7.2.3 Ethanol

Ethanol (C₂H₆O) is a flammable alcohol, but that can be safely handled in a diluted form. Because the fermentation pathway for ethanol is less complex than a product such as molasses, a stoichiometric approach is typically used to determine initial substrate loading rates. For the Area 20 demonstration at the Aerojet Facility in California (Appendix C), the substrate loading rate was based on field observations and calculating the electron acceptor demand. A 3:1 electron donor to electron acceptor ratio (equivalent to 50 mg/L of ethanol) was found to be effective for degradation of DO, nitrate, sulfate, perchlorate, and TCE with little donor wasted on non-required microbial processes (i.e., iron and sulfate reduction, and methanogenesis).

These calculations were based on balanced redox reactions directly with ethanol, versus calculations based on fermentation of ethanol to produce molecular hydrogen. While these conventions may underestimate the substrate requirement, the use of three times the calculated electron acceptor demand resulted in highly efficient transformation of perchlorate and TCE without significant production of methane.

7.3 SUBSTRATE DESIGN FOR PERMEABLE MULCH BIOWALLS AND BIOREACTORS

Mulch and compost substrates are intended to be long-term sources of organic carbon, with anticipated life spans exceeding 5 to 10 years or more. Mulch and compost mixtures are often amended with other agricultural byproducts such as cotton seed hulls and mushroom compost. Other investigators have installed trenches and backfilled excavations with a variety of waste cellulose solids (e.g., sawdust and mulch) since the mid-1990s for the treatment of nitrate-contaminated water, and have found little reduction in performance during 7 years of operation (Robertson *et al.*, 2008).

Selection of solid substrates requires careful consideration of substrate composition, as the degradation characteristics of mulch and compost products may vary significantly. Bench scale tests (e.g., batch or column studies) may be useful for screening the biowall material design (e.g, Ahmad *et al.*, 2007a; GSI, 2005; Shen and Wilson, 2007). Typically, mulch and compost are mixed with coarse-grained sand or pea gravel at a ratio of 40 to 60 percent by volume (AFCEE, 2008; Ahmad *et al.*, 2007b).

Monitoring of biowall systems to date indicates that the effective life span of a biowall system without substrate replenishment may vary from 3 to 6 years, or more. Replenishment of a biowall or bioreactor system involves the injection of a supplemental organic substrate (such as EVO) in the biowall trench or bioreactor cell. An O&M plan with contingencies for substrate replenishment is useful to maintain biowall or bioreactor performance over periods of 3 years or more. Development of an O&M plan will be highly site-specific in regards to the hydrogeology, geochemistry, contaminants present, and biowall system configuration. Guidance for developing an O&M Plan and test protocols to determine when replenishment are required can be found in AFCEE (2008).

7.3.1 Biowall Replenishment Options

Replenishment of biowall or bioreactor systems involves the delivery of an organic substrate to the biowall trench or bioreactor cell. The primary options include substrate selection and the injection protocol. EVO was the substrate used for biowall replenishment at the former NWIRP in McGregor Texas, and has also been used to replenish biowalls at Altus AFB, Oklahoma. The use of vegetable oil and oil-in-water emulsions for enhanced bioremediation of chlorinated solvents is described in the AFCEE edible oil protocol (AFCEE, 2007). Biowalls at NWIRP McGregor are being replenished every 3 to 4 years based on experience with perchlorate degradation (EnSafe, Inc., 2005 and 2008).

7.3.2 Substrate Loading

Methods to determine how much substrate to apply may be based on 1) mass discharge of contaminants and native electron acceptors, 2) a ratio of substrate to the mass of solid media in the biowall or bioreactor, or 3) an empirical concentration of substrate based on past experience. Because biowalls are typically constructed perpendicular to groundwater flow and are typically only 2 to 3 feet wide, there is little transverse dispersion within the biowall itself. For this reason the substrate should be physically distributed throughout the entire biowall volume, requiring injection volumes equal to or greater than the effective pore volume of the biowall.

Often a significant design factor is applied when using calculations based on contaminant mass flux and native electron acceptor stoichiometric calculations. Due in part to this uncertainty, some practitioners may base substrate loading on ratios or percentage of substrate relative to the mass of solid media, or to the pore space of the treatment zone. For example, applying sufficient vegetable oil to account for 2 to 5 percent of the pore space (by volume) of the treatment zone could be expected to provide sufficient substrate to stimulate reductive dechlorination of CAHs for a year or more at most sites.

Three methods were used to determine substrate loading rates for biowall replenishment at NWIRP McGregor, Texas (EnSafe, Inc., 2005). The first method was based on a recommendation from the emulsified vegetable oil vendor (EOS Remediation) to use a ratio of 0.1 to 0.4% EOS product by weight of the mass of solid media in the biowall. As an example, 2,090 pounds of EOS product was calculated to be required for biowall segment S-1B of 380 feet in length, 2.5 feet in width, a saturated thickness of 10 feet, an assumed "soil" mass of 110 pounds per cubic feet, and a oil to soil mass ratio of 0.2%. This is equivalent to 1,254 pound of soybean oil assuming the EOS product is 60% oil by weight.

The second method used the EOS Remediation design spreadsheet and was based on electron acceptor demand and groundwater specific discharge through the biowall. For the S-1B biowall example above, the design spreadsheet yielded a substrate requirement of approximately 3,780 pounds of EOS product (2,268 pounds of oil) assuming a 2 year design life and an average perchlorate concentration of 1,000 µg/L.

The third method used an assumption initially used when the biowalls were installed. The assumption was that 10 pounds of oil per cubic yard of biowall material was needed for each biowall. For the S-1B biowall, this yielded a requirement of 5,870 pounds of EOS product (3,522 pounds of oil, assuming the product is 60 percent oil by weight). The first method yielded the lowest of the three calculated substrate requirements, and was selected based on economic considerations.

7.3.3 Injection Volumes

To ensure that substrate is uniformly distributed throughout the biowall, the injection volume should be sufficient to displace at least one pore volume of the section of biowall being treated. Although some substrate will flow into the surrounding formation, the total pore volume of the biowall section is a first approximation of the volume of the substrate mixture to inject. The total volume to inject in each biowall section can be calculated by multiplying the biowall dimensions to obtain a total trench volume, then multiplying by the matrix porosity to estimate the trench

section pore volume. For example, given a trench 100 feet long, by 2 feet wide, with a maximum saturated thickness of 10 feet, the volume of the saturated portion of the trench is:

$$\begin{aligned}\text{Biowall Volume} &= 100 \text{ feet (length)} \times 2 \text{ feet (thickness)} \times 10 \text{ feet (depth)} \\ &= 2,000 \text{ cubic feet}\end{aligned}$$

Then the pore volume may be calculated as:

$$\begin{aligned}\text{Pore Volume} &= 2,000 \text{ (cubic feet)} \times 0.40 \text{ (estimated matrix porosity)} \\ &= 800 \text{ cubic feet} \\ &= 800 \text{ cubic feet} \times 7.48 \text{ gallons per cubic feet} = 5,984 \text{ gallons}\end{aligned}$$

If the substrate loading specifies a concentration based on pore volume, the volume of substrate product to use can be calculated by multiplying the substrate loading concentration times the total pore volume. Assuming the substrate is emulsified oil, that the loading specifies 2 percent by volume of the pore space is filled with oil, and that the product is 50 percent oil by volume, then the amount of product required is calculated by:

$$\begin{aligned}\text{Product Volume} &= \frac{800 \text{ cubic feet (pore volume)} \times 0.02 \text{ (loading strength)}}{0.50 \text{ (percent oil)}} \\ &= 32 \text{ cubic feet} \\ &= 32 \text{ cubic feet} \times 7.48 \text{ gallons per cubic feet} = 239 \text{ gallons of product}\end{aligned}$$

If the substrate loading is specified in weight per unit volume of the trench (e.g., pounds of vegetable oil per cubic yard of biowall), then the weight of the product needed is derived from the total volume of the biowall trench. The product is still mixed with sufficient make-up water to meet or exceed the biowall pore volume to ensure uniform distribution.

7.3.4 Injection Procedures

The procedure for replenishment of a biowall includes 1) procurement and mixing of the substrate, 2) injection and monitoring of volumes and injection pressures, and 3) confirmation of uniform substrate delivery. Examples of mixing emulsified vegetable oil are described in AFCEE (2007). Make-up water for the substrate mixture should be native groundwater, preferably extracted from within or downgradient of the biowall. The high permeability of the biowall materials should allow for high rates of extraction.

Substrates may be injected via dedicated injection wells or perforated piping. Alternatively, biowall materials are readily penetrated by direct-push techniques and the substrate may be injected through direct-push probes without dedicated injection systems. Simultaneously extracting and injecting from alternating wells installed along the biowall trench is one option to enhance distribution of substrate within the biowall trench. In this case, it may be possible to amend the substrate mixture in-line using proportional feed equipment. For biowalls with horizontal perforated piping along both the bottom and top of the biowall, groundwater may be

extracted from the bottom pipe, amended with substrate, and injected in the top pipe. Inflatable packers may be used to section off the horizontal pipe into more manageable injection segments.

Confirming the distribution of the substrate in a biowall or bioreactor should include 1) documentation that the appropriate volumes of substrate were injected at each location, and 2) post-injection monitoring to document that target levels of TOC were obtained at representative sampling locations. Sampling and analysis of TOC during routine O&M monitoring is one option for confirming substrate delivery. It may also be beneficial to install additional or temporary well points in select locations between injection wells or between injection piping, particularly where there are not sufficient locations in the system monitoring network to document uniform delivery. These locations only need be sampled and analyzed once following injection to confirm that substrate has been delivered throughout the biowall or bioreactor system as designed.

7.4 USING THE SUBSTRATE ESTIMATING TOOL

The previous discussions summarize common methods to determine substrate loading rates. To evaluate substrate requirements, a spreadsheet tool has been developed to assist the practitioner in determining site-specific electron acceptor demand and to estimate the substrate required to meet that demand over the design life of the application. ***This tool to evaluate substrate requirements is not intended to be used as a design tool, rather it is intended only for the purpose of site screening and to evaluate the scientific basis of determining electron acceptor demand and substrate requirements.***

Several providers of organic substrates for enhanced *in situ* bioremediation provide design tools using similar calculations as the substrate requirements tool. The calculations and assumptions used are not always readily apparent in these design tools. The substrate requirements tool provides information on the reactions, calculations, and assumptions employed in an effort to educate the user on how an estimate of the substrate requirement is determined for a specific site. It is not intended to replace or be used in lieu of a vendors proprietary design tool.

The technical basis of the substrate estimating tool is described in Appendix B. Substrate loading comparisons for the demonstration sites were conducted (Appendix C), and summary results are listed in Table 7.4. The following is a discussion of the demonstration case study results, and a discussion of how the tool is useful for the site screening and evaluation of enhanced bioremediation designs.

The demand from individual electron accepting processes (assuming they all go to completion) ranges in percent as follows:

- Aerobic Respiration: 0.1 to 12.9 percent, but typically 2 percent or less.
- Nitrate Reduction: <0.1 to 37.4 percent, but typically 3 percent or less.

Table 7.4
Summary of Substrate Loading Calculations

Site	Design Life (years)	Volume Treated (gallons)	Hydrogen Requirement (lb/gal)	Demand from CAHs/ Perchlorate (percent)	Demand from Aerobic Respiration (percent)	Demand from Nitrate Reduction (Percent)	Demand from Manganese Reduction (percent)	Demand from Iron Reduction (percent)	Demand from Sulfate Reduction (percent)	Demand from Methanogenesis (percent)	Estimated Design Factor	Notes
Hangar K, CCAFS, FL	5	154,877	5.00E-04	75.8	0.1	<0.1	0.9	0.8	5.6	16.8	21	Potential DNAPL Source Area
Area C, Alliant Techsystems, Inc., Elkton, MD	3	814,453	6.62E-05	6.7 (CAHs) 8.8 (Perchlorate)	4.3	11.7	6.9	6.8	29.3	24.4	1+	Higher than anticipated rate of groundwater flow
SA-17, NTC Orlando, FL (Upper Zone/Lower Zone)	5	95,685/ 138,971	2.66E-04/ 2.67E-04	9.9/ 7.5	2.0/ 2.0	3.1/ 3.0	0.6/ 0.6	2.8/ 5.6	56.9/ 65.6	15.8/ 15.7	10/ 7.2	High iron and sulfate site
DP98, Elmendorf AFB, AK	3	78,673	7.32E-05	8.7	1.4	0.1	16.7	6.2	9.6	57.3	14	High iron, high manganese site
Kenney Avenue Plume, Elmendorf AFB, AK	2	3,225,640	3.25E-05	<0.1	1.5	0.5	14.4	0.8	32.4	50.4	20	High manganese, low CAHs, high rate of groundwater flow
Contemporary Cleaners, Orlando, FL (Upper Zone/Lower Zone)	2	794,087/ 10,388	1.04E-04/ 9.43E-05	18.2/ 11.3	2.0/ 1.1	1.2/ 1.3	1.5/ 1.6	2.9/ 3.2	13.5/ 14.9	60.7/ 66.7	4.7/ 9.4	High production of methane, low pH site
Springdale Cleaners Site, Portland, OR (Dissolved-HRC®/ Source-HRC-X™)	1.5/ 3.0	151,859/ 102,229	9.92E-05/ 1.57E-04	11.5/ 44.0	1.1/ 0.7	0.1/ 0.1	3.1/ 1.0	11.7/ 8.4	30.4/ 19.2	42.3/ 26.7	7.5/ 2.6	Substrate persisted at target levels over intended design life
East Gate Disposal Yard, Fort Lewis, WA	0.67	484,497	6.03E-05	31.4	2.1	1.5	0.5	0.7	22.1	41.7	NA	High dosage rates were used for to enhance DNAPL dissolution
Site 1, Hanscom AFB, MA	2	345,399	3.52E-05	6.3	1.8	<0.1	1.0	26.4	52.5	11.9	2.9	High iron and sulfate site
Site 35, Vandenberg AFB, CA	2	359,360	2.18E-04	0.3	1.4	3.0	0.1	1.4	82.7	11.2	3.0	High sulfate site
Area 20, Aerojet Facility, CA	1	8,349,912	3.27E-05	3.6/ 14.7	12.9	37.4	1.9	0.5	27.9	1.3	3.0	A 1 year design life was used for estimating substrate requirements
Building 1419, Indian Head NWS, MD	0.3	55,690	2.43E-04	48.4 (perchlorate)	0.6	0.7	<0.1	<0.1	50.1	0.2	1.7	Dosing rates were selected to limit sulfate reduction and methanogenesis
Building 301, Offutt AFB, NE	5	4,196,467	4.51E-05	0.9	1.2	4.5	3.4	1.7	41.9	46.4	NA	Mulch substrate

- Manganese Reduction: <0.1 to 16.7 percent.
- Iron Reduction: <0.1 to 26.4 percent.
- Sulfate Reduction: 5.6 to 82.7 percent.
- Methanogenesis: 0.2 to 66.7 percent, but typically greater than 10 percent.
- Contaminant Reduction (CAHs or perchlorate): <0.1 percent to 75.8 percent.

The variability in these percentages reflects the variability in site conditions that may be encountered. Sulfate reduction and methanogenesis have the greatest potential to dominate electron acceptor demand and to increase substrate requirements. This is due to the magnitude of sulfate concentrations that may occur (up to several thousand milligrams per liter), and to the high utilization rate of hydrogen by methanogenesis (1.99 weight of carbon dioxide produced per weight of hydrogen, for example compared to 11.91 weight of sulfate reduced per weight of hydrogen).

In source areas, the electron acceptor demand from chlorinated solvents may predominate. For example, the site with the highest percentage of CAH electron acceptor demand (75.8 percent) and the highest overall substrate requirement (5.00E-04 pounds of molecular hydrogen per gallon of groundwater treated) was for the source area application at Hangar K, CCAFS, Florida where concentrations of TCE as high as 300,000 µg/L were observed.

Overall substrate requirements calculated as molecular hydrogen equivalents ranged from 3.27E-05 to 5.00E-04 pounds of molecular hydrogen per gallon of groundwater treated. As an example, the concentration of ethanol required to produce this much hydrogen is calculated by the tool to be from 45 mg/L (Area 20, Aerojet Facility, California) to 684 mg/L (Hangar K, CCAFS, Florida) (calculations in Appendix C case studies).

Substrate estimates using a design factor of one-times the electron acceptor demand over the design life of the application were compared to the total amount of substrate applied to calculate an overall design factor. Design factors ranged from approximately one-times the electron acceptor demand to 21-times the electron acceptor demand, a considerable range. A more common range is from 3 to 10 times the estimated electron acceptor demand.

7.5 SUMMARY OF DETERMINING SUBSTRATE LOADING RATES

The substrate estimating tool in Appendix B is useful to screen site conditions that will impact substrate delivery and utilization. The tool provides an estimate of **total** substrate required over the design life of the application given a user specified design factor. The tool calculates a time-weighted average concentration of substrate by dividing the total volume of groundwater treated by the total substrate quantity.

The variability in the relative percentage of electron acceptor demand for common electron accepting processes reflects the variability in site conditions that may be encountered. Sulfate reduction and methanogenesis have the greatest potential to dominate electron acceptor demand and to increase substrate requirements. This is due to the magnitude of sulfate concentrations that may occur (up to several thousand milligrams per liter), and to the high utilization rate of

hydrogen by methanogenesis. In source areas, the electron acceptor demand from chlorinated solvents may predominate.

The substrate estimating tool is useful to understand how the substrate will be utilized and to screen for potential adverse geochemical conditions. For example, high manganese and iron sites may require monitoring to ensure secondary water quality is not impacted downgradient of the treatment zone. pH and alkalinity are included in the tool to screen for sites with low buffering capacity.

The quantities and time-weighted average substrate concentrations can be used for comparison to proposed or planned bioremediation applications as a check on the quantities of substrate being proposed or the performance targets for TOC or DOC. This should help avoid application of either too little substrate or generating excessive substrate levels.

While the substrate estimating tool provides a first approximation of total substrate required, it does not provide for any guidance or indication on how the substrates should be applied. Design tools are often provided by substrate vendors, and the estimated substrate quantity should always be compared to recommendations by the provider or with case studies in the literature.

The primary objective when selecting a substrate loading rate is to achieve a uniform distribution of substrate over time and space. In practice, a high concentration solution or slow-release product is injected which create a range of substrate concentrations downgradient of the point of injection. A typical target concentration is from 50 to 500 mg/L of DOC. Design tools that assist the practitioner with the configuration (well spacing) and injection volumes are being developed and should be incorporated into the design process. Examples include the Edible Oil Substrate tool being developed under ESTCP Project ER-0626 (Borden *et al.*, 2008; available at the ESTCP on-line library at <http://docs.serdp-estcp.org/>).

For slow release substrates injected in a one-time event, a conservative design factor on the order of 3- to 7-times the estimated substrate requirement should be suitable for limiting the potential for insufficient substrate. For soluble substrates, lower design factors on the order of 2- to 3-times the estimated substrate requirement are beneficial to avoid over-stimulating the aquifer and driving down pH. Substrate quantities can be increased if initial loading rates are insufficient to create suitable reducing conditions throughout the treatment zone. The delivery methods for soluble substrates should target uniform substrate concentrations without excessive “spikes” in concentration.

The use of very high substrate concentrations to enhanced dissolution of DNAPL into the aqueous phase represents an exception to typical substrate loading rates. Solutions with concentrations of lactate as high as 6 percent by weight, whey as high as 10 percent by weight, and molasses as high as 1 to 2 percent by weight have been used for this purpose. These applications require special consideration of the buffering capacity of the aquifer and the system configuration. For example, it may be acceptable to induce adverse geochemical conditions in the source zone to mobilize CAH mass if a suitable downgradient reaction zone for biodegradation and geochemical recovery is established. In most all cases, these types of injections are performed in pulses of every 4 to 12 weeks to allow the aquifer geochemistry to stabilize.

8. TEMPERATURE, PH, AND BIOREMEDIATION BUFFERING AMENDMENTS

Several factors affect the rate at which biological and chemical reactions occur in the subsurface, including temperature and pH. Temperature and pH have an impact on the growth and activity of dechlorinating bacteria, particularly *Dehalococcoides* species, during anaerobic dechlorination of chlorinated solvents in groundwater. Control of pH excursion is a primary geochemical objective for both biotic reductive dechlorination and for biogeochemical transformation processes. This section describes the importance of these two parameters. Two tools for estimating pH buffering requirements have been recently developed and are described below.

8.1 IMPACTS OF TEMPERATURE

Most biological and chemical reactions that occur in the subsurface are time dependent (i.e., not instantaneous) and are referred to as kinetic reactions. In general, reaction kinetics is the study of the effects of temperature, pressure, and concentration on the rate of chemical or biological reactions. For example, groundwater temperatures may have a significant impact on the rate of growth of microbial species in the subsurface. This may affect both the rate of utilization (e.g., fermentation) of substrate and the rate of activity and growth of dechlorinating bacteria such as *Dehalococcoides* species.

8.1.1 Temperature and Reaction Kinetics

In general, the rate of chemical reactions increases with temperature. This is described by the Arrhenius temperature-dependent relationship (equation not shown), which is often re-arranged to:

$$k_2 = k_1 \Theta^{(T_2 - T_1)}$$

where k_1 and k_2 = reaction rate constant at temperature 1 and 2, respectively;
 Θ = temperature coefficient specific to the reaction; and
 T_1 and T_2 = absolute temperature 1 and temperature 2 (degrees Kelvin)

Based on empirical observations for temperature coefficients (Θ), the rate of most chemical reactions will increase by approximately a factor of two times for each rise in temperature of 10 °C (or 18 degrees Fahrenheit [°F]) (Krauskopf, 1979; Henry and Heinke, 1996).

Biochemical processes are often composed of a complex pathway with intermediate reactions that involve enzymes (biological catalysts). Even so, the Arrhenius relationship holds for many biological phenomena under natural temperature ranges. This includes mesophilic microorganisms, organisms that grow best in moderate temperatures typically between 15 and 40 °C (59 and 104 °F).

However, many native microbial species adapt to the cold temperature environment in which they grow and evolve over time. In cold water environments (defined here as <10 °C) this includes psychrophilic microorganisms (cold-loving microorganisms that grow from 0 to 20 °C), or psychrotrophic microorganisms (cold-tolerant microorganisms that have the ability to grow at low temperatures, but have optimal and maximal growth temperatures above 15 to 20 °C).

Therefore, it may not be valid to assume that the rates of biological or biogeochemical processes will follow the Arrhenius relationship (i.e., a doubling in rate for every 10 °C rise in temperature) between two different sites with differing groundwater temperature. This is the primary reason that temperature cannot be directly incorporated into calculations for substrate requirement. Nonetheless, temperature should be considered as a potential limiting factor for enhanced *in situ* bioremediation. The following subsection describes its impact on anaerobic dechlorination of chlorinated solvents in cold water environments.

8.1.2 Impact of Temperature on Dechlorinating Bacteria

The impact of temperature on native dechlorinating species is often overlooked in bioremediation studies, particularly for *Dehalococcoides* species (Friis *et al.*, 2007). Bradley *et al.* (2005) report that TCE was dechlorinated to *cis*-DCE and VC in microcosms constructed with soil and groundwater collected from two sites in Alaska. The microcosms were incubated at 4 °C and spiked with radiolabeled (carbon 14) TCE, *cis*-DCE, and VC. However, dechlorination to ethene or ethane was not observed. Losses in *cis*-DCE and VC (ranging from 25 to 70 percent) were attributed to anaerobic oxidation based on an accumulation of radiolabeled carbon dioxide (CO₂).

Bradley *et al.* (2005) concluded that assumptions regarding low to insignificant microbial activity at water temperatures below 5 °C do not consider the presence of cold-adapted (psychrotolerant and psychrophilic) microorganisms. However, it is not clear from this study which microorganisms are facilitating the dechlorination reactions and whether anaerobic oxidation will occur at rates high enough to limit the accumulation and persistence of *cis*-DCE and VC.

Data collected at the DP98 Site (USAF, 2007) and the Kenney Avenue Plume (USAF, 2009) during enhanced bioremediation treatability studies at Elmendorf AFB, Alaska showed near molar conversion of TCE to *cis*-DCE, with limited dechlorination to VC. Evidence of further dechlorination to ethene or ethane was not observed, and *cis*-DCE and VC continue to persist at elevated concentrations at the DP98 site. Data collected under this demonstration (Parsons, 2009) indicate that the growth of native *Dehalococcoides* species was limited (if it occurred at all) under ambient groundwater conditions of 7 to 8 °C at the two sites. A microcosm study (GeoSyntec, 2007) performed under the Kenney Avenue Plume Treatability Study further indicated that the growth of a *Dehalococcoides* mixed bioaugmentation culture (KB-1[®]) could not be sustained at a laboratory controlled temperature of 10 °C.

Groundwater analytical data for these studies indicate that dechlorination of TCE to *cis*-DCE and VC may be stimulated in cold water environments. However, the ability to stimulate the growth of native *Dehalococcoides* species to further dechlorinate *cis*-DCE and VC to ethene appears to be a significant limitation.

In 2002, the KB-1[®] bioaugmentation culture was used to bioaugment a cold temperature site contaminated with PCE at the River Terrace Site in Soldotna, Alaska (Oasis Environmental, 2006). Prior to bioaugmentation, PCE was converted through TCE and stalled at *cis*-DCE. VC concentrations peaked 1 to 2 years after bioaugmentation, and some ethene production was observed approximately 2.5 years after bioaugmentation. This suggests that while *Dehalococcoides* may be able to grow at low groundwater temperatures, the rate of growth and dechlorination activity will be slow.

Based on these observations, temperature is included as a site-specific input parameter for screening purposes in the substrate estimating tool (Appendix B). A typical range of groundwater temperature is specified as 15 °C to 25 °C. If the user inputs a temperature between 10 and 15 °C, then the tool will return a note that anaerobic bioremediation processes may be slower at groundwater temperatures below 15 °C and the user is referred to this discussion of temperature impact. For temperatures below 10 °C, the tool returns a more strongly worded note of caution that utilization of substrate and the growth and activity of *Dehalococcoides* species are likely to be significantly slower below 10 °C, and may have a significant impact on bioremediation performance. The user is advised to read a full description of the impacts of temperature in this demonstration report.

8.2 IMPACTS OF PH

Enhanced anaerobic bioremediation is primarily an acid producing process, and the lowering of pH may result in slow or incomplete dechlorination of chlorinated solvents. Acidification caused by addition of an organic substrate has been observed to inhibit dechlorination in laboratory studies (Cirpka, *et al.*, 1999; Carr and Hughes, 1998; Aulenta *et al.*, 2006; McCarty *et al.*, 2007) and in field studies (Volkering and Pils, 2004). The bioremediation processes that lead to acidification of the aquifer are described below, along with the impact of low pH on the activity of dechlorinating species such as *Dehalococcoides*.

8.2.1 Enhanced Bioremediation Processes and pH

Processes that affect pH during enhanced bioremediation include the following:

- Biological reductive dechlorination produces acidity. During biological reductive dechlorination, molecular hydrogen (H_2) is utilized as an electron donor where a chloride ion (Cl^-) is replaced by a hydrogen ion (H^+). This results in release of both a chloride ion and a hydrogen ion into solution. The increase in hydrogen ion lowers pH.
- Fermentation of organic substrates produce metabolic acids (e.g., butyric, propionic, and acetic), which further degrade to form carbonic acid (H_2CO_3).
- The production of carbon dioxide (CO_2) gas further depresses the pH equilibrium.
- Terminal electron accepting processes such as sulfate reduction produce alkalinity by production of hydroxide (OH^-).

The acidity produced by both dechlorination and fermentation processes is most pronounced when applying enhanced bioremediation to DNAPL source zones. In addition to very high concentrations and mass of chlorinated solvents, applications for DNAPL sites typically apply relatively high concentrations of substrate (electron donor) in an attempt to enhanced dissolution of DNAPL mass (Payne *et al.*, 2006a and 2006b; Macbeth and Sorenson, 2008).

The ability of the aquifer matrix to buffer the addition of acids produced during enhanced bioremediation is dependent on the following:

- Concentrations of inorganic species in groundwater that potentially neutralize acid (primarily alkalinity).

- Concentrations of aquifer minerals that dissolve to neutralize acid added by biological processes.
- Proton exchange with charged clay particles.

Groundwater pH is strongly controlled by dissolved inorganic carbon, particularly the equilibrium of carbonate species. A source of carbonate minerals in the aquifer matrix may help to further buffer pH.

8.2.2 pH and Biotic Reductive Dechlorination (Halorespiration)

Dechlorinating species such as *Dehalococcoides* are selective in regards to the range of pH at which they are active. In a literature review of several dechlorinating species (*Dehalobacter restrictus*, *Dehalospirillum multivorans*, *Desulfitobacterium*, and *Desulfuromonas chloroethenica*), Middeldorp *et al.* (1999) report that the optimum range of pH for dechlorinating activity was from 6.8 to 7.8 standard pH units.

Zhuang and Pavlostathis (1995) evaluated the effect of temperature, pH, and electron donor on microbial reductive dechlorination of PCE and its dechlorination products using acetate-fed methanogenic cultures developed from a contaminated field site. They reported that optimum conditions for reductive dechlorination were achieved at a temperature of 35 °C and a pH of 7 SU. Zhuang and Pavlostathis (1995) evaluated PCE dechlorination at pH of 4, 6, 7, 8, and 9.5. The highest rate of dechlorination was at a pH of 7. The rate of dechlorination of PCE dramatically declined below a pH of 6 and above a pH of 8. In addition, production of VC was observed at a pH of 7, but not at a pH of 6 or lower or at a pH of 8 or higher. This resulted in an accumulation of *cis*-DCE at the lower and higher pH ranges.

Figure 8.1 shows the activity of the SDC-9 *Dehalococcoides* mixed culture over a range of pH values for a laboratory microcosm study conducted by Shaw Environmental, Inc. (Vainberg *et al.*, 2006; Steffan *et al.*, 2008). For this culture the rate of dechlorination of PCE drops off dramatically below a pH of approximately 6.0, or above a pH of approximately 7.5. Dechlorination of *cis*-DCE and VC by *Dehalococcoides* may be even more sensitive to pH excursion (Christ *et al.*, 2005). For example, Rosner *et al.* (1997) investigated the effect of pH on vinyl chloride dechlorination by a mixed anaerobic culture derived from a site in Victoria, Texas. The optimum pH for vinyl chloride dechlorination was 8.5 with only 1% relative activity at a pH of 5.0, 50% relative activity at a pH of 7.0, and 50% relative activity at a pH of 10.0.

8.3 PH AND ALKALINITY IN AQUIFER SYSTEMS

The basic science of pH, acidity, and alkalinity in groundwater systems is described below. This forms the basis for evaluating the buffering of pH in aquifer systems during enhanced *in situ* bioremediation.

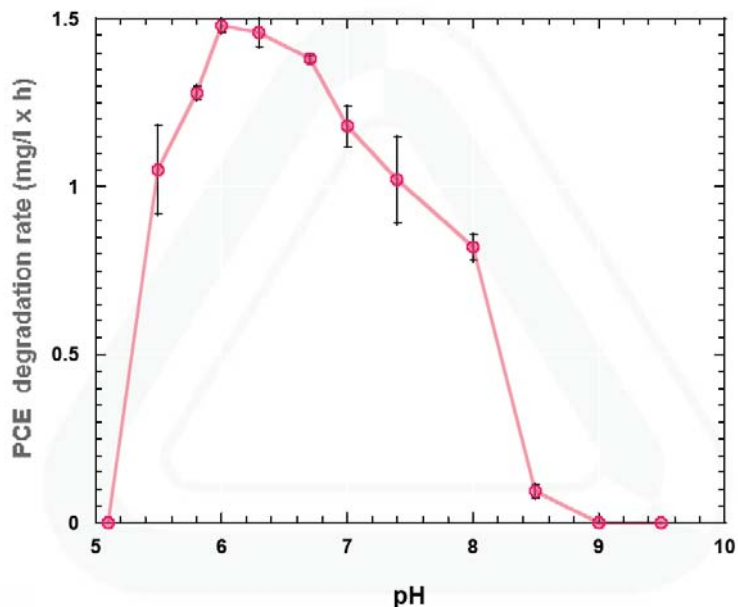
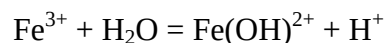
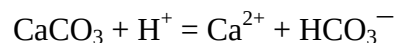


Figure 8.1 Impact of pH on Dechlorination of PCE With the SDC-9 Culture
(Steffan *et al.*, 2008)

8.3.1 Hydrogen Ion Activity (pH)

The reactivity of the hydrogen ion (H^+) is an important variable in groundwater geochemistry because the hydrogen ion participates in most of the chemical reactions that affect water composition. For example in the mineral dissolution/precipitation of calcium carbonate (calcite) or aqueous complexation of ferric iron (Deutsch, 1997):



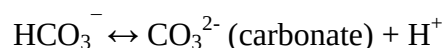
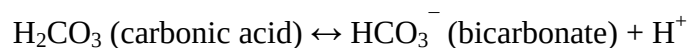
The activity of hydrogen is measured as pH as follows:

$$pH = -\log_{10}(a_{H^+})$$

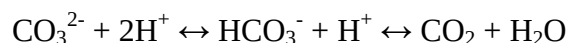
where a_{H^+} is the activity of the hydrogen ion (moles/kilogram).

The measured pH does not by itself provide any information on the capacity of the aquifer system to maintain (buffer) pH as an acid or base is added by biological or chemical processes.

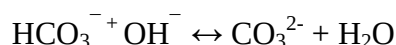
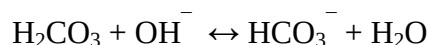
Inorganic carbon species are often the dominant anion in groundwater systems and they can take up or release hydrogen ions as part of their speciation reactions. Therefore, they provide much of the buffering capacity in natural groundwater systems and buffer pH by the following reactions (Deutsch, 1997):



As an acid (H^+) is added to groundwater, some of the carbonate will be consumed to form bicarbonate, and some of bicarbonate will be consumed to form carbonic acid. These reactions take up the added hydrogen ion and lessens its effect on the solution pH. Therefore, the dissolved carbonate equilibrium (below) strongly controls pH.



Similarly, if a base (OH^-) is added to the solution, some of the carbonic acid would be converted to bicarbonate and some of the bicarbonate would be converted to carbonate, taking up some of the OH^- and lessening its effect on pH:



In both cases, the strongest buffering occurs when concentrations of the dissolved inorganic carbon (DIC) constituents is high.

Hydrogen ions released into solution (either from dechlorination or dissociation of acids) during enhanced bioremediation react with bicarbonate to produce carbon dioxide. Dissolved carbon dioxide is not readily released to the atmosphere, and an increase in carbon dioxide coupled with a decrease in bicarbonate depresses the pH even further (Robinson *et al.*, 2009) according to the following equilibrium expression:

$$[H^+][HCO_3^-] / [CO_2] = K = 10^{-6.3}$$

Where K is the equilibrium constant and concentrations are dissolved molar concentrations.

The most common measure of carbonate and bicarbonate in groundwater is alkalinity. Therefore, alkalinity is a key groundwater parameter in evaluating the pH and buffering capacity of groundwater.

8.3.2 Alkalinity

Alkalinity is a measure of the total acid-neutralization capacity of water, while acidity is the base-neutralizing capacity of water. Alkalinity includes all species dissolved in water that can potentially neutralize acid, although most of the alkalinity in groundwater is due to the amount of inorganic carbon ions present in solution. Therefore, alkalinity is commonly used to measure the bicarbonate and carbonate concentration of groundwater where it is assumed that all other species that can potentially neutralize acid have negligible concentrations.

Alkalinity is normally reported in units of mg/L as calcium carbonate ($CaCO_3$). Carbonate can accept two hydrogen ions to form carbonic acid, while bicarbonate can only accept one hydrogen ion. Therefore, a factor of two must be used to convert carbonate units to milliequivalents per liter (meq/L). The distribution between carbonate and bicarbonate can be calculated using the equilibrium constants for the speciation reaction between carbonate and bicarbonate and the measured pH of the solution (see Deutsch, 1997 for equations).

In the subsurface, the acid neutralizing capacity of the system must also consider the minerals in the aquifer matrix that may also react with acid added to the system, which causes weathering of the minerals. Weathering of silicate minerals is a relatively slow process compared to carbonate minerals, so in most cases the acid neutralizing potential of the aquifer matrix is due to the carbonate minerals present. Therefore, characterization of both groundwater and the aquifer matrix is required when evaluating the potential for buffering of pH from the acid-producing processes of enhanced *in situ* bioremediation.

8.4 DESIGN TOOLS FOR DETERMINING BUFFERING REQUIREMENTS

Two design tools have been recently developed for evaluating buffering requirements to maintain pH at optimal levels for anaerobic dechlorination of chlorinated solvents. The first tool, BUCHLORAC (Buffering of deCHLORination ACidity), has been developed by the Source Area BioREmediation (SABRE) project, and is based on the PHREEQC geochemical model with modifications to estimate the amount of acid that is produced by anaerobic dechlorination of chlorinated ethenes and biodegradation of organic substrates. The second tool is being developed by EOS Remediation and North Carolina State University under the direction of Dr. Robert Borden. The EOS design tool is based on an Excel spreadsheet and is intended to determine the amount of a commercial substrate/buffering product (AquaBufpH™) to apply based on site-specific conditions.

The two tools differ in the input parameters required to determine buffering requirements (Table 8.1). In general, the BUCHLORAC model uses speciation of anions and cations in groundwater and the amount of carbonate and iron oxide minerals in the aquifer matrix as input to a geochemical equilibrium model, while the EOS tool uses direct measurements of soil and groundwater acidity as input to the spreadsheet tool. The following subsections describe these two tools, including the input parameters required for their use.

8.4.1 BUCHLORAC Model

BUCHLORAC is a geochemical model program in the public domain developed by the SABRE project team (Robinson and Barry, 2009a and 2009b; Robinson *et al.*, 2009). The model was initially implemented through the geochemical program PHREEQC, version 2.15. After studying the results of detailed modeling exercises, the developers have released a simplified version of the model for preliminary estimates of bicarbonate buffering requirements.

In essence, the BUCHLORAC Model is designed to predict the amount of bicarbonate required to maintain a suitable (minimum) pH for dechlorinating bacteria. The model accounts for the amount of chlorinated compounds degraded, site groundwater chemistry, type of substrate applied, alternative terminal electron accepting processes, gas (carbon dioxide) release, and soil mineralogy. Input parameters and model default values for the BUCHORAC Model are listed in Table 8.2.

Table 8.1
Factors in Evaluating Impact of Enhanced Bioremediation on pH

Process or Parameter	Impact on pH	BUCHLORAC Model	EOS Design Tool
Bioremediation Processes			
Reductive Dechlorination	Increases acidity (H^+)	Yes	Yes
Fermentation Reactions	Increases acidity (metabolic acids such as acetic acid)	Carbonate and Acetate Species	No
Gas Production	Generation of carbon dioxide (CO_2) further depresses pH	Yes	No
Terminal Electron Accepting Processes	Increases alkalinity (OH^-)	Iron and Sulfate Reduction Only	Yes
Aquifer Matrix (Mineralogy and Bulk Soil Parameters)			
Mineralogy	Adds alkalinity (buffers addition of acids)	Yes (calcite and iron oxides)	No
Bulk Soil Alkalinity (neutralization potential)	Buffers addition of acid	No	No
Bulk Soil Acidity	Requires buffer (OH^-) to Neutralize	No	Yes
Groundwater Geochemistry			
Anions/Cations (aqueous speciation)	Controls saturation of calcium carbonate and balance of inorganic carbon	Yes	No
pH	Buffers addition of acids	Yes	No
Groundwater Alkalinity	Buffers addition of acids	Yes	No
Groundwater Acidity	Requires buffer (OH^-) to Neutralize	No	Yes

The user of BUCHLORAC may select either sodium bicarbonate ($NaHCO_3$) or potassium bicarbonate ($KHCO_3$) as the buffering additive. Other buffering additives such as sodium hydroxide ($NaOH$), magnesium hydroxide ($Mg(OH)_2$), sodium carbonate (Na_2CO_3), and lime (CaO) are not included as the developers did not consider them to be practical alternatives. This may be inconvenient when considering commercial buffering additives offered by EOS Remediation (AquaBuf pH^{TM} with $Mg(OH)_2$) or by Remediation and Natural Attenuation Services, Inc. (Neutral Zone TM with $CaCO_3$), although it may be possible to calculate equivalent quantities of the different buffering compounds.

The developers indicate that bicarbonate requirements are strongly dependent on the substrate (electron donor) used and the availability of native electron acceptors (particularly ferric iron and sulfate). As the program has only recently been released, there is currently a lack of case studies to document how effective the model is at estimating appropriate buffering quantities.

Table 8.2
Summary of BUCHLORAC User Specified Input Parameters

Parameter Options	Parameters (Default Values)
Site Water Chemistry – General Water Quality	pH - (7.0 SU) Temperature - (15 °C) Electron potential (pe) - (4.0) Nitrogen gas partial pressure [N ₂ (g)] - (0.79 atm) Alkalinity or Carbonate (CO ₃ ⁻²) - (0.0)
Site Water Chemistry – Cations/Anions	Concentrations of Ag ⁺ , Al ⁺³ , Ca ⁺² , Cd ⁺² , Cl ⁻ , Cu ⁺² , Fe ⁺² , Fe ⁺³ , K ⁺ , Mg ⁺² , Mn ⁺² , NO ₃ ⁻ , NO ₂ ⁻ , NH ₄ ⁺ , Na ⁺ , Ni ⁺² , PO ₄ ⁻³ , Pb ⁺² , HS ⁻ , S ⁻ , SO ₄ ⁻² , Zn ⁺² (default values are zero)
Site Mineralogy	Calcite, goethite, ferrihydrite (default values are zero)
Buffering additive	Sodium bicarbonate (NaHCO ₃) or potassium bicarbonate (KHCO ₃) (0.2 moles added before dechlorination commences)
Organic Substrate	Linoleic acid, lactic acid, sodium lactate, butyric acid, methanol, glucose, ethanol, or formate
Minimum Design pH	pH – (6.5 SU)
Minimum H ₂ Efficiency (f _{min})	f _{min} – (0.2)
Fraction of acetate used as direct electron donor (p)	Acetate Oxidation Fraction (p) – (0.5)
Residence time of water in bioremediation zone	Residence time in days – (50 days)
Average Pressure in Bioremediation Zone	Pressure in atmospheres – (1.2 atm)
Expected Extent of Dechlorination	Moles per liter PCE, TCE, DCE, VC (TCE at its solubility limit [0.008 mols/L] will be completely degraded)

It is interesting that the BUCHLORAC model also provides for iron sulfide precipitation when the solution becomes over saturated with soluble iron and hydrogen sulfide following iron and sulfate reduction. This tool may prove to be useful in evaluating pH stability and formation of iron sulfides for natural or engineered *in situ* biogeochemical transformation of chlorinated solvents.

8.4.2 EOS Design Tool for AquaBufpH™

The EOS spreadsheet model is not in the public domain, but is available for use or review by contacting EOS Remediation (www.eosremediation.com) and requesting client log-in access to the on-line design tool site. The input parameters for the EOS design tool include the acidity of

the aquifer matrix (sediment) and the acidity of the groundwater. Other input parameters include hydraulic properties, size of the treatment zone, concentrations of dissolved chlorinated compounds, and concentrations of common native electron acceptors.

The primary difference between the EOS design tool and the BUCHLORAC Model is that the EOS design tool uses values of soil and groundwater acidity instead of modeling the geochemical equilibrium of anions/cations in groundwater and with the aquifer matrix. This is more simplistic approach and data for groundwater and soil acidity may be easier and less costly to collect.

The acidity of the sediment is input in units of milliequivalents of hydroxide per kilogram of sediment (OH^- meq/kg), with a range limited from 1 to 100 OH^- meq/kg. Similarly, the acidity of groundwater is input in units of milliequivalents of hydroxide per liter of groundwater (OH^- meq/L), with a range limited from 0.1 to 10 OH^- meq/L. The spreadsheet tool calculates a total OH^- demand in groundwater by multiplying the groundwater acidity times the pore volume and flux of groundwater through the treatment zone over the design life of the application.

The EOS design tool also accounts for production of H^+ and OH^- from dechlorination and electron accepting processes, respectively. The input parameters required include concentrations of chlorinated compounds in groundwater and concentrations of common native electron acceptors. This data is typically available from remedial investigations or natural attenuation studies. Stoichiometric calculations are used to determine meq of OH^- for dechlorination and electron accepting processes, although the stoichiometric relationships used are not readily apparent in the tool, (i.e., calculations are password protected).

The tool is limited to the application of the vendors AquaBufpHTM product. The buffering requirements are listed in OH^- equivalents, and the product uses magnesium hydroxide ($\text{Mg}(\text{OH})_2$) as the primary buffering agent.

8.5 DATA REQUIREMENTS FOR EVALUATING PH AND BUFFERING REQUIREMENTS

The minimum data that should be collected at a bioremediation site to evaluate pH and the buffering capacity of an aquifer system includes groundwater pH, alkalinity, and acidity; and soil pH and acidity. Groundwater data are usually easy to collect and analyze, while data for soil pH and acidity may be less frequently available. Other useful parameters may include DIC for groundwater and cation exchange capacity (CEC) for soil.

8.5.1 Soil and Groundwater Analytical Data

Table 8.3 and Table 8.4 list soil and groundwater geochemical parameters and analytical methods that are recommended for evaluating pH and buffering requirements during design of an enhanced *in situ* bioremediation application. The recommended soil analytical data include pH, acidity, and major anions and cations. Soil data such as CEC (or base saturation) and neutralization potential are also useful for evaluating the need to add buffering compounds during *in situ* bioremediation.

Table 8.3
Soil Analytical Protocol for Evaluating pH and Buffering Requirements

Analyte	Example Methods	Data Use	Recommendations
Soil			
pH	USEPA SW9045	Measurement of natural soil pH	Recommended
Soil Acidity	SM2310	Can be used to calculate amount of buffering agent required to neutralize soil acidity.	Recommended
Major Anions - Cl^- , NO_3^- , CO_3^{2-} , HCO_3^- , and SO_4^{2-}	USEPA SW9056 or E300 series	Used for geochemical modeling of buffering requirements (BUCHLORAC model)	Recommended
Major Cations - Ca^{+2} , Fe^{+2} , Fe^{+3} , K^+ , Mg^{+2} , Mn^{+2} , and Na^+	USEPA SW6010B	Used for geochemical modeling of buffering requirements (BUCHLORAC model)	Recommended
Soil Mineralogy (calcite, gypsum, goethite, ferrihydrite)	Laboratory-specific standard operating procedures (SOP) such as x-ray diffraction	Useful for geochemical modeling or to evaluate potential buffering capacity of site sediments.	Optional
Neutralization Potential	Laboratory-specific SOP	Measurement of buffering capacity of sediments	Optional method
Cation Exchange Capacity	Agricultural Methods – Laboratory-specific SOP	Indication of potential buffering capacity of sediments	Optional method

Recommended groundwater analytical data include temperature, pH, alkalinity, acidity, and major anions and cations. These data are useful to evaluate the primary electron-accepting processes that will occur, and may be used for geochemical modeling (e.g., the BUCHLORAC Model).

8.5.2 Evaluation in the Substrate Estimating Tool

A number of geochemical parameters are useful for the design of enhanced *in situ* bioremediation systems. The parameters that are incorporated into the substrate estimating tool for screening purposes include pH and alkalinity. These are commonly measured values and can be used for initial screening of site conditions. Any pH value below 6.5 entered into the substrate estimating tool will return a note of caution and direct the user to a discussion in the associated guidance document of the impacts of pH on dechlorinating activity. Similarly, an alkalinity value of less than 300 mg/L will also return a note of caution on the buffering capacity of the aquifer system. These threshold values are based on a summary evaluation of pH and alkalinity of the demonstration case studies.

Table 8.4
Groundwater Analytical Protocol for Evaluating pH and Buffering Requirements

Analyte	Example Methods	Data Use	Recommendations
Groundwater			
Temperature	Direct-Reading Meter	Qualitative evaluation of substrate utilization rate	Recommended
pH	Direct-Reading Meter; SM4500B; or Hach Method 8156	Indication of suitability of site groundwater to support dechlorination reactions	Recommended
Alkalinity	EPA 151.1; SM2320B; or Hach Method 8203 or 8221	Indication of potential buffering capacity of native groundwater	Recommended
Acidity	SM2310B; Hach Method 8010; Hach Method 8201; or Hach Method 8202	Indication of amount buffer needed to neutralize pH	Recommended
Anion Suite - Cl^- , NO_3^- , NO_2^- , PO_4^{3-} , HS^- , S^{2-} , and SO_4^{2-}	USEPA E300 series; E365.3 or SM4500 for PO_4^{3-}	Used for geochemical modeling of buffering requirements (BUCHLORAC model)	Recommended for major anions (Cl^- , NO_3^- , NO_2^- , and SO_4^{2-})
Cation Suite - Ag^+ , Al^{3+} , Ca^{+2} , Cd^{+2} , Cu^{+2} , Fe^{+2} , Fe^{+3} , K^+ , Mg^{+2} , Mn^{+2} , NH_4^+ , Na^+ , Ni^{+2} , Pb^{+2} , and Zn^{+2}	USEPA SW6010B; SM4500 for NH_4^+	Used for geochemical modeling of buffering requirements (BUCHLORAC model)	Recommended for major cations (Ca^{+2} , Fe^{+2} , Fe^{+3} , K^+ , Mg^{+2} , Mn^{+2} , NH_4^+ , and Na^+)
Dissolved Inorganic Carbon	Laboratory SOP	Indication of potential buffering capacity of native groundwater	Optional

In soil science, CEC is the capacity of a soil for ion exchange of positively charged ions between the soil and the soil solution. CEC is used as a measure of fertility, nutrient retention capacity, and the capacity to protect groundwater from cation contamination.

The quantity of positively charged ions (cations) that a clay mineral or similar material can accommodate on its negatively charged surface, expressed as milli-ion equivalents per 100 grams, or more commonly as milliequivalents (meq) per 100 grams. Clays are aluminosilicates in which some of the aluminum and silicon ions have been replaced by elements with different valence, or charge. For example, aluminum (Al^{3+}) may be replaced by iron (Fe^{2+}), leading to a net negative charge. This charge attracts cations when the clay is immersed in an electrolyte such

as salty water and causes an electrical double layer. The CEC is often expressed in terms of its contribution per unit pore volume.

Closely related to CEC is the base saturation, which is the fraction of exchangeable cations that are base cations (Ca, Mg, K and Na). The higher the amount of exchangeable base cations, the more acidity can be neutralized in the short time perspective. Thus, a site with high CEC takes longer time to acidify than a site with a low CEC (assuming similar base saturations).

8.6 CASE STUDY EVALUATIONS OF PH

Of the fifteen case studies, six sites exhibited adverse pH excursion that impacted performance (Table 8.5). Three sites required modifications to account for adverse pH excursions (Table 8.5):

- SA17, NTC Orlando, Florida. Low pH was due in part to previous chemical oxidation application, although the low alkalinity at the site indicates the aquifer has a low buffering capacity. Follow-up injections at the site are utilizing a buffered emulsified oil product (AquaBufpH™ with Mg(OH)₂).
- Site 1, Hanscom AFB, Massachusetts. The substrate loading for each injection event was based field observations to limit pH excursion in the injection well, while trying to maximize target concentrations of TOC in downgradient wells. The amount of substrate injected had to be limited until a buffering agent was added to the injection solution. This initially resulted in limited distribution of substrate and poor initial results. Once the buffering agent was added, higher strength substrate solutions could be injected and degradation results improved.
- Site 25, Vandenberg AFB, California. The site exhibited low buffering capacity, and pH was initially controlled by limiting the substrate dose, reducing the frequency of injection, and injection of an occasional clean water “push” to disperse dissolved substrate away from the immediate vicinity of the injection wells. This revised dosing regime was necessary to avoid further drops in pH, but negatively affected the consistency of the TOC level in the injection and downgradient monitoring wells and resulted in a limited reaction zone. Sodium bicarbonate was added to the injection regimen at 20 months after injections started in an attempt to control pH excursion. This allowed for a nearly four-fold increase in the molasses loading rate and helped to expand the reaction zone. Stabilization and mild recovery of pH was observed at most downgradient monitoring wells following the addition of a buffering agent.

For the Building 1419 Site at Indian Head NWS, it was known from microcosm studies that reduction of perchlorate would be inhibited below a pH of 4.0. Therefore, 1,175 gallons of buffer was added to the aquifer during the course of the demonstration. Approximately 875 gallons of this buffer was a 6.67% stock solution containing 80% sodium bicarbonate and 20% sodium carbonate. The other 300 gallons was a 6.67% solution containing a mixture of 70% bicarbonate and 30% carbonate. The latter solution was added to the aquifer 1 month after the beginning of the demonstration to increase the rate at which the aquifer was buffered. After this addition was complete, the 80% bicarbonate and 20% carbonate mixture was used for the remainder of the demonstration.

Table 8.5
Summary of Adverse pH Impacts on Case Study Sites

Site Identification	Background pH	Background Alkalinity (mg/L)	Reaction Zone pH	Impacts on Performance	pH or Buffering Amendment Strategy
SA-17, NTC Orlando, Florida (EVO)	5.4 to 6.3	8.6 to 111	NA	Low pH was due in large part to a previous chemical oxidation application.	Follow-up injections planned using a buffered EVO product.
Contemporary Cleaners, Orlando, Florida (HRC®)	5.0 to 6.0	NA	4.15 to 5.97 (Typically below 5.0)	Accumulation of <i>cis</i> -DCE in the lower surficial aquifer was attributed to competition from methanogenesis (Kean <i>et al.</i> , 2003). However, the impacts of low pH were not evaluated by the authors.	This site may have benefitted from use of amendments to control pH.
East Gate Disposal Yard, Fort Lewis, Washington (Whey)	6.1 to 6.4	66 to 78	4.6 to 5.9	Initially limited dechlorination with accumulation of <i>cis</i> -DCE and VC. Eventually the aquifer was able to buffer the change in pH and complete dechlorination to ethene proceeded.	None. The slow dissolution of the aquifer matrix resulted in greater buffering capacity of groundwater over time, and pH was neutralized to the point that dechlorination proceeded to completion.
Site 1, Hanscom AFB, Massachusetts (Molasses)	5.8 to 6.3	Not analyzed during baseline sampling	Close to 4.0 in the injection well	Without a buffer amendment the amount of substrate that could be injected was limited, which reduced the size of the effective treatment zone.	Sodium bicarbonate was added to the injection regimen.
Site 35, Vandenberg AFB, California	6.2 to 6.6	96 to 143	4.3 to 5.6	Without a buffer amendment the amount of substrate that could be injected was limited, which resulted in poor performance.	Sodium bicarbonate was added to the injection regimen 20 months after initial injection.
Building 1419, Indian Head NWS, Maryland	3.8 to 6.0	<2.0 to 92	Buffered to above 7.0	It was known from microcosm studies that perchlorate reduction would not occur below a pH of 4.0.	The injection mixture was amended with a stock solution of sodium carbonate and sodium bicarbonate to maintain pH above 7.0 SU.

For the East Gate Disposal Yard application at Fort Lewis Logistics Center, the pH excursion was likely exacerbated by the use of high concentration whey solutions. An initial drop in pH due to the whey conditions delayed the onset of methanogenesis and further dechlorination of DCE to VC and ethene. While dechlorination was initially incomplete, this was useful for maintaining a mass balance to evaluate enhanced dissolution. Over time, the slow dissolution of the aquifer matrix due to acids produced by biological activity was sufficient to produce enough alkalinity to stabilize pH to the point that dechlorination of DCE to VC and ethene occurred.

The last site which exhibited low pH was the Contemporary Cleaners Site in Florida. Kean *et al.* (2003) attributed the stall in dechlorination of *cis*-DCE to excessive methanogenesis. They report a correlation between the accumulation of *cis*-DCE and methanogenesis, such that dechlorination of *cis*-DCE began to occur after methanogenesis subsided. This suggested to the authors that methanogens were out competing the halorespiring bacteria. An alternative explanation may be that pH was less than optimal, with pH of less than 5.0 in many locations shortly after the first injection. An evaluation of the impact of low pH was not mentioned in any result documents or case study papers.

For all these sites, initial background pH values were typically below 6.5 and alkalinity was below 150 mg/L. For screening purposes, a combination of pH below 6.0 to 6.5 and alkalinity below 300 mg/L should indicate that modifications to buffer and control pH excursion will be necessary.

Sodium bicarbonate was the most common buffering compound used, typically at concentrations in excess of 10,000 mg/L. Sodium bicarbonate is a relative weak buffering compound and may be most suitable for applications using frequent injections of soluble substrates. The use of stronger and more persistent buffering compounds may be necessary for applications using slow release substrates, and further research and investigation will be beneficial for sites with low buffering capacity.

9. COST ASSESSMENT

9.1 ENHANCED *IN SITU* BIOREMEDIATION COST ASSESSMENT

A cost assessment was conducted for the demonstration case studies (Appendix C). Actual cost data are used for comparison purposes (Section 9.2). While actual cost data are often not available, a qualitative assessment of cost impacts for the case studies can be made by comparing the system design to actual operations.

Table 9.1 identifies the causes of potential cost impacts for the case studies. The table identifies cases where additional costs are associated with 1) costs for additional substrate injections beyond that specified in project designs or work plan documents, 2) the need to modify the injection protocol to include additional substrate or for unanticipated amendments such as pH buffering compounds, and 3) extended monitoring beyond the system design life.

For the vegetable oil substrate sites, the SA-17 Site and the Kenny Avenue Plume Site had operational cost impacts associated with additional injections or the need for greater quantities of substrate. For the two molasses sites, it was anticipated that the dosing rate and frequency would be adjusted based on field observations, and determining the optimal strength and frequency of reagent delivery was a primary objective of the demonstration. However, the number of injections and period of operation for both sites was significantly greater than planned.

It is anticipated that biowall and bioreactor applications may require substrate replenishment on the frequency of every 3 to 5 years (AFCEE, 2008). While this does not represent a “cost impact”, these costs should be considered during technology screening. An example of comparing the long-term cost of a biowall application relative to other enhanced *in situ* bioremediation techniques can be found in ESTCP (2008). Even if a biowall system is designed with replenishment in mind, the economics of long-term operation are typically favorable relative to many other *in situ* bioremediation techniques.

More difficult to evaluate than cost impacts in terms of dollars is the impact of failing to meet performance objectives. Several of the case studies did not meet performance expectations and follow-up with modified bioremediation techniques was not conducted (e.g., the Elmendorf AFB DP98 and Kenney Avenue Plume sites, Contemporary Cleaners Site in Florida, Site 1 at Hanscom AFB, and Site 35 at Vandenberg AFB). In the case of the Elmendorf AFB sites, it may simply be that enhanced *in situ* bioremediation is not an appropriate technology based on site-specific conditions. For the other sites, it is unknown whether the technology applied could be modified to successfully meet performance objectives.

The lack of successful initial results may lead to a lack of confidence in the technology, perhaps leading to more expensive remedial technologies. This reinforces the need to screen for site-specific conditions and to use the best available practices when designing and implementing enhanced *in situ* bioremediation applications.

Table 9.1
Summary of Modifications to Case Study Applications

Site/Facility	Additional Injections?	Injection Modifications?	Cost Impacts (actual or potential)
Vegetable Oil Substrates			
Hangar K, CCAFS, FL	No	None	None, although an extended monitoring event for research purposes was conducted in 2006.
Area C, Alliant Tech Systems Facility, Elkton, MD	No	None	The costs associated with an optional extended monitoring period were \$12,000 for four additional sampling events (\$48,000 total).
SA17, NTC Orlando, FL	Yes – direct-push injections to provide adequate substrate distribution	Use of buffered EVO product	Primarily associated with secondary injection
DP98, Elmendorf AFB, AK	No	None	Enhanced <i>in situ</i> bioremediation may not be appropriate for this site.
Kenney Avenue Plume, Elmendorf AFB, AK	No, three injections were planned	Yes – greater quantities of substrate and a switch to a field-mixed emulsion were required to achieve reducing conditions.	Additional substrate requirements increased from a proposed cost of \$14,900 to a final cost of \$62,600, a difference of \$47,700.
HRC® Products			
Contemporary Cleaners, Orlando, FL	No	None	It is likely that additional injections (including a buffering compound and/or bioaugmentation) would be needed to meet performance objectives.
Springdale Cleaners, Portland, OR	No	None	It is likely additional injections would be required to meet performance objectives.

Table 9.1
Summary of Modifications to Case Study Applications

Site/Facility	Additional Injections?	Injection Modifications?	Cost Impacts (actual or potential)
Whey			
East Gate Disposal Yard, Fort Lewis Logistics Center, WA	No	None	Other than having to re-install the extraction and injection wells, no significant modifications were required.
Molasses			
Site 1, Hanscom AFB, MA	Yes- 32 weekly injections were planned, while a total of 47 injections were conducted over 2-year period	Yes – addition of buffering amendment and water chase	Increased time for each injection due to rates of injection that were reduced from approximately 10 gpm 1 to 2 gpm due to biofouling and compromise of the injection well seal
Demonstration Site, Vandenberg AFB, CA	Yes - 27 weekly injections were initially planned, while a total of 31 injections were conducted over a 27-month period	Yes – addition of buffering amendment and water chase	Additional monitoring associated with extended operations.
Ethanol			
Aerojet Facility, CA	No	None	Biofouling control would be required for long-term operations
Lactate			
Test Area North, INEEL, ID	Required for optimization and long-term operation	Yes – for optimization purposes	Modifications were primarily for optimization of the system and do not represent a cost impact
Building 1419, Indian Head NSWC, MD	No	None	The pilot test was conducted as planned
Mulch Biowalls			
Area E, S, M, and F, NWIRP McGregor, TX	Yes – required to sustain biowall performance	No – additional injections have been performed according to plan.	Biowall rejuvenation was anticipated as part of long-term operations, and has been performed as anticipated.
Building 301, Offutt AFB, NE	No	No	Substrate replenishment may be beneficial in the near future.

9.2 SITE-SPECIFIC COST ASSESSMENTS

Cost data were tracked to aid in establishing realistic costs for the differing approaches to implementing enhanced *in situ* anaerobic bioremediation, and for comparison to potential alternative technologies. A typical cost model breaks down costs into elements for system design and engineering, system installation, baseline characterization, waste disposal (if applicable), system operation, and long-term monitoring. Long-term monitoring may be a significant cost element, and often exceeds the capital cost of installation over the life of the application.

Cost assessments are included in the Site Summary and Phase I Evaluations in Appendix C. An example of costs from the Hangar K site at CCAFS, Florida is shown in Table 9.2. The cost to design, install, conduct baseline characterization, and to prepare an initial construction report totals \$97,000. Note that the cost to conduct six monitoring events over a period of approximately 5 years is approximately \$144,000, greater than the initial cost to implement the remedy.

9.3 SUMMARY AND ANALYSIS OF COST DRIVERS

Cost drivers identified for the demonstration case studies include costs for operations and maintenance and costs for additional injections and for additional monitoring. More specifically, cost drivers for enhanced *in situ* bioremediation include the following (with examples):

- Cost for modifying frequent injections of soluble substrates, including more frequent injections than designed and changes to the substrate amendment (e.g., higher substrate quantities, buffering agents). Examples include the molasses applications at Hanscom AFB and Vandenberg AFB.
- Cost for additional injections of slow-release substrates, or for modification of the injection protocol. Examples include the SA-17 Site at NTC Orlando and the Kenney Avenue Plume at Elmendorf AFB.
- Cost to replenish permeable mulch biowalls with EVO (NWIRP McGregor).
- Cost associated with buffering or bioaugmentation for sites with incomplete dechlorination. Examples include the molasses applications at Hanscom AFB and Vandenberg AFB.
- Costs for biofouling control (well re-development, chemical treatments, and operations down time). An example is the Area 20 application at the Aerojet Facility.
- Cost for additional monitoring and reporting beyond the projected design.

The primary benefit of identifying these cost drivers is to limit or mitigate the potential for additional injections and monitoring during design and operations. For frequent injections of soluble substrate it should be anticipated that modifications and additional injections may be needed, and contingencies to do so built into the design.

Table 9.2
Example of Site-Specific Cost Summary, Hangar K Site, CCAFS, Florida

Cost Element	Data to be Tracked	Project Cost
System Design/ Work Plan (Total = \$11,000)	• Labor for system design and work plan • Permitting costs	• \$11,000 • \$0
Capital Construction/ System Installation (Total = \$62,000)	• Recommended installation method • Mobilization (includes travel and per diem) • Site Labor • Subcontractor - USACE CPT • Subcontractor - Surveyor • Construction material cost (well materials and injection equipment) • Substrate or amendment cost (including \$/lb and total cost)	• Direct Injection • \$2,800 • \$15,000 • \$30,000 (estimated) • \$1,500 • \$7,000 • \$5,700 (\$0.44 per pound delivered)
Baseline Characterization and Construction Completion Report (Total = \$24,000)	• Sampling labor • Reporting Labor • Sampling equipment and supplies • Laboratory analytical costs	• \$5,000 • \$11,000 • \$2,000 • \$6,000
Operating Cost	• Not Required – One time injection of neat vegetable	• \$0
Long-Term Monitoring (per event) (Total = \$144,000)	• Mobilization (includes travel and per diem) • Sampling labor • Sampling equipment and supplies • Analytical cost • Labor for project management and reporting • Number of events	• \$2,500 • \$7,500 • \$2,000 • \$6,000 • \$6,000 • Six events

It is also useful to identify the buffering capacity of the aquifer to be treated. Incorporating a buffering amendment into the design for sites with low buffering capacity is a relatively inexpensive strategy to mitigate the need for more costly and difficult to implement modifications to control pH once treatment has been initiated. As mentioned earlier, this reinforces the benefits of adequate screen for site-specific conditions and using the best available practices when designing and implementing enhance *in situ* bioremediation applications.

10. RECOMMENDATIONS FOR DESIGN OF SUBSTRATE AMENDMENTS

This section provides recommendations for design of substrate amendments based on industry practices and observations from the demonstration case studies.

10.1 SITE CHARACTERIZATION FOR DESIGN OF ENHANCED *IN SITU* BIOREMEDIATION SYSTEMS

Prior to designing an enhanced *in situ* bioremediation system, thorough site characterization and screening are required to develop a strategy to mitigate any site-specific limiting factors.

10.1.1 Site Characterization

Characterization necessary for adequate site screening should include the following:

- *Hydrogeology.* It is important to quantify the hydraulic conductivity and rate of groundwater flow, and to evaluate the degree of heterogeneity for the candidate site. Sites with relatively high or low rates of groundwater flow require special considerations, as do sites with a moderate or high degree of heterogeneity.
- *Contaminant Distribution.* The type, magnitude of concentration, and distribution of contaminants is necessary to determine an appropriate treatment configuration. Of particular importance is the presence of DNAPL.
- *Distribution of Native Electron Acceptors.* The distribution of native electron acceptors directly correlates to substrate requirements. Due to the range of sulfate concentration that may be present, sulfate often dominates the electron acceptor demand. In addition, it is difficult to predict the degree of iron and manganese reduction that may occur, and it is desirable to collect soil samples whenever possible for analysis of total and bioavailable iron and manganese. This data, along with contaminant concentrations, is useful for a first approximation of substrate requirements.
- *Microbiology.* Many sites exhibit incomplete dechlorination which may be due to a lack of, or slow growth of, *Dehalococcoides* species. Molecular screening techniques with low detection limits are readily available to screen for the presence of *Dehalococcoides* and reductase enzymes that indicate the strain is capable of complete dechlorination.
- *pH and Alkalinity.* Both groundwater pH and alkalinity should be known. For sites with pH below 6.5 or alkalinity below 300 mg/L, it is recommended that soil samples be collected for analysis of soil pH and some type of titration analysis be performed to estimate the buffering capacity of the aquifer. Alternately, groundwater geochemical data may be entered into a geochemical model (e.g., the BUCHLORAC Model) to evaluate buffering requirements.

Preliminary site screening is described in detail in further detail in Section 3 of AFCEE *et al.* (2004). The evaluation of limiting factors for the demonstration case studies re-enforces the need for adequate site characterization and to evaluate potential limiting factors.

10.1.2 Evaluation of Limiting Factors

Once site characterization data have been collected and a conceptual site model has been developed, a final site screening exercise should be conducted to evaluate the most common limiting factors for enhanced *in situ* bioremediation. This includes the following (Section 6.2):

Insufficient Substrate Distribution. The ability to effectively distribute substrate is often impacted by site-specific lithology (low or high permeability, heterogeneity) and groundwater hydraulics (low or high rates of groundwater flow). In some cases the quantity of substrate that can be injected is limited by a low aquifer buffering capacity and adverse lowering of pH. In most cases these conditions can be mitigated by modifying the injection mixture and substrate loading rate (for example more frequent and less concentrated substrate solutions, or adding a buffering amendment), or selecting an appropriate delivery technique (for example closer spaced injection points and larger injection volumes).

Adverse Geochemical Conditions. The most common geochemical condition was an adverse excursion (lowering) of pH, resulting from a combination of low buffering capacity of the aquifer and high concentrations of DOC. Control of the substrate loading rate is critical when treating aquifers with low buffering capacity. Mitigation measures include careful screening of the site to determine whether a buffering compound should be added to the injection protocol, and selecting substrate delivery techniques that provide for more uniform distribution of substrate without excessive “spikes” in DOC.

Loss of Hydraulic Conductivity or Biofouling of Injection Wells. A decrease in hydraulic conductivity (permeability) may result in bypass of contaminated groundwater around the reaction zone or uneven distribution of substrate during subsequent injections. One option to mitigate the potential for loss of hydraulic conductivity is to conservatively design the reaction zone to extend beyond the limits of contaminated groundwater to be treated. For example, a biobarrier may be installed an additional 20 to 50 feet beyond the edge of the groundwater contaminant plume to avoid potential for bypass around the ends of the reaction zone. It may also be beneficial to provide a degree of overlap (perhaps 20 to 30 percent) for injection well radius of influence to compensate for reductions in the ability to distribute substrate during subsequent injections.

Substrate Persistence and Longevity. Based on observations from the demonstration case studies, the minimum threshold concentrations of DOC or TOC range from 5 to 10 mg/L for perchlorate, to 20 to 100 mg/L for CAHs. While the threshold concentration to sustain dechlorination of CAHs is highly site specific, sustaining concentrations of DOC greater than 50 to 100 mg/L should be effective for most sites. These concentrations of DOC need to be sustained over the design life of the application for effective reductive dechlorination of CAHs. Concentrations of DOC to sustain perchlorate reduction are typically lower because sulfate reducing and methanogenic conditions are not necessary (or desirable). Buildup of biomass may sustain the reaction zone and limit the amount of rebound that may occur after the initial substrate is depleted. Rebound of concentrations in the treatment zone will depend on whether a

residual source of contaminant mass remains upgradient of the treatment zone, or with low permeability sediments within the treatment zone.

Difficult Hydrogeological Conditions. Rates of groundwater flow less than 0.1 ft/day (37 ft/yr) or greater than 2.7 ft/day (1,000 ft/yr) require special design considerations. Low rates of groundwater flow may require closer injection point spacing because distribution of soluble substrate or organic acids from slow release substrates by dispersion will be limited. High rates of groundwater flow will require more frequent and higher concentration injections. In the case of EVO products, the retention of the oil droplets is a critical parameter to sustain adequate substrate concentrations in the reaction zone. Oil retention in coarse grained sediments, combined with a high rate of groundwater flow, may not be sufficient to sustain the reaction zone without additional injections. In addition, as the degree of aquifer heterogeneity increases, so may the need for closer injection well spacing or for “targeted” injections within lower permeability sediments.

The variety of substrates and configurations that can be used for enhanced *in situ* bioremediation allows the practitioner to design around these limiting factors. Careful site screening and evaluation of each of these limiting factors will lead to higher rates of success and greater effectiveness of the remedy.

10.2 DETERMINING SUBSTRATE REQUIREMENTS

The substrate estimating tool in Appendix B is useful to screen site conditions that will impact substrate delivery and reactivity. The tool provides an estimate of **total** substrate required over the design life of the application given a user specified design factor. The tool also provides a time-weighted average concentration of substrate for the total volume of groundwater treated.

This exercise is useful to understand how the substrate will be utilized and to screen for potential adverse geochemical conditions. An example includes high manganese and iron sites where elevated concentrations of dissolved iron and manganese may require monitoring to ensure secondary water quality is not impacted downgradient of the treatment zone. pH and alkalinity are included in the substrate estimating tool to screen for sites with low buffering capacity.

The quantities and time weighted average substrate concentrations can be used for comparison to proposed or planned bioremediation applications as a check on the quantities of substrate being proposed and the performance targets for DOC. This should help to avoid application of either too little substrate or generating excessive substrate levels.

10.3 DETERMINING SUBSTRATE LOADING RATES

Substrate loading rates are defined as the volume, concentration, and frequency of injection of organic substrates for *in situ* anaerobic bioremediation. While the substrate estimating tool provides a first approximation of total substrate required, it does not provide for any guidance or indication on how the substrates should be applied. Design tools are often provided by substrate vendors, and the estimated substrate quantity should always be compared to recommendations by the provider or with case studies in the literature.

The primary objective when selecting a substrate loading rate is to achieve a uniform distribution of substrate over time and space. Design tools that assist the practitioner with the configuration (well spacing) and injection volumes are being developed and should be incorporated into the design process. Examples include the Edible Oil Substrate tool being developed under ESTCP Project ER-0626 (Borden *et al.*, 2008; available at the ESTCP on-line library at <http://docs.serdp-estcp.org/>).

For slow release substrates injected in a one-time event, a conservative design factor on the order of 3- to 7-times the estimated substrate requirement should be suitable for limiting the potential for insufficient substrate. For soluble substrates, lower design factors on the order of 2- to 3-times the estimated substrate requirement are beneficial to avoid over-stimulating the aquifer and driving pH downward. Substrate quantities can be increased if initial loading rates are insufficient to create suitable reducing conditions throughout the treatment zone. The delivery methods for soluble substrates should target uniform substrate concentrations without excessive “spikes” in concentrations of DOC.

The use of very high substrate concentrations to enhanced dissolution of DNAPL into the aqueous phase is an exception to typical substrate loading rates. Solutions with concentrations of lactate as high as 6 percent by weight, whey as high as 10 percent by weight, and molasses as high as 1 to 2 percent by weight have been used for this purpose. These applications require special consideration of the buffering capacity of the aquifer and the system configuration. For example, it may be acceptable to induce adverse geochemical conditions in the source zone to mobilize CAH mass, if a suitable downgradient reaction zone for biodegradation and geochemical recovery is established. In most all cases, these types of injections are performed in pulses every 4 to 12 weeks to allow the aquifer geochemistry to stabilize between injections.

10.4 ENHANCED BIOREMEDIATION AMENDMENTS

Six of the fifteen case study sites exhibited issues with pH excursion (Section 8.6). For all these sites, initial background pH values were below 6.5 and alkalinity was below 150 mg/L. For screening purposes, a combination of pH below 6.0 to 6.5 and alkalinity below 300 mg/L should indicate that modifications to buffer and control pH excursion will be necessary.

Sodium bicarbonate was the most common buffering compound used, typically at concentrations in excess of 10,000 mg/L. Sodium bicarbonate is a relative weak buffering compound and may be most suitable for applications using frequent injections of soluble substrates. The use of stronger and more persistent buffering compounds (e.g., magnesium hydroxide or sodium phosphates) may be necessary for applications using slow release substrates, and further research and product development will be beneficial for sites with low buffering capacity.

10.5 DESIGNING FOR UNCERTAINTY

In practice, the amount of site characterization data that is available or that can be economically obtained is always limited to some extent. It is not unusual to design an enhanced *in situ* bioremediation application at a “well characterized” site, only to encounter difficult hydrogeological conditions such as low permeability sediments or heterogeneity that limits effective substrate distribution. Therefore, it is useful to consider practices that mitigate the

uncertainty associated with subsurface environments. Examples of system modifications are listed in Table 10.1.

Table 10.1 Example Enhanced Bioremediation System Modifications

Potential Condition	Modification
Low pH or low buffering capacity	• Addition of a buffering compound • Use of water push for soluble substrates • Use of slower-release substrates
Low permeability/groundwater velocity	• Closely spaced injection points • Targeted injections into low permeability horizons
High permeability/groundwater velocity	• Higher substrate loading rates • More frequent injections • Multiple rows of injection wells or biowalls • High retention (coarse droplet) EVO products
Incomplete dechlorination	• Microbial characterization • Allow for longer lag times • Lower the redox environment • Bioaugmentation

Modified from AFCEE *et al.*, 2004 and Suthersan *et al.*, 2002.

Soluble substrate systems that use frequent injections have the most flexibility in modifying injection scenarios. When using infrequent applications of slow-release substrates, potential problems such as the need to add a buffering agent should be evaluated prior to substrate addition, and buffer should be added during substrate injection as a precautionary measure when in doubt.

Inadequate or excessive distribution of substrate due to aquifer permeability and/or groundwater flow rates can be adjusted by increasing or decreasing the substrate loading rate, and/or by modifying injection frequency or well spacing. Substrate loading rates may be increased in the event of inhibitory electron acceptor demand (e.g., sulfate over 50 to 100 mg/L).

Finally, incomplete or delayed dechlorination is a common limitation resulting in accumulation of intermediate dechlorination products. Prior to considering bioaugmentation, the system should be evaluated to ensure that the proper geochemical conditions have been achieved and that a sufficient acclimation period has been allowed for ecological succession and development of appropriate microbial consortia. Bioaugmentation with commercially available cultures can be implemented if it has been determined that indigenous *Dehalococcoides* species are lacking, or do not exhibit the reductase enzymes for complete dechlorination of VC to ethene.

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APPENDIX A
PROJECT TEAM

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PROJECT TEAM

The project points of contact are listed in Table A.1. The ESTCP program is managed by Dr. Andrea Leeson in the Arlington, Virginia ESTCP Program Office. Ms Erica Becvar of AFCEE is the Contracting Officer's Representative assigned by ESTCP, and is located at AFCEE Headquarters at Brooks City-Base, Texas.

Table A.1
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APPENDIX B
SUBSTRATE ESTIMATING TOOL

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DETERMINING SUBSTRATE REQUIREMENTS

(Version 1.1 – February 2010)

B.1 Substrate Requirements for Enhanced *In Situ* Bioremediation

To stimulate *in situ* anaerobic reductive dechlorination of chlorinated solvents in groundwater, a sufficient mass of organic substrate (electron donor) is required to satisfy both native (inorganic) and chlorinated solvent (organic) electron acceptor demand in the reactive treatment zone. An inadequate substrate loading rate may result in reducing conditions that are insufficient to support complete anaerobic dechlorination of chlorinated solvents, thereby increasing the potential for accumulation of regulated intermediate dechlorination products. Conversely, excessive levels of organic substrate may lead to adverse geochemical conditions (e.g., low pH), excessive methanogenesis and inefficient utilization of substrate for anaerobic dechlorination, production of regulated fermentation products (e.g., acetone and methyl ethyl ketone), and an increased potential for long-term adverse impacts to secondary groundwater quality. Therefore, determining an appropriate substrate loading rate is a critical design and operational objective to successful implementation of enhanced *in situ* bioremediation.

To evaluate substrate requirements, a spreadsheet tool has been developed to assist the practitioner in determining site-specific electron acceptor demand and to estimate the substrate required to meet that demand over the design life of the application. ***This tool to evaluate substrate requirements is not intended to be used as a design tool, rather it is intended only for the purpose of site screening and to evaluate the scientific basis of determining electron acceptor demand and substrate requirements.***

Several providers of organic substrates for enhanced *in situ* bioremediation provide design tools using similar calculations as the substrate requirements tool. The calculations and assumptions used are not always readily apparent in these design tools. This substrate requirements tool provides information on the reactions, calculations, and assumptions employed in an effort to educate the user on how an estimate of the substrate requirement is determined for a specific site. It is not intended to replace or be used *in lieu* of a vendors proprietary design tool.

B.2 Methods Used to Determine Substrate Requirements

Two general approaches have been used to estimate substrate requirements and to derive a substrate loading rate. One approach is to target an empirical concentration of substrate in the reaction zone that is based upon previous experience and experimentation at sites with similar hydrogeology, geochemistry, and contaminant distribution. The other approach is to calculate a substrate (electron donor) requirement based on estimates of native and chlorinated aliphatic hydrocarbon (CAHs, commonly referred to as chlorinated solvents) electron acceptor mass. The most appropriate approach to designing an enhanced *in situ* bioremediation application is to calculate the electron acceptor demand and the corresponding substrate requirement, and then check or revise the calculation based on experience gained from past applications.

B.2.1 Calculating Substrate Requirements

Spreadsheets to estimate substrate requirements have been developed by several vendors of bioremediation products to estimate the quantity (mass or volume) of product that should be applied. These spreadsheets are typically used for slow release substrates that are applied infrequently, often in a single event. These design tools are specific to the vendors product, and

it is advisable to consult with the vendor to verify that the calculations are appropriate based on their experience with the product.

Controlling and maintaining a “target” substrate concentration over time for slow-release substrates is dependent on the physical and chemical characteristics of the substrate. Slow-release substrates are designed to release a soluble organic carbon component continuously over a long period of time. Experience has shown that slow-release substrate systems can be effective in maintaining appropriate geochemical conditions for anaerobic dechlorination to occur over periods of months to several years following a single injection or emplacement.

B.2.2 Empirical Methods for Determining Substrate Requirements

The exact electron acceptor demand that exists in a natural subsurface system is often difficult to determine. When considering the theoretical basis for substrate requirements, many practitioners base determination of substrate loading rate on achieving an empirical concentration of substrate in groundwater throughout the treatment zone based on experience. This may be a more common method than stoichiometric calculations due to the uncertainty involved in the calculations. In practice, both methods may be compared to each other to increase the confidence in selecting a substrate loading rate.

Analytical data for total organic carbon (TOC, unfiltered samples) or dissolved organic carbon (DOC, filtered samples) from injection and monitoring wells is commonly used to measure the effective dilution and mixing of substrate with groundwater and the effective radius of influence of the reaction zone. For example, Suthersan *et al.* (2002) suggest that loading rates for soluble substrates of between 0.001 and 0.01 pounds of organic carbon per gallon of groundwater flux per day are sufficient to create and maintain a reducing reactive zone. This equates to a TOC concentration of approximately 15 to 150 milligrams per liter (mg/L). Suthersan *et al.* (2002) further suggest that the loading rate also should be sufficient to maintain between 50 and 100 times as much TOC in the reactive zone as there is CAH in the target area (i.e., 50 to 100 mg/L of TOC for every 1 mg/L of CAH).

Soluble organic substrates are transported, diluted, and degraded rapidly in groundwater, resulting in a TOC concentration gradient between the point of injection and the downgradient treatment zone. To account for these effects, higher concentrations of TOC are required at the point of injection to maintain sufficient TOC concentrations throughout the designated treatment zone. Therefore, the objective with soluble substrate systems employing direct injection or recirculation is to maintain an effective range of substrate concentration throughout the treatment zone, rather than targeting a singular concentration. Variations in the volume, strength, and/or frequency of substrate addition are used to achieve a particular target minimum concentration in the aquifer after mixing and dilution.

Table B.1 lists some common substrates and the range of substrate concentrations targeted in historical enhanced bioremediation applications. The substrate strength (concentration), volume, and injection frequency may vary widely, even for a single substrate type. The values in Table B.1 can be used as a check on concentrations produced by the substrate requirement tool described below. Note that the concentrations in Table B.1 do not account for applications in dense non-aqueous phase (DNAPL) source areas where very high concentrations of substrate (>10,000 mg/L) are often applied in an attempt to enhance dissolution of DNAPL.

Table B.1 Typical Substrate Loading Rates and Injection Frequencies of Common Organic Substrates (modified from AFCEE *et al.*, 2004)

Substrate		Injected Form and Concentration	Targeted Concentration in the Treatment Zone	Typical Injection Frequency
Soluble Substrates	Sodium Lactate, Lactic Acid	Diluted to 3 to 60 percent by weight	50 to 300 mg/L	Continuous to Monthly
	Butyrate	Diluted to 3 to 60 percent by weight	50 to 300 mg/L	Continuous to Monthly
	Methanol	Diluted to 3 to 60 percent by weight	50 to 300 mg/L	Continuous to Weekly
	Ethanol	Diluted to 3 to 60 percent by weight	50 to 300 mg/L	Continuous to Weekly
	Molasses	Diluted to 1 to 10 percent by weight	50 to 500 mg/L	Daily to Quarterly
	High Fructose Corn Syrup	Diluted to 1 to 10 percent by weight	50 to 500 mg/L	Daily to Quarterly
Slow-Release Substrates	Whey (fresh/powdered)	Powdered form can be dissolved, fresh form can be injected as a slurry.	50 to 500 mg/L	Monthly to Annually
	Hydrogen Release Compound (HRC®)	Pure product injected at 4 to 12 pounds per vertical foot of injection.	100 to 500 mg/L	Every 18 to 24 months, less frequently with HRC-X™ or 3DMe™ products. One-time injection may suffice in some cases.
	Vegetable Oil (e.g., food-grade soybean oil)	Oil-in-water emulsions with 2 to 10 percent oil by volume	100 to 500 mg/L	Every 2 to 3 years. May require a second injection for dilute emulsions. One-time injection may suffice in some cases.
	Mulch and Compost (cellulose)	Mixed with sand at 20 to 60 percent mulch or compost by volume	50 to 100 mg/L TOC within biowall reaction zone	One-time emplacement

Prior to utilizing either of these approaches, the practitioner should understand the theoretical basis for estimating electron acceptor demand and substrate (electron donor) requirements, and the factors of uncertainty inherent in these methods. ***Caution is urged with any approach to estimating substrate requirements. Given the current state of knowledge, field testing and experimentation may be the only way to optimize substrate loading rates for anaerobic dechlorination of chlorinated solvents.***

The following section describes the theoretical basis used for determining substrate requirements in the substrate requirement tool. An example of using the tool is included in Section B.6.

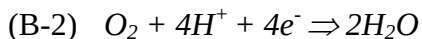
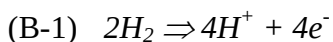
B.3 Theoretical Basis for Determining Substrate Requirements

In order to determine site-specific substrate requirements, the total amount of electron acceptor demand exerted by both native (inorganic) and anthropogenic (i.e., chlorinated solvents) electron acceptor mass within and entering the treatment zone over the life-cycle of the application must be estimated. Note that the rate at which the substrate is applied (volume, concentration, and frequency) is equally as important as determining the total substrate requirement for the life-cycle of the application. But a first step is to estimate and evaluate the total or average substrate requirement over the design life of a proposed application.

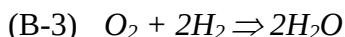
B.3.1 Electron and Hydrogen Equivalents

Because anaerobic reductive dechlorination is based on coupled oxidation-reduction (redox) and fermentation reactions, substrate (electron donor) requirements can theoretically be estimated by determining the amount of **electron equivalents** consumed by electron accepting processes utilizing both native and CAH electron acceptors, and the amount of electron equivalents generated by biodegradation of the substrate (electron donor).

For example, consider the following half reactions for reduction of oxygen (O_2) as an electron acceptor:

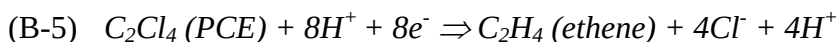
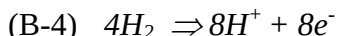


The reduction of oxygen by these reactions requires the transfer of 4 electrons; provided by molecular hydrogen (H_2) as the electron donor. The net balanced reaction for reduction of oxygen can then be written:

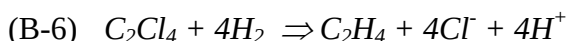


where it takes 2 molecules of molecular hydrogen to reduce 1 molecule of molecular oxygen.

Because molecular hydrogen is the primary electron donor in reductive dechlorination of chlorinated solvents, it is convenient to calculate a substrate requirement based on **hydrogen equivalents** (i.e., mass of molecular hydrogen). For example, consider the following half reactions for reduction of tetrachloroethene (PCE) as an electron acceptor:



The net balanced reaction for reduction of PCE to ethene using hydrogen as the electron donor can then be written:



where on a mass basis it takes 4 moles of molecular hydrogen (weight of molecular hydrogen = 4 moles $\times$ 2.016 grams per mole [gm/mole] = 8.064 grams) for every mole of PCE (weight of PCE = 1 mole $\times$ 165.8 gm/mole = 165.8 grams). More simply stated, theory predicts that it takes 1.0 gram of molecular hydrogen to degrade 20.6 grams of PCE to ethene based on the molecular weights of the reactants in equation B-6.

Although reduction of PCE to ethene typically occurs sequentially from PCE to trichloroethene (TCE) to dichloroethene (DCE) to vinyl chloride (VC) to ethene, the overall electron and hydrogen equivalents required for complete dechlorination of PCE to ethene remains the same.

B.3.2 Electron Acceptor Demand

The amount of hydrogen required (stoichiometric requirement) to reduce chlorinated solvents and native electron acceptors can similarly be calculated given that the reaction sequences are known. Table B.2 lists examples of some common reactions that utilize hydrogen as an electron donor for reduction of native electron acceptors and chlorinated compounds.

Table B.2 Examples of Net Balanced Reactions Using Hydrogen as the Electron Donor

Electron Acceptor	Electron-Acceptor (Reduction) Reaction	Electron Equivalents per Mole of Electron Acceptor	Moles of H ₂ consumed per mole of Electron Acceptor	Stoichiometric Requirement (wt/wt H ₂)
Oxygen	$2H_2 + O_2 \Rightarrow 2H_2O$ <i>aerobic respiration</i>	4	2	7.94
Nitrate (1)	$2H^+ + 5H_2 + 2NO_3^- \Rightarrow N_2 + 6H_2O$ <i>denitrification</i>	5	2.5	12.30
Nitrate (2)	$2H^+ + 4H_2 + NO_3^- \Rightarrow NH_4^+ + 3H_2O$ <i>nitrate reduction to ammonia</i>	8	4	7.69
Manganese	$2H^+ + H_2 + MnO_2 \Rightarrow Mn^{2+} + 2H_2O$ <i>"pyrolusite" dissolution/reduction</i>	2	1	27.25 (per mole Mn ²⁺ produced)
Ferric Iron	$4H^+ + H_2 + 2FeOOH \Rightarrow 2Fe^{2+} + 4H_2O$ <i>"ferric oxyhydroxide" dissolution/reduction</i>	1	0.5	55.41 (per mole Fe ²⁺ produced)
Sulfate	$4H_2 + H^+ + SO_4^{2-} \Rightarrow HS^- + 4H_2O$ <i>sulfate reduction</i>	8	4	11.91
Carbon Dioxide	$4H_2 + CO_{2,g} \Rightarrow CH_{4,g} + 2H_2O$ <i>Methanogenesis</i>	8	4	1.99 (per mole CH ₄ produced)
Perchlorate	$4H_2 + ClO_4^- \Rightarrow Cl^- + 4H_2O$ <i>perchlorate reduction</i>	8	4	12.33
PCE	$4H_2 + C_2Cl_4 \Rightarrow C_2H_4 + 4HCl$ <i>PCE reductive dechlorination to ethene</i>	8	4	20.57
TCE	$3H_2 + C_2HCl_3 \Rightarrow C_2H_4 + 3HCl$ <i>TCE reductive dechlorination to ethene</i>	6	3	21.73
DCE	$2H_2 + C_2H_2Cl_2 \Rightarrow C_2H_4 + 2HCl$ <i>cis-1,2-DCE reductive dechlorination to ethene</i>	4	2	24.05
VC	$H_2 + C_2H_3Cl \Rightarrow C_2H_4 + HCl$ <i>VC reductive dechlorination</i>	2	1	31.00

Table B.2 Examples of Net Balanced Reactions Using Hydrogen as the Electron Donor (continued)

Electron Acceptor	Electron-Acceptor (Reduction) Reaction	Electron Equivalents per Mole of Electron Acceptor	Moles of H ₂ consumed per mole of Electron Acceptor	Stoichiometric Requirement (wt/wt H ₂)
Carbon Tetrachloride (CT)	$4H_2 + CCl_4 \Rightarrow CH_4 + 4HCl$ <i>CT reductive dechlorination to methane</i>	8	4	19.08
Chloroform (CF)	$3H_2 + CHCl_3 \Rightarrow CH_4 + 3HCl$ <i>CF reductive dechlorination to methane</i>	6	3	19.74
Methylene Chloride (MC)	$2H_2 + CH_2Cl_2 \Rightarrow CH_4 + 2HCl$ <i>MC reductive dechlorination to methane</i>	4	2	21.06
Chloromethane	$H_2 + CH_3Cl \Rightarrow CH_4 + HCl$ <i>Chloromethane reductive dechlorination</i>	2	1	25.04
Tetrachloroethane (PCA)	$4H_2 + C_2H_2Cl_4 \Rightarrow C_2H_6 + 4HCl$ <i>1,1,1,2-PCA reductive dechlorination to ethane</i>	8	4	20.82
Trichloroethane (TCA)	$3H_2 + C_2H_3Cl_3 \Rightarrow C_2H_6 + 3HCl$ <i>1,1,1-TCA reductive dechlorination to ethane</i>	6	3	22.06
Dichloroethane (DCA)	$2H_2 + C_2H_4Cl_2 \Rightarrow C_2H_6 + 2HCl$ <i>1,2-DCA reductive dechlorination to ethane</i>	4	2	24.55
Chloroethane (CA)	$H_2 + C_2H_5Cl \Rightarrow C_2H_6 + HCl$ <i>CA reductive dechlorination to ethane</i>	2	1	32.00

These reactions may be used to determine the mass of molecular hydrogen required to reduce a given mass of electron acceptor. Molecular formulas and weights for common compounds involved in anaerobic dechlorination reactions are listed on Table B.3.

Table B.3 Molecular Weights for Various Compounds Associated with Anaerobic Dechlorination of Chlorinated Solvents

Compound	Formula	Molecular Weight (grams/mole)
Tetrachloroethene (PCE)	C ₂ Cl ₄	165.8
Trichloroethene (TCE)	C ₂ HCl ₃	131.4
Dichloroethene (DCE)	C ₂ H ₂ Cl ₂	96.95
Vinyl Chloride (VC)	C ₂ H ₃ Cl	62.51
Ethene	C ₂ H ₄	28.05
Tetrachloroethane (PCA)	C ₂ H ₂ Cl ₄	167.85
Trichloroethane (TCA)	C ₂ H ₃ Cl ₃	133.4
Dichloroethane (DCA)	C ₂ H ₄ Cl ₂	98.96
Chloroethane (CA)	C ₂ H ₅ Cl	64.51
Ethane	C ₂ H ₆	30.07
Tetrachloromethane/Carbon Tetrachloride (CT)	CCl ₄	153.8
Trichloromethane/Chloroform (CF)	CHCl ₃	119.4
Dichloromethane (DCM)/ Methylene Chloride (MC)	CH ₂ Cl ₂	84.93
Chloromethane (CM)	CH ₃ Cl ₁	50.49
Methane	CH ₄	16.04
Oxygen	O ₂	31.98
Nitrate	NO ₃ ⁻	61.99
Manganese (oxide)	MnO ₂	86.93
Ferric Iron (oxy-hydroxide)	FeOOH	88.86
Sulfate	SO ₄ ²⁻	96.04
Carbon Dioxide	CO ₂	44.01
Hydrogen	H ₂	2.016
Perchlorate	ClO ₄ ⁻	99.45

As hydrogen is produced by fermentative organisms, it is rapidly consumed by other bacteria, including denitrifiers, manganese-reducers, iron-reducers, sulfate-reducers, methanogens, and dechlorinating microorganisms. The production of hydrogen through fermentation does not, by itself, guarantee that hydrogen will be available for anaerobic reductive dechlorination of chlorinated solvents. For anaerobic dechlorination to occur, dechlorinators must successfully compete against the other microorganisms that also utilize hydrogen. Thus, a direct stoichiometric relationship does not exist between hydrogen and dechlorination of chlorinated solvents in the subsurface or laboratory environment. However, even though the efficiency of utilization of hydrogen for anaerobic dechlorination is often estimated to be relatively low, the stoichiometric relationships for the direct anaerobic dechlorination of chlorinated solvents are relatively favorable.

Based on the reactions in Table B.2, the number of electron equivalents or moles of molecular hydrogen used to reduce one mole of the electron acceptor can be calculated. This allows the calculation of a stoichiometric hydrogen requirement of hydrogen per unit weight of electron acceptor. For example, it would take 1.0 grams of molecular hydrogen to reduce 7.94 grams of molecular oxygen.

The substrate requirement tool calculates the mass of each individual electron acceptor, then divides that value by the stoichiometric requirement in weight of electron acceptor per weight of molecular hydrogen (wt/wt H₂) listed in Table B.2 to yield the hydrogen requirement for each individual electron acceptor.

B.3.3 Electron Donor or Hydrogen Production Potential

For anaerobic reductive dechlorination be effective, sufficient electron equivalents must be provided by electron donors to satisfy both native and contaminant electron acceptor demand. Organic substrates may serve as an electron donors to provide the necessary electron equivalents. Hydrogen is thought to be the primary electron donor used in dechlorination reactions, although other electron donors such as acetate and formate may be utilized.

Hydrogen is generated by fermentation of non-chlorinated organic substrates, including naturally occurring organic carbon, accidental releases of anthropogenic carbon (fuel hydrocarbons), or introduced substrates such as alcohols, low-molecular-weight fatty acids, carbohydrates (sugars), and vegetable oils. In the natural environment, the electron equivalents available to satisfy the electron transfer requirements of coupled reduction reactions is produced by fermentation or other oxidation reactions.

Each organic substrate is capable of producing a particular mass of hydrogen per unit mass of substrate. This **hydrogen production potential** is directly related to the molecular structure of the organic substrate. The hydrogen production potential can be estimated in one of three ways:

- 1) **Hydrogen potential as the product of fermentation reactions.** For example, the fermentation of ethanol illustrated in Table B.4 yields 2 moles of hydrogen for each mole of ethanol. Based on molecular weights of the reactants, the amount of molecular hydrogen produced by weight is 0.0875 grams of hydrogen per gram of ethanol. The hydrogen potential for several common substrates using this method are presented in Table B.4.
- 2) **Hydrogen potential from complete oxidation.** The hydrogen production potential (in terms of molecular weight of the substrate that is hydrogen) for several common organic substrates using this method are also presented in Table B.4. Based on a comparison to fermentation reactions, it could be assumed that approximately one-third of the hydrogen potential from complete oxidation (mineralization) will be available as molecular hydrogen. Using this method may be oversimplified, but it is used for estimation purposes in light of the uncertainty regarding fermentation pathways of complex substrates.

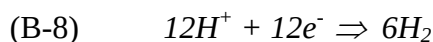
Table B.4 Examples of Reactions Using Organic Substrates as an Electron Donor to Yield Hydrogen

Substrate (Electron Donor)	Electron-Donor (Oxidation) Reaction	Molecular Weight (gm/mole)	Moles of H ₂ produced per Mole Substrate	Ratio of H ₂ produced to Substrate (gm/gm)
Ethanol	$C_2H_6O + H_2O \Rightarrow C_2H_3O_2^- + H^+ + 2H_2$ <i>ethanol fermentation to acetate</i>	46.11	2	0.0875
Ethanol	$3H_2O + C_2H_6O \Rightarrow 2CO_2 + 6H_2$ <i>ethanol oxidation</i>	46.11	6	0.263
Methanol	$CH_4O + 2H_2O \Rightarrow CO_2^- + H_2O + 3H_2$ <i>methanol fermentation</i>	32.04	3	0.189
Acetate	$C_2H_3O_2^- + 4H_2O \Rightarrow 2CO_2^- + 2H_2O + 4H_2$ <i>acetate fermentation</i>	59.04	4	0.137
Butyrate	$C_4H_7O_2^- + 2H_2O \Rightarrow 2C_2H_3O_2^- + H^+ + 2H_2$ <i>butyrate fermentation to acetate</i>	87.10	2	0.0463
Propionate	$C_3H_5O_2^- + 3H_2O \Rightarrow C_2H_3O_2^- + CO_2^- + H_2O + 3H_2$ <i>propionate fermentation to acetate</i>	73.07	3	0.0828
Lactate	$C_3H_5O_3^- + 2H_2O + \Rightarrow C_2H_3O_2^- + CO_2^- + H_2O + 2H_2$ <i>lactate fermentation to acetate</i>	89.07	2	0.0453
Fructose/Glucose	$C_6H_{12}O_6 + 6H_2O \Rightarrow 6CO_2^- + 12H_2$ <i>fructose/glucose oxidation</i>	180.2	12	0.134
Sucrose/Lactose	$C_{12}H_{22}O_{11} + 13H_2O \Rightarrow 12CO_2^- + 24H_2$ <i>Sucrose/lactose oxidation</i>	342.3	24	0.141
Linoleic Acid (soybean oil)	$C_{18}H_{32}O_2 + 34H_2O \Rightarrow 18CO_2^- + 50H_2$ <i>lineoleic oxidation</i>	280.5	50	0.359
Glycerol	$C_3H_5(OH)_3 + 3H_2O \Rightarrow 3CO_2^- + 7H_2$ <i>glycerol oxidation</i>	92.09	7	0.153
HRC [®]	$C_{39}H_{56}O_{39} + 39H_2O \Rightarrow 39CO_2^- + 67H_2$ <i>lineoleic oxidation</i>	956	67	0.141

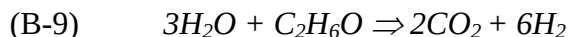
Note: Fermentation reactions from Fennel and Gossett (1998) and He *et al.* (2002).

- 3) **Hydrogen potential as the ratio (i.e., percent) of the mass of hydrogen to the sum of the molecular mass of the substrate compound.** A third approach is to estimate the hydrogen potential from the percent of the mass of hydrogen to the sum of the molecular mass of the substrate compound. For example, the hydrogen production potential of the oxidation of sucrose ($C_{12}H_{22}O_{11}$) would be equal to the molecular weight of hydrogen ($22 \times 1.008 = 22.176$ gm/mole) in sucrose divided by the molecular weight of sucrose (342.3 gm/mole). For sucrose, the ratio of molecular weight that is hydrogen is 6.48 percent, or 0.0648 grams of hydrogen per gram of sucrose. This method for calculating the hydrogen production potential of an organic substrate may also be oversimplified, and usually provides a hydrogen potential approximate to, or greater than, a one-third estimation from complete oxidation (e.g., compare to 0.0471 gm/mole for sucrose in Table B.4). The method is sometimes used by vendors of complex substrates for estimation purposes.

Consider ethanol as a substrate to compare these three methods. Theoretically, oxidation of a substrate can produce hydrogen. For example, consider the following half reactions for the oxidation of ethanol:

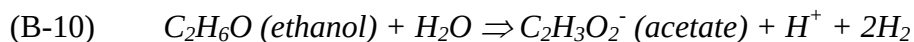


The net balanced reaction for oxidation of ethanol can then be written:



where the **oxidation of 1 molecule of ethanol produces 6 molecules of molecular hydrogen**. Theoretically, this is the **maximum amount** of hydrogen that can be produced from ethanol.

However, ethanol is , more commonly fermented to acetate. Fermentation of a molecule of ethanol to acetate is shown in the following balanced fermentation reaction:



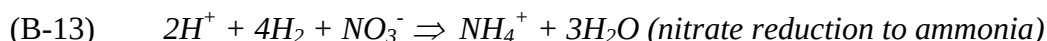
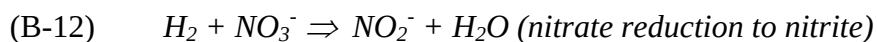
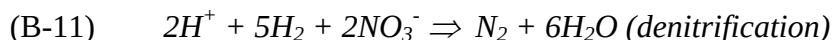
In this reaction, the **fermentation of 1 molecule of ethanol to acetate produces 2 molecules of molecular hydrogen**. This may be a more reasonable expectation of hydrogen potential than the coupled oxidation-reduction reactions above. The acetate produced in this reaction may be used directly as a direct electron donor for reduction reactions or may be further fermented to produce hydrogen. Without consideration of the role of acetate produced, then this is a **conservative reaction** for determining an appropriate amount of substrate required to provide a given amount of molecular hydrogen. In this case, the estimate of hydrogen produced from the fermentation reaction is one-third of the theoretical maximum amount from coupled oxidation reactions.

The third approach is to estimate the hydrogen potential from the percent of the mass of hydrogen to the sum of the molecular mass of the substrate compound. The hydrogen production potential of ethanol (C_2H_6O) would be equal to the atomic weight of hydrogen ($6 \times 1.008 = 6.048$ gm/mole) in ethanol divided by the molecular weight of ethanol (46.11 gm/mole). For ethanol, the ratio of molecular weight that is hydrogen is 13.1 percent, or 0.131 grams of hydrogen per gram of ethanol. This value is between the maximum ratio of hydrogen produced by coupled oxidation reactions (0.2625 gm/gm) and the ratio produced by a fermentation reaction (0.0875 gm/gm).

Given the reactions by which native and CAH electron acceptors are reduced and organic substrates are fermented or otherwise oxidized, the theoretical quantity of organic substrate that is required to provide sufficient electron or hydrogen equivalents for complete electron acceptor consumption can be calculated. Therefore, substrate loading rates may be estimated, in terms of these equivalents, based on known stoichiometric reactions for both the electron acceptor mass present in the treatment zone and the electron donor reactions associated with the substrate(s) applied.

These computations require that the substrate composition and the exact stoichiometry of each anticipated degradation reaction be known. ***However, the assumptions used to calculate the substrate requirement for a given substrate may result in a moderate degree of uncertainty in the calculation.*** In practice, these calculations only serve as a theoretical guidelines for the required substrate loading because of the potential for multiple degradation pathways for some reactants, for variation in natural or chlorinated solvent electron acceptor loading into the treatment zone, and for electron equivalents that may be used for other processes.

As another example, nitrate reduction may occur by several processes, including the following:



where 5 molecules of molecular hydrogen are required to degrade 2 molecules of nitrate (NO_3^-) to nitrogen (N_2) by denitrification; 1 molecule of molecular hydrogen is required to degrade 1 molecule of nitrate by nitrate reduction to nitrite (NO_2^-); and 4 molecules of molecular hydrogen are required to degrade 1 molecule of nitrate by nitrate reduction to ammonia (NH_4^+). Therefore, the required number of electron or hydrogen equivalents varies significantly between these three reactions.

As mentioned previously, for oxidation reactions of complex substrates such as sucrose ($C_{12}H_{22}O_{11}$), the biodegradation or intermediate reaction sequences that may occur in nature to produce a given quantity of electron equivalents are difficult to predict. Furthermore, these reactions assume that no substrate is converted to biomass by microbial growth (i.e., zero yield). Therefore, the yield of electron equivalents from biodegradation of organic substrates will be less than theoretically possible, and the amount of electron equivalents produced is subject to a moderate degree of uncertainty.

B.3.4 Distribution and Loading of Native and Contaminant Electron Acceptor Mass

The substrate calculations described above require that the distribution and mass loading of native electron acceptors be known, including dissolved and solid-phase (e.g., bioavailable iron) electron acceptors. The most abundant dissolved native electron acceptors are dissolved oxygen (DO), nitrate, sulfate, and carbon dioxide (methanogenesis). The most abundant solid-phase native electron acceptors include ferric iron and manganese in the form of hydroxides or oxyhydroxides (see Table B.2 for an example). Similarly, chlorinated solvent electron acceptor mass may be present in the aqueous phase, sorbed to the aquifer matrix, or present as DNAPL. Assuming knowledge of the electron accepting reactions that will occur, estimating total substrate requirements in terms of hydrogen equivalents involves summing the potential hydrogen requirement exerted by each

individual electron acceptor, and then determining the amount of substrate theoretically required to generate that mass of hydrogen.

The total native electron acceptor mass is typically calculated in the following three components:

1. The amount of dissolved native electron acceptor mass in the treatment zone (one pore volume);
2. The mass loading of dissolved native electron acceptor mass into the treatment zone over time; and
3. Solid-phase electron acceptor mass within the aquifer matrix of the treatment zone (assumed to be immobile).

Dissolved native electron acceptor mass within the treatment zone is simply the concentration of the dissolved electron acceptor multiplied by the pore volume of the treatment zone (total volume multiplied by total porosity).

The average linear groundwater velocity can be estimated by multiplying a measured or estimated horizontal hydraulic gradient (e.g., foot per foot) times the treatment zone average hydraulic conductivity (e.g., feet per day). Multiplying the average groundwater linear velocity by the area of the treatment zone cross-section through which groundwater will flow (horizontal length x vertical thickness x effective porosity) perpendicular to the direction of groundwater flow yields a groundwater flow rate in terms of volume per unit time (e.g., gallons or liters per day).

Multiplying the volumetric flow rate by the average upgradient concentration of each dissolved electron acceptor yields an estimated mass loading of dissolved electron acceptor over time. Concentrations of dissolved native electron acceptors are readily measured by conventional groundwater sampling and analysis techniques.

Calculating native bioavailable solid-phase electron acceptor mass is more difficult. Soil analytical results for iron and manganese mineral concentration and type are typically not available, and are costly to collect due to the need for additional drilling to collect soil samples and specialized procedures for laboratory analysis. Furthermore, it is difficult to determine how much of the iron or manganese minerals are readily available for biological processes. There are also other solid-phase electron acceptors (e.g., arsenic) that may be significant in particular lithologies. Given the current state of practice, a moderate level of uncertainty is associated with estimating solid-phase electron acceptor mass. This uncertainty can be reduced by estimating the amount of iron and manganese reduced based on the concentrations of the soluble reduced forms of iron (Fe^{+2}) and manganese (Mn^{+2}) that may be produced, and multiplying this times the volume of groundwater treated over the design life.

The distribution of chlorinated solvent acceptor mass is similar to that of native electron acceptors, except that the distribution is likely not as uniform due to the nature of the release, and also includes the presence of sorbed mass and in some cases DNAPL. The average residence time of dissolved contaminant mass in the treatment zone (not accounting for sorption/desorption) can be calculated by dividing the effective treatment zone pore volume (treatment zone volume multiplied by effective porosity) by the groundwater volumetric flow rate. For recirculation systems, the pumping rate and residence time for contaminated groundwater within the system should be assessed; although this is most readily accomplished using numerical flow models.

B.5 Designing for Uncertainty in Substrate Loading Estimates

Once the distribution and amount of electron acceptor mass is estimated, the total hydrogen requirement exerted by electron accepting processes is estimated by summing the electron or hydrogen equivalents required to reduce each electron acceptor species.

The amount of substrate required is then estimated based on the potential electron equivalents or hydrogen mass that is generated by biodegradation of the substrate. In theory, this could be done by balancing half reactions of electron acceptor and electron donor processes. In practice, the potential amount of electron equivalents or hydrogen mass produced from a given mass of substrate are estimated.

There is a great deal of uncertainty involved in these estimates. The primary factors for uncertainty in substrate requirements calculations include (but may not be limited to) the following:

- 1) **Microbial Efficiency.** The stoichiometric reactions described in this section represent only a subset of the possible reactions that may occur in the coupled oxidation-reduction and fermentation reactions that results from the addition of an organic substrate to a natural aquifer. Therefore, there is a moderate degree of uncertainty in estimating the electron or hydrogen equivalents that will be produced per unit mass of substrate, and in how those equivalents will be utilized in native and CAH electron accepting processes. Furthermore, substantial amounts of the substrate may be converted to biomass (and not hydrogen) during microbial growth. Therefore, there is an inherent hydrogen production inefficiency that is not accounted for in the theoretical amount of substrate required to completely degrade the estimated native and CAH electron acceptor mass.
- 2) **Estimate of Native Electron Acceptor Demand and the Degree of Methanogenesis.** There is a moderate level of uncertainty in determining the amount of native electron acceptors that are present in the aquifer system. Solid-phase electron acceptors (e.g., bioavailable iron and manganese) are difficult and/or expensive to determine, and many other inorganic species may also exert an electron acceptor demand. Aquifer heterogeneity and seasonal fluctuations in groundwater recharge may further complicate estimates of native electron acceptor demand.

It is also difficult to determine the amount of substrate that will be utilized for methanogenesis. Biodegradation reactions create large amounts of carbon dioxide, the electron acceptor used in methanogenic reactions. While the supply of carbon dioxide as an electron acceptor is relatively inexhaustible, methanogenesis will be limited until more favorable electron acceptors are depleted. After conditions conducive to methanogenesis are induced, it is difficult to estimate how much substrate will be utilized for methanogenesis relative to anaerobic dechlorination of CAH mass. The electron acceptor demand associated with methanogenesis is typically estimated through observations from applications at similar sites.

- 3) **Estimate of CAH Electron Acceptor Demand.** There is also uncertainty in the amount of CAH mass present in the aqueous, sorbed, or DNAPL phases. The degree of uncertainty in CAH electron acceptor demand is a function of how well the site is characterized. The electron acceptor demand exerted by CAH mass is typically much less than exerted by native electron acceptors, and the uncertainty associated with CAH distribution is therefore considered low relative to native

electron acceptors. Nonetheless, the mass of CAHs present in DNAPL or sorbed to the aquifer matrix should be accounted for.

- 4) ***Substrate Migrating Out of the Reaction Zone.*** The design of an enhanced *in situ* bioremediation application usually involves specification of a reaction zone of known dimensions. It is then the objective of the application to achieve a target level of substrate within the “treatment zone.” In practice, a substantial amount of substrate or metabolic acids may migrate out the treatment area. This represents a substrate utilization inefficiency that should be accounted for.

Substrate calculations such as those described here should be used only as order-of-magnitude guidelines for determining substrate requirements. In practice, design factors on the order of 2 to 20 times the calculated electron acceptor or hydrogen demand are typically used to account for the uncertainty factors described above.

For soluble substrates, substrate requirements are factored into a substrate loading rate, or the amount of substrate delivered per injection event over time. The discussion in this appendix only addresses total or average substrate requirements. ***The rate at which the substrate is applied (amount and frequency) is equally as important as determining a total substrate requirement.*** The reader is referred to Section 6 of the main text for further discussion of substrate loading rates for soluble substrate applications.

For slow-release substrates, the loading rate is multiplied by the designed lifespan of the substrate (typically 1 to 5 years) and all the substrate is injected during a single event. The slow-release characteristics (limited solubility) of these substrates are intended to release soluble substrate continuously (controlled loading rate) over the designed lifespan of the application. A soluble substrate such as sodium lactate is often mixed with a slow release substrate to produce an initially high soluble substrate load to rapidly induce anaerobic conditions.

Analytical data collected during field sampling provides the best indication of the effectiveness of a particular substrate loading rate, and whether the substrate loading rate is appropriate for stimulating complete anaerobic dechlorination without excessive impacts to secondary water quality. Field analytical data (e.g., DO, oxidation-reduction potential [ORP], pH, TOC or DOC, and metabolic acids) from the injection and monitoring wells within the treatment zone are often used to confirm that the amount of substrate applied has created an appropriate reactive zone.

Given the level of uncertainty involved in substrate calculations, many practitioners still utilize an empirical approach as described in Section B.2. Any calculations of substrate requirements should be compared to past applications as a check that the amount of substrate being applied is within the range of typical industry practice.

B.6 Example of Estimating Substrate Requirements Based on Hydrogen Equivalents

As discussed in Section B.3, practitioners have attempted to calculate substrate requirements based on hydrogen equivalents in coupled redox and fermentation reactions. This method calculates the mass of molecular hydrogen required to satisfy native and CAH electron acceptor demands. These computations assume that a limited, known set of stoichiometric degradation reactions occurs, and should be considered order of magnitude estimates only. The following is an example of estimating substrate requirements based on calculations of hydrogen equivalents.

B.6.1 Hypothetical Site Conditions

Tables S.1 through S.5 (attached) are for a hypothetical example site used to illustrate the calculation of substrate requirements. Table S.1 contains the input used for the sample site. Table S.2 illustrates calculation of total electron acceptor demand in terms of hydrogen equivalents. Table S.3 lists the molecular formula, molecular weight, and potential hydrogen production rates for some common substrates based on fermentation or oxidation-reduction reactions (see Section B.3.3 for the source of this data). These data are used in Table S.4 to calculate the amount of substrate required to meet the hydrogen requirement estimated in Table S.1. Finally, Table S.5 is a summary table of the electron acceptor and substrate requirement calculations, including the distribution of differing electron acceptors.

The characteristics of the example site and system design are as follows:

- The treatment zone is a barrier configuration of 200 feet in length (perpendicular to groundwater flow) and 20 feet in width (parallel to groundwater flow), with a saturated thickness of 10 feet.
- The design period for the substrate calculations is 1 year.
- The groundwater potentiometric surface slopes uniformly in one direction with an average horizontal gradient of 0.01 foot per foot (ft/ft).
- The total porosity, effective porosity, and hydraulic conductivity of the aquifer matrix are assumed to be 25 percent, 20 percent, and 10 feet per day (ft/day), respectively.
- The soil bulk density and fraction organic carbon of the aquifer matrix are assumed to be 1.7 grams per cubic centimeter (gm/cm^3) and 0.05 percent, respectively.
- Contaminant concentrations are uniform throughout the treatment zone. Aqueous phase contaminant concentrations are 10,000 micrograms per liter ($\mu\text{g}/\text{L}$) PCE and 1,000 $\mu\text{g}/\text{L}$ of TCE.
- The existing groundwater geochemistry is relatively aerobic, with an average DO concentration of 5.0 mg/L, average nitrate concentration of 5.0 mg/L, and average sulfate concentration of 50 mg/L. Anaerobic processes utilizing carbon dioxide as an electron acceptor are expected to generate a concentration of 10 mg/L of methane.
- Anaerobic processes utilizing solid-phase electron acceptors are expected to generate a concentration of 5.0 mg/L manganese (Mn^{2+}) and 25 mg/L ferrous iron (Fe^{2+}) for a single pore volume.

The hypothetical site conditions listed above constitute a basic conceptual site model. Application of a substrate for enhanced bioremediation can take many forms in regards to substrate type, injection configuration, and injection frequency. ***For the purposes of this example, the following discussion describes the calculation of the total hydrogen requirement and substrate requirements for a 1-year design life.***

B.6.2 Calculation of Hydrogen Requirement

In this example, the total treatment zone volume is 40,000 cubic feet (ft^3) (Table S.2). Given an effective porosity of 20 percent, a pore volume for effective groundwater flow is equivalent to approximately 59,856 gallons. The application of Darcy's Law (calculation

not shown) yields a groundwater seepage velocity of 0.5 ft/day, or 182.5 feet per year (ft/yr). Based upon an effective porosity of 20 percent (the volume of interconnected porosity through which groundwater will flow), the volumetric groundwater flow rate (discharge) through the treatment zone is equivalent to approximately 546,186 gallons per year.

The mass of hydrogen required to theoretically reduce the mass of each native electron acceptor species and each CAH species is calculated in Steps 3 and 4 in Table S.2. For example, the hydrogen requirement for aqueous native electron acceptor mass in the initial pore volume of the treatment zone is 5.12 pounds (lbs) of molecular hydrogen (Step 3A in Table S.2).

The total hydrogen requirement required for the selected 1-year design life is calculated by summing the hydrogen requirements for initial aqueous and solid-phase native electron acceptors, initial aqueous and sorbed phase CAH electron acceptors, and the soluble native and CAH electron acceptor mass flux over time. Based upon these calculations, the total electron acceptor demand (in pounds of hydrogen equivalents) for the example site can be summarized as follows:

Initial aqueous native electron acceptor demand in treatment zone:	5.12 lbs
Solid-phase native electron acceptor demand in treatment zone:	3.21 lbs
Initial soluble CAH electron acceptor demand in treatment zone:	0.27 lbs
Sorbed CAH electron acceptor demand in treatment zone:	0.28 lbs
Soluble native electron acceptor mass loading (1 year):	47.1 lbs
Soluble CAH electron acceptor mass loading (1 year):	2.43 lbs

Total Hydrogen Requirement for 1-Year Design Life: 58.4 lbs

The design factor typically used by practitioners (to account for microbial efficiency and uncertainty in electron acceptor demand) using this method is between 2 and 10 times the calculated total hydrogen requirement of the system. For this example, if a design factor of 3 times was used it would yield a total hydrogen requirement of 175.3 pounds of molecular hydrogen over 1 year.

B.6.3 Calculation of Substrate Requirements

The mass of a particular organic substrate required to meet the total estimated hydrogen requirement can be calculated by dividing the total hydrogen requirement (including the design factor) of the system by the hydrogen production potential associated with the particular substrate of interest. Table S.4 lists the estimated mass of selected substrates that would be required to meet the hydrogen requirement calculated in Table S.2 for a design factor of 1 times the calculated hydrogen demand.

For example, the mass of ethanol required to meet the example hydrogen requirement with a design factor of 3 times (Table S.4) is approximately 2,003 pounds (175.3 pounds of hydrogen divided by 0.0875) of pure ethanol, or 2,504 pounds of ethanol product assuming the product is 80 percent ethanol and 20 percent water.

The substrate requirements listed in Table S.4 are first listed for 100 percent pure product. When estimating required substrate mass, it is important to account for the fact that most commercially available organic substrate products are less than 100 percent pure product,

and some are mixtures of different organic substrates. For example, HRC[®] is a complex molecule containing lactate and glycerol, and commercial emulsified vegetable oil products are mixtures of soybean oil, sodium lactate, emulsifiers, and water. Therefore, when estimating substrate requirements for purchase of substrate products, the composition of a substrate mixture should be known with a reasonable degree of certainty. Values for the amount of substrate product in Table S.4 assume that each product is a certain percentage of active (pure) ingredient.

As an example, the material safety data sheet (MSDS) for HRC[®] lists the product as ranging from 52.5 to 65.0 percent glycerol tripoly lactate and from 35.0 to 47.5 percent glycerol. For practical purposes, one could consider the product 60 percent glycerol tripoly lactate and 40 percent glycerol by weight. It is not known by the authors how much of the 60% glycerol tripoly lactate yields lactic acid or how much is inactive polymer material. Raymond *et al.* (2003) writes the formula for HRC[®] as C₃₉H₅₆O₃₉. If 40% of this compound were lactic acid (C₃H₆O₃) and 40% were glycerol (C₃H₈O₃), you could conceivably end up with the same amount of hydrogen ions per mole of substrate. For the substrate requirements tool, it is assumed that 22 moles of molecular hydrogen are produced per mole of HRC[®] assumed to be equivalent to C₃₉H₅₆O₃₉. This value yields comparable substrate quantities when evaluating a similar example site between the substrate requirement tool and the Regenesys design software. ***The practitioner should always refer to the manufacturers software or recommendations for design purposes. The substrate requirement tool is only intended for screening or evaluating the electron accepting processes at a site.***

As mentioned previously, it is a good practice to compare substrate loading estimates using the hydrogen equivalent method with empirical estimates. As an example, consider the 2003 pounds of pure ethanol estimated for the example case. Given an effective pore volume of approximately 59,856 gallons, a groundwater flux of approximately 546,186 gallons per year (Table S.5), and assuming the 2,003 pounds of pure ethanol is uniformly distributed in space and in time over the entire design life, the ***average time weighted dissolved concentration*** of ethanol would be approximately 396 mg/L. In practice ethanol would be injected in multiple, frequent events (perhaps daily) at higher concentrations to achieve the overall, long-term target concentration.

This concentration of ethanol is slightly higher than the range typically targeted for ethanol of 50 to 300 mg/L (see Table B.1). In this case, a design factor of 3 or more times may err on the high side due to conservative assumptions in the substrate requirement tool, and perhaps a design factor of 1.5 to 2 times may be more suitable. In practice, design factors for soluble substrate are almost always less than slow-release substrates, because greater control of average substrate concentrations over time can be achieved with the multiple injections of soluble substrate.

While there are many uncertainties in estimating substrate loading rates using either empirical or a stoichiometric approach, the use of a stoichiometric approach can provide a reasonable first estimate.

B.7 Using the Substrate Requirement Tool

An input table (Table S.1) is used to enter site specific data for an evaluation of substrate requirements, and a series of calculations are carried out to 1) calculate the rate of groundwater flow and volume of groundwater to be treated over the specified design life, 2) calculate the electron acceptor demand in hydrogen equivalents, and 3) calculate the

substrate requirement in hydrogen equivalents and estimates of some common substrates to meet that requirement. The basic treatment zone properties, hydrogen equivalents, relative distribution of electron accepting processes, and estimates of different substrates to meet the electron acceptor demand are summarized in Table S.5. The following subsections describe the input requirements, calculations, and tool output.

B.7.1 Input to the Substrate Requirement Tool (Table S.1)

Treatment zone dimensions and hydrogeological data are entered in Table S.1 to determine the pore volume of the treatment zone and the volume of groundwater flowing through the treatment zone over the design life of the application. The total volume treated is calculated as the initial pore volume and the volume of flow into the treatment zone over time. This may overestimate the amount of groundwater treated if large volumes of makeup water for the substrate mixture are derived from an outside water supply.

Background concentrations of native electron acceptors and contaminants are entered to calculate the hydrogen equivalents required to completely reduce the electron acceptor demand. ***It is recommended that average background concentrations be entered.*** This may overestimate the hydrogen equivalents needed if all electron acceptors are not reduced (e.g., sulfate is not completely reduced). But in general, the objective is to reduce all competing native electron acceptors to achieve a high efficiency of dechlorination of CAHs.

The electron acceptor demand from manganese, iron, and methanogenesis are calculated from the anticipated concentrations of soluble ferrous iron (Fe^{2+}), manganese (Mn^{4+}), and methane produced. This creates some uncertainty in the calculations, and conservative values should be considered. It may be useful to review case studies of enhanced *in situ* bioremediation in aquifers with similar lithology (e.g., sand and gravel versus silty clay) and groundwater geochemistry (e.g., naturally aerobic versus naturally anaerobic) to estimate the amount of iron, manganese, and methane that may be produced.

Aquifer geochemical parameters may also be entered as an option, but are not required for calculation of hydrogen equivalents. These parameters are intended to provide additional information that may impact bioremediation performance. For example, pH values less than 6.0 or an alkalinity concentration less than 300 mg/L are an indication that pH excursion may be an issue that could result in poor dechlorination efficiency and/or accumulation of intermediate dechlorination products. Cautionary notes are provided when the input values are outside of optimal conditions for enhanced *in situ* bioremediation of chlorinated solvents.

B.7.2 Substrate Requirement Tool Calculations (Tables S.2 through S.4)

Table S.2 is used to calculate the electron and molecular hydrogen equivalents necessary to meet the total electron acceptor demand over the design life of the application. No additional input is needed for these calculations.

The pore volume of the treatment zone is simply calculated as the total volume of the treatment zone times the estimated porosity. The rate of groundwater flow through a treatment zone may be calculated based on site-specific hydrogeologic properties of the aquifer. A simplistic approach using Darcy's Law is used. Darcy's Law states that the volumetric flow rate (Q) through a pipe filled with sand can be calculated as follows:

$$(B-14) \quad Q = -KA(dh/dl)$$

where

K = proportionality constant (length divided by time [L/T])

A = the cross sectional area of the pipe (L^2)

dh/dl = the horizontal hydraulic gradient (unitless)

More simply stated, Equation B-14 can be solved to yield the Darcy velocity or specific discharge. As defined, the specific discharge (q) is a volumetric flow rate per unit surface area of porous media:

$$(B-15) \quad q = Q/A = -K(dh/dl)$$

This equation is useful because the water balance through a treatment zone can be assumed to be approximately the volumetric flow of water through the aquifer, where values for the proportionality constant are measured as hydraulic conductivity (K). Both K and the horizontal hydraulic gradient (dh/dl) are commonly known from site investigation activities. For the example site in Section B.6, the average groundwater discharge through the treatment zone was calculated to be 546,186 gallons per year assuming a cross-sectional area of 2,000 square feet (200 feet in width by 10 feet saturated thickness), a hydraulic gradient of 0.01 ft/ft, an average hydraulic conductivity of 10 ft/day, and a conversion factor of 7.481 gallons per cubic feet.

Because water only moves through the interconnected pore openings of an aquifer, Darcy's q is a superficial or apparent velocity. That is, q represents the velocity at which water would flow if the aquifer were an open conduit, but does not account for the fact that only a portion of the aquifer volume consists of voids that causes water to flow through different pore spaces at different rates along individual flow paths that vary in length. The velocity of water through the aquifer pore spaces is termed the average linear or seepage velocity where:

$$(B-16) \quad v = -K(dh/dl) / n_e$$

where

v = pore water (seepage) velocity (L/T)

n_e = effective porosity of the aquifer matrix (unit less)

Typical groundwater seepage velocities for enhanced anaerobic bioremediation applications range from 30 to 1,000 ft/yr. Seepage velocities outside of this range require special consideration.

Table S.3 lists some common substrates and the weight of molecular hydrogen produced per unit weight of pure substrate (grams per gram). As discussed in Section B.3, this is perhaps the most subjective aspect of the substrate requirement tool. Therefore, the user is allowed to modify the moles of molecular hydrogen produced per mole of substrate. In the authors judgment, the values listed are conservative and may lead to higher than required substrate estimates in some cases.

Table S.4 then calculates the amount of pure substrate and bulk substrate product based the hydrogen produced per unit weight of substrate in Table S.3. This is a simple calculation where the hydrogen demand (pounds) is divided by the ratio of hydrogen produced per unit weight of substrate. For the example site above, 58.4 pounds of molecular hydrogen divided by a ratio of hydrogen produced per unit weight of ethanol of 0.0875 produces an ethanol equivalent of 668 pounds. Multiplying by a design factor of 3 times results in an

ethanol equivalent of 2,003 lbs of pure ethanol, or 2,504 lbs of ethanol product at 80% ethanol.

B.7.3 Substrate Requirement Tool Output (Table S.5)

Output from the substrate requirements tool is summarized in Table S.5. This table summarizes the treatment zone physical dimensions, hydrogeological properties, the hydrogen requirement for each electron accepting process, and a plot of the relative distribution of the electron acceptor demand for each electron accepting process. Table S.5 also calculates the hydrogen requirement in pounds per gallon or grams per liter. This information is useful when comparing multiple sites with varying geochemical and contaminant conditions.

Finally Table S.5 summarizes the substrate requirements for some common substrate types based on the design factor that is input in Table S.1. This information is provided in pounds of the substrate product (assuming the percent of active ingredient in each product), the quality of product for those typically sold by the gallon, and the effective time-weighted average concentration of substrate for the total volume of water treated.

This information may be used to evaluate the design of different enhanced bioremediation applications. It is a useful first approximation of substrate requirements, but professional experience and judgment should always be applied on a site by site basis when designing an enhanced *in situ* bioremediation application.

B.8 Summary

Practitioners using the methods described in this appendix should recognize the degree of uncertainty involved. One concern is that an inadequate substrate loading rate may lead to reducing conditions that are insufficient for complete dechlorination, with the potential for accumulation of intermediate dechlorination products. Conversely, excessive levels of organic substrate may lead to an adverse excursion in pH affecting dechlorination efficiency, high levels of methanogenesis with low utilization of substrate for anaerobic dechlorination, and potential for adverse impacts to secondary groundwater quality.

While the scientific basis for determining substrate requirements remains an area of uncertainty, the practitioner of enhanced *in situ* bioremediation must still design or evaluate a substrate loading rate with the methods currently available. The two approaches most commonly employed are to either: 1) target an empirical range of substrate concentration in the reaction zone that is based upon previous experience and experimentation, or 2) calculate a substrate (electron donor) requirement based on estimates of the native and CAH electron acceptor mass and mass flux. ***In practice, both methods should be performed and used as a check against the other that the substrate loading rate applied is within practical limits used in other successful bioremediation applications.***

Given the state of knowledge and practice, pilot testing and experimentation may be the best way to optimize substrate loading rates for anaerobic dechlorination of chlorinated solvents. As the level of uncertainty increases, the practitioner may also want to consider designs and techniques that provide for more latitude in modifying substrate loading rates (e.g., recirculation designs). It is anticipated that continued implementation and documentation of enhanced *in situ* bioremediation will lead to an improved understanding and less uncertainty in the design of substrate loading rates.

B.10 References

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SUBSTRATE ESTIMATING TOOL FOR ENHANCED ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS

Version 1.1
February 2010

Site Data Input Table

TABLE S.1 - INPUT TABLE

Calculation Tables

Table S.2 - Substrate
Calculations in Hydrogen
Equivalents

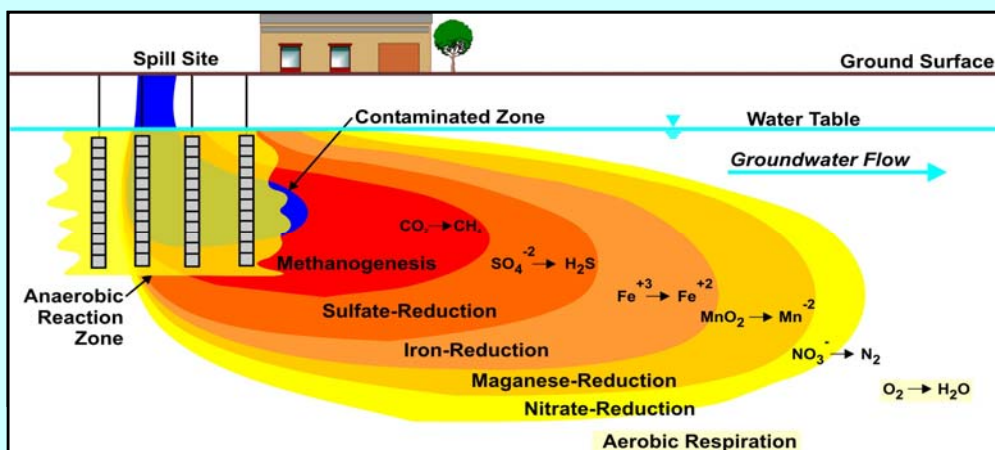
Table S.3 - Hydrogen Produced
by Common Substrates

Table S.4 - Estimated Substrate
Requirements for Hydrogen
Demand

Output Summary Table

TABLE S.5 - OUTPUT TABLE

PRINT SUMMARY TABLE



This Substrate Estimating Tool for Enhanced Anaerobic Bioremediation of Chlorinated Solvents has been developed by Parsons Infrastructure & Technology Group, Inc. (Parsons) for the Environmental Security Technology Certification Program (ESTCP). This substrate estimating tool is made available on an as-is basis without guarantee or warranty of any kind, express or implied. The United States Government, Parsons, the authors, and the reviewers accept no liability resulting from the use of this substrate estimating tool or its documentation; nor does the above warrant or otherwise represent in any way the accuracy, adequacy, efficacy, or applicability of the contents hereof. This substrate estimating tool is intended solely for educational and site screening purposes. Implementation of the substrate estimating tool and interpretation or use of the results provided in the model are the sole responsibility of the user. The substrate estimating tool is provided free of charge for everyone to use, but is not supported in any way by the United States Government or Parsons. Mention of trade names in this report is for information purposes only; no endorsement is implied.

Table S.1 Input for Substrate Requirements in Hydrogen EquivalentsSite Name: **Example Site**[RETURN TO COVER PAGE](#)

NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	200	1-10,000	feet	This table is populated with an example site.
Length (Parallel to predominant groundwater flow)	20	1-1,000	feet	Please input your site data.
Saturated Thickness	10	1-100	feet	
Treatment Zone Cross Sectional Area	2000	--	ft ²	
Treatment Zone Volume	40,000	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	74,820	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	59,856	--	gallons	
Design Period of Performance	1.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	3.0	2 to 20	unitless	

2. Treatment Zone Hydrogeologic Properties

Total Porosity	25%	.05-50	percent	
Effective Porosity	20%	.05-50	percent	
Average Aquifer Hydraulic Conductivity	10	.01-1000	ft/day	
Average Hydraulic Gradient	0.01	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.50	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	182.5	--	ft/yr	
Average Groundwater Discharge through the Treatment Zone	546,186	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm ³	
Soil Fraction Organic Carbon (foc)	0.05%	0.01-10	percent	

3. Native Electron Acceptors**A. Aqueous-Phase Native Electron Acceptors**

Oxygen	5.0	0.01 to 10	mg/L	
Nitrate	5.00	0.1 to- 20	mg/L	
Sulfate	50	10 to 5,000	mg/L	
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	

B. Solid-Phase Native Electron Acceptors

Manganese (IV) (estimated as the amount of Mn (II) produced)	5	0.1 to 20	mg/L	
Iron (III) (estimated as the amount of Fe (II) produced)	25	0.1 to 20	mg/L	

4. Contaminant Electron Acceptors

Tetrachloroethene (PCE)	10.000	--	mg/L	
Trichloroethene (TCE)	1.000	--	mg/L	
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	--	mg/L	
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	

5. Aquifer Geochemistry (Optional Screening Parameters)**A. Aqueous Geochemistry**

Oxidation-Reduction Potential (ORP)	100	-400 to +500	mV	
Temperature	20	5.0 to 30	°C	
pH	7.0	4.0 to 10.0	su	
Alkalinity	300	10 to 1,000	mg/L	
Total Dissolved Solids (TDS, or salinity)	100	10 to 1,000	mg/L	
Specific Conductivity	200	100 to 10,000	µs/cm	
Chloride	10	10 to 10,000	mg/L	
Sulfide - Pre injection	0.0	0.1 to 100	mg/L	
Sulfide - Post injection	0.0	0.1 to 100	mg/L	

B. Aquifer Matrix

Total Iron	10000	200 to 20,000	mg/kg	
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	
Neutralization Potential	10.0%	1.0 to 100	Percent as CaCO ₃	

NOTES:

Table S.2 Substrate Calculations in Hydrogen Equivalents**Site Name:****Example Site**[RETURN TO COVER PAGE](#)

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
200	1-10,000	feet
20	1-1,000	feet
10	1-100	feet
2000	--	ft ²
40,000	--	ft ³
59,856	--	gallons
1.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.25	.05-50	
0.2	.05-50	
10	.01-1000	ft/day
0.01	0.1-0.0001	ft/ft
0.50	--	ft/day
182.5	--	ft/yr
546,186	--	gallons/year
1.7	1.4-2.0	gm/cm ³
0.0005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
5.0	2.50	7.94	0.31	4
5.0	2.50	12.30	0.20	5
50	24.97	11.91	2.10	8
10.0	4.99	1.99	2.51	8
Soluble Competing Electron Acceptor Demand (lb.)			5.12	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
5.0	25.29	27.25	0.93	2
25.0	126.43	55.41	2.28	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			3.21	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
10.000	4.99	20.57	0.24	8
1.000	0.50	21.73	0.02	6
0.000	0.00	24.05	0.00	4
0.000	0.00	31.00	0.00	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.000	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			0.27	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x C_{gw})
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	1.32	5.58	20.57	0.27	8
107	0.05	0.23	21.73	0.01	6
45	0.00	0.00	24.05	0.00	4
3.0	0.00	0.00	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			0.28		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	5.0	22.79	7.94	2.87	4
Nitrate (denitrification)	5.0	22.79	10.25	2.22	5
Sulfate	50	227.88	11.91	19.13	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	45.58	1.99	22.90	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				47.1	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	10.000	45.58	20.57	2.22	8
Trichloroethene (TCE)	1.000	4.56	21.73	0.21	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	0.00	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				2.43	

Initial Hydrogen Requirement First Year (lb)**58.4****Total Life-Cycle Hydrogen Requirement (lb)****58.4****5. Design Factors**

Microbial Efficiency Uncertainty Factor
Methane and Solid-Phase Electron Acceptor Uncertainty
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)

2X - 4X

2X - 4X

1X - 3X

Design Factor**3.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)****175.3****6. Acronyms and Abbreviations**

°C =degrees celsius

μS/cm = microsiemens per centimeter

cm/day = centimeters per day

cm/sec = centimeters per second

ft² = square feet

ft/day = feet per day

ft/ft = foot per foot

ft/yr = feet per year

gm/cm³ = grams per cubic centimeterkg of CaCO₃ per mg = kilograms of calcium carbonate per milligram

lb = pounds

meq/100 g = milliequivalents per 100 grams

mg/kg = milligrams per kilogram

mg/L = milligrams per liter

m/m = meters per meters

mV = millivolts

m/yr = meters per year

su = standard pH units

wt/wt H₂ = concentration molecular hydrogen, weight per weight

Table S.3

Hydrogen Produced by Fermentation Reactions of Common Substrates

[RETURN TO COVER PAGE](#)

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 1

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	3.0	3,917	3,917	1.78E+09	774
Sodium Lactate Product (60 percent solution)	3.0	3,917	8,126	1.78E+09	774
Molasses (assuming 60 percent sucrose)	3.0	3,721	6,201	1.69E+09	736
HFCS (assuming 40% fructose and 40% glucose by weight)	3.0	3,918	4,897	1.78E+09	775
Ethanol Product (assuming 80% ethanol by weight)	3.0	2,003	2,504	9.09E+08	396
Whey (assuming 100% lactose)	3.0	2,704	3,862	1.23E+09	535
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	3.0	2,969	2,969	1.35E+09	470
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	3.0	1,525	1,525	6.92E+08	301
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	3.0	1,525	2,541	6.92E+08	301

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents**Site Name:****Example Site**[RETURN TO COVER PAGE](#)**1. Treatment Zone Physical Dimensions**

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	200	feet	61	meters
Length (parallel to groundwater flow)	20	feet	6.1	meters
Saturated Thickness	10	feet	3.0	meters
Design Period of Performance	1	years	1	years

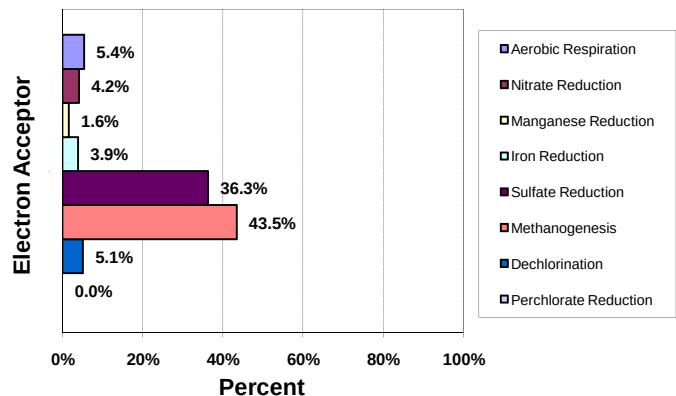
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.25	percent	0.25	percent
Effective Porosity	0.2	percent	0.2	percent
Average Aquifer Hydraulic Conductivity	10	ft/day	3.5E-03	cm/sec
Average Hydraulic Gradient	0.01	ft/ft	0.01	m/m
Average Groundwater Seepage Velocity	0.50	ft/day	1.5E+01	cm/day
Average Groundwater Seepage Velocity	183	ft/yr	55.6	m/yr
Total Treatment Zone Pore Volume	59,856	gallons	226,573	liters
Groundwater Flux (per year)	546,186	gallons/year	2,067,481	liters/year
Total Groundwater Volume Treated (over entire design period)	606,042	gallons total	2,294,054	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	5.4%	3.185
Nitrate Reduction	4.2%	2.426
Sulfate Reduction	36.3%	21.231
Manganese Reduction	1.6%	0.928
Iron Reduction	3.9%	2.282
Methanogenesis	43.5%	25.413
Dechlorination	5.1%	2.973
Perchlorate Reduction	0.0%	0.000
Totals:	100.00%	58.44

Hydrogen demand in pounds/gallon:	9.64E-05
Hydrogen demand in grams per liter:	1.16E-02

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor =****3.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	8,126	739	774	as lactic acid
2. Molasses Product	6,201	517	736	as sucrose
3. Fructose Product	4,897	437	775	as fructose
4. Ethanol Product	2,504	363	396	as ethanol
5. Sweet Dry Whey (lactose)	3,862	sold by pound	535	as lactose
6. HRC®	2,969	sold by pound	470	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	1,525	195	301	as soybean oil
8. Emulsified Vegetable Oil	2,541	326	301	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

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APPENDIX C
CASE STUDY SUMMARIES

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SITE SUMMARY**Hangar K, Cape Canaveral Air Force Station, Florida**

For: Project Files for ESTCP Substrate Loading Study (Project No. 745255)

Revision: 01 June 2009

SITE IDENTIFICATION

Hangar K, Cape Canaveral Air Force Station (CCAFS), Florida

CONTAMINANT SOURCE

<i>COC</i>	<i>Max. Conc.</i>	<i>DNAPL Present?</i>	<i>Notes</i>
TCE	300,000 µg/L	Inferred	Ref (3) - Baseline at HGRK-VEG1 in July 2000
<i>cis</i> -1,2-DCE	120,000 µg/L	--	Ref (3) - Baseline at HGRK-VEG1 in July 2000
VC	550 µg/L	--	Ref (3) - Baseline at HGRK-VEG1 in July 2000

SUBSTRATE DESIGN/INSTALLATION INFORMATION

<i>Parameter</i>	<i>Original Design</i>	<i>Modifications?</i>	<i>Notes/Reference</i>
Project Scale	Expanded Pilot Test		Ref (1), (2)
Substrate Type	Neat Soybean Oil	No change	
Number of Injection Points (IP)	33	No change	
IP Spacing Information	10 feet	No change	
Injection Date	August 2000	No change	
Injection Interval (depth bgs)	22-32 feet bgs	No change	
Substrate Loading	• Total of 8,415 gal injected • Substrate concentration of 21.6 percent oil. • Effective treatment zone volume = 102,129 gallons. • Effective treatment zone concentration = 1.78 percent oil by volume.	No change	55 gallons oil followed by 200 gallons water into each of 33 direct-push injection points.
Substrate Loading Rate	55 gallons neat vegetable oil per injection point	No change	
Basis for Loading Rate	Empirical. Injected one 55-	N/A	Injection pressures of

<i>Parameter</i>	<i>Original Design</i>	<i>Modifications?</i>	<i>Notes/Reference</i>
	gallon drum of soybean oil into each point, followed by 200 gallon water push.		15- 28 psi, and flow rates of 6 to 8 gpm. Pressure was maintained below approx 28 psi to avoid breakthrough or fracturing.
Injection amendment?	Oil soluble tracer and bromide tracer in select injection points		Oil soluble tracer and approximately 500 mg/L bromide added to water push in four select points.
Pre-injection Specified?	No	No change	
Post-injection Specified?	Yes	No change	
Type of post-injection	Groundwater	No change	Chase water from nearby clean monitoring well.
Volume of post-injection	200 gallons per point	No change	

MONITORING INFORMATION

<i>Sample Collection Date (Reference)</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Reference</i>
July 2000 (baseline)	Yes	Yes	Yes	No	Ref (3)
Feb/March 2001	Yes	Yes	Yes	No	Ref (3)
April 2002	Yes	Yes	Yes	No	Ref (3)
October 2002	Yes	Yes	Yes	No	Ref (3)
April 2003	Yes	Yes	Yes	No	Ref (3)
December 2003	Yes	Yes	Yes	No	Ref (3)
April 2006	Yes	Yes	Yes	No	Ref (3)

REFERENCES

- (1) Parsons. 2000. *Expanded Pilot Test for Enhanced Bioremediation of Chlorinated Solvents via Vegetable Oil Injection at the Hangar K Site, Cape Canaveral Air Station, Florida*. Technical Memorandum prepared for the Air Force Center for Environmental Excellence. March. **(Work Plan)**
- (2) Parsons. 2002. *Final Phase II Field Feasibility Test for In Situ Bioremediation of Chlorinated Solvents Via Vegetable Oil Injection at Hangar K Area, Cape Canaveral Air Force Station, Florida*. Prepared for the Air Force Center for Environmental Excellence, San Antonio, Texas. March. **(Interim Report)**

- (3) Parsons. 2007. *Field Feasibility Study for Enhanced In Situ Bioremediation of Chlorinated Solvents at Hangar K, Cape Canaveral Air Force Station, Florida*. Prepared for the Air Force Center for Engineering and the Environment, Brooks City-Base, Texas. Draft, June. **(Final Report)**

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates calculated or designed?

Stoichiometric calculations were not used for this demonstration. An empirical approach was used, based in part on a pilot test “push-pull” test. During the pilot test, 110 gallons of neat oil was injected into a 1-foot long well screen, and approximately 62 gallons of neat oil was then extracted, leaving 48 gallons of residual oil in the formation. This was done to leave the oil in a residual (non-mobile) phase, and to reduce the effect of the oil to plug the formation and inhibit groundwater flow.

The expanded pilot test used an injection of 55 gallons neat oil per injection point with 10-foot screens, followed by 200 gallons of native groundwater to push the oil into the formation at a low enough saturation to limit mobility of the oil.

2. What modifications to the substrate amendment protocol were required (e.g., depletion and additional injection of substrate).

No modifications were required. The application had an effective life span of approximately 5 years. Concentrations of TCE within the treatment zone were reduced from baseline concentrations of greater than 100,000 µg/L to below the USEPA MCL of 5.0 µg/L for TCE within three years of the Phase II injection. Only a moderate rebound in TCE was observed in April 2006 (68 months post-injection) at monitoring point MP10, located on the upgradient fringe of the reaction zone.

3. Evaluation from Substrate Demand Tool

Site data were input into the substrate demand tool (attached) using a design life of 5 years. The substrate requirement to treat 154,877 gallons (586,258 liters) of groundwater over 5 years was 77.4 pounds of molecular hydrogen, or 5.00E-04 pounds per gallon (5.99E-02 grams per liter) of groundwater treated.

This hydrogen requirement could be met by 673 pounds of neat soybean oil. Based on the mass of substrate applied at the Hangar K Site (1,815 gallons or 14,157 pounds of oil), the effective design factor applied at the site was 21 times the estimated hydrogen demand.

The distribution of primary electron acceptors was chlorinated solvents (75.8%), followed by methanogenesis (16.8%), sulfate reduction (5.6%), manganese reduction (0.9%), iron reduction (0.8%), aerobic oxidation (0.1%) and nitrate reduction (<0.1%). The site is naturally depleted in dissolved oxygen and nitrate.

PERFORMANCE OBJECTIVES

No. 1: Ability to Uniformly Distribute Substrate : Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

An application is considered successful when the targeted concentrations of soluble organic carbon are achieved in all monitoring locations within the intended reaction zone. This demonstration did not attempt to achieve a perfectly uniform distribution of the neat oil substrate. Rather, the oil substrate was injected in a series of uniformly spaced well points with the oil being distributed only a few feet from the injection point. The intent was for soluble substrate from breakdown of the oil (i.e., metabolic acids) to be uniformly distributed by the processes of advection, dispersion, and diffusion.

Data for TOC and VFA indicate that soluble substrate was broadly distributed throughout the treatment zone. Concentrations of TOC measured for monitoring points within the treatment zone in April 2002 (21 months post-injections) had concentrations of TOC ranging from 37 to 900 mg/L. Concentrations of TOC in monitoring points downgradient of the treatment zone had concentrations of TOC ranging from 6.6 to 11 mg/L, versus a background of <5.0 mg/L. While concentrations of TOC did range by an order of magnitude, there were no apparent gaps or areas that were not impacted by the injection.

No. 2: Achieving Optimal Geochemical Conditions

Successful geochemical conditions for stimulating anaerobic degradation of chlorinated solvents is defined as when the groundwater environment is highly anaerobic with DO less than 0.5 mg/L, ORP is less than -200 mV, sulfate is reduced by more than 50 percent relative to background conditions, and methane is greater than 1.0 mg/L. These criteria may not apply in all cases.

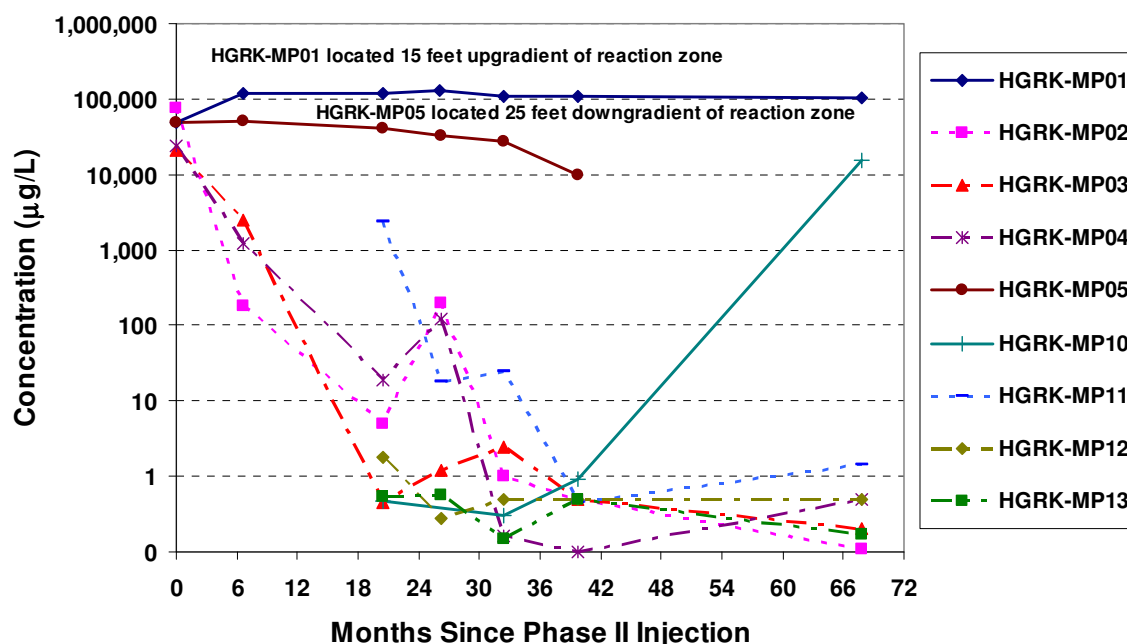
Groundwater in the Hangar K study area is naturally anaerobic, with DO concentrations less than 0.5 mg/L. The addition of vegetable oil lowered the reducing environment at the site, with ORP measurements ranging from -100 mV to -250 mV in April 2006 (68 months after injection). This indicates the groundwater environment is sufficiently reducing to support iron reduction, sulfate reduction and methanogenesis, which are optimal conditions for reductive dechlorination to occur. Elevated concentrations of ferrous iron and methane, and reduced concentrations of sulfate, in the treatment zone indicate that these processes were successfully stimulated by injection of the vegetable oil.

No. 3: Remediation Effectiveness: Evaluate efficiency in removal of VOCs based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Determine “threshold” concentrations of dissolved organic carbon that represent the minimum levels required to sustain complete reductive dechlorination.

Pre- and post-treatment concentrations of the targeted contaminants are evaluated to determine the effectiveness of the remedy. The success of the application is evaluated by comparing concentrations to site-specific performance criteria, if established. Otherwise, a reduction in contaminant concentration of 99 percent or greater (over two orders of magnitude) is considered successful. For chlorinated aliphatic hydrocarbons (CAHs, or chlorinated solvents) where

production of regulated intermediate dechlorination products may occur, a reduction in the total molar concentration of CAHs of greater than 90 percent is also considered to be a success.

Concentrations of TCE for all of the Phase II monitoring points within the vegetable oil treatment zone decreased substantially from July 2000 to December 2003, with only a small rebound in TCE at location HGRK-MW10 in April 2006 (see figure below). Concentrations of TCE within the treatment zone were reduced from baseline concentrations of greater than 100,000 µg/L to below the USEPA MCL of 5.0 µg/L for TCE within three years of the Phase II injection. This represents a reduction in concentrations of TCE of over four orders of magnitude (>99 percent).



During the same period, concentrations of the dechlorination products *cis*-1,2-DCE and VC showed variable trends, generally peaking at approximately 7 to 21 months post injection respectively, then declining. During the April 2006 sampling event, *cis*-1,2-DCE and VC concentrations were below USEPA MCLs at 7 of 11 locations sampled and 6 of 11 locations sampled, respectively. While VC has apparently accumulated at a few locations within the treatment zone, the observed increases in ethene concentrations indicate that VC is being dechlorinated.

Of the eight well locations sampled for both the baseline (July 2000) and final sampling events (April 2006), reductions in total molar concentrations of chlorinated ranged from approximately 96 percent for location HGRK-VEG1 to over 99 percent for the other seven well locations. Therefore, the remedial effectiveness of the demonstration is considered successful.

No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

Secondary water quality parameters that were evaluated for the Hangar K site include pH, sulfide, dissolved metals or semi-metals (ferrous iron, manganese, arsenic, and selenium), and the fermentation products acetone and 2-butanone.

Summary of Secondary Water Quality – Hangar K Site

Parameter	Comparison Criteria	Background	Treatment Zone	Down-gradient	Issues?
pH	<6.5 or >8.5 (b)	6.93 to 8.00	6.10 to 7.39	6.52 to 7.09	None
Sulfide (mg/L)	NA	<0.10	<0.10 to 2.0	<0.10 to 0.9	None – only a few isolated detections above 0.1 mg/L
Total Manganese (mg/L)	0.05 (b)	<0.1 to 0.3	<0.1 to 17	<0.1 to 12	Potential – elevated within and downgradient of injection zone.
Total Ferrous Iron (mg/L)	0.3 (b)	0.8 to 2.5	1.8 to 29	0.65 to 22	Potential – background above criteria
Dissolved Manganese (mg/L)	0.05 (b)	0.017 to 0.045	0.036 to 0.57	0.051 to 0.091	Potential – slightly above criteria with and downgradient of injection zone.
Arsenic (mg/L)	0.01 (a)	<0.010 to 0.018	<0.010	<0.010	None
Selenium (mg/L)	0.05 (a)	<0.020	<0.020	<0.020	None
Acetone (mg/L)	5.5 (c)	4.1 M	Up to 0.390 F	<0.010	None
2-butanone (mg/L)	7.0 (c)	<50	<10	<10	None

Notes:

Background values from well HGRK-MP01 (upgradient).

Downgradient values from well HGRK-MP04 and HGRK-MP05 (post-injection).

mg/L = milligrams per liter; µg/L = micrograms per liter. F-flag indicates concentration is estimated.

Criteria based on (a) USEPA MCL; (b) USEPA Secondary Standard; or (c) USEPA Region 9 PRG.

pH and Sulfide. With few exceptions, pH remained in a range from approximately 6.3 to 7.0 and an adverse decrease in pH was not observed. Only a few low level detections of sulfide were observed.

Dissolved metals. Filtered samples for arsenic, selenium, and manganese were analyzed in samples collected from wells along the axis of the treatment zone. Unfiltered samples for

manganese and ferrous iron were measured in the field. With a single exception, concentrations of arsenic were below detection (less than 0.010 mg/L) for all samples within and downgradient of the reaction zone. Arsenic was measured at a concentration of 0.018 mg/L in a single sample collected from upgradient monitoring location HRGK-MP01 in December 2003. For all samples, concentrations of selenium were less than 0.020 mg/L, compared to the USEPA primary drinking water standard of 0.05 mg/L. Therefore, solubilization of arsenic and selenium is not of concern at the Hangar K Site.

Concentrations of dissolved manganese were low, ranging from 0.018 mg/L to 0.57 mg/L, with no discernable increase following substrate injection. The secondary drinking water standard issued by the USEPA for this analyte is 0.05 mg/L. However, concentrations of total manganese and ferrous iron were elevated within and downgradient of the reaction zone. Total manganese was measured as high as 17 mg/L and ferrous iron was measured as high 29 mg/L. Concentrations of total manganese and ferrous iron remained elevated in April 2006, even after concentrations of TOC were depleted. This indicates that the groundwater geochemistry at the site will be slow to rebound to natural background conditions. The shallow groundwater at the Hangar K Site is not a drinking water source, and the magnitude of the increase in concentrations of total manganese and ferrous iron does not appear to be an issue at this site.

Undesirable VOCs. Acetone and 2-butanone were only measured at the end of the study, and were not above the comparison criteria (USEPA Region 9 PRGs) in any of the wells within and downgradient of the injection zone.

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

Baseline tests for hydraulic conductivity were not conducted. Slug tests were conducted during the April 2003 and December 2003 sampling rounds, and calculated hydraulic conductivities were relatively consistent from well to well and over time, ranging from 1.2E-03 cm/sec to 6.2E-03 cm/sec. The Hangar K site also has a very low hydraulic gradient. There were no site-wide impacts on the hydraulic gradient, probably because the oil was only distributed over a limited portion of the aquifer (i.e., less than 2 percent of the aquifer pore space).

No. 6: Substrate Persistence and Long-Term Effectiveness

After substrate injection, the average concentration of TOC increased to 1,000 mg/L, then began a steady decline that appears to match a first-order degradation rate. With the exception of one well location (HGRK-MP10), concentrations of TOC in December 2003 had declined to less than 20 mg/L, indicating that the vegetable oil substrate had been depleted to near background levels. At 68 months post injection, concentrations of TOC have been depleted to background levels and a rebound in the concentration of TCE has been observed at location HGRK-MP10. HGRK-MP10 was installed at the upgradient fringe of the treatment zone in April 2002, 21 months after injection. Therefore, comparison of the rebound to a baseline concentration is not possible.

Overall, the data indicate that the effective life span of the application is on the order of 4 to 5 years. It is difficult to determine a “threshold” concentration of TIC necessary to sustain

dechlorination at this site. But it appears that concentrations of chlorinated ethenes did not exhibit any rebound until TOC dropped below approximately 20 mg/L.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

No modifications were required. Additional injections were not necessary to sustain effective degradation of chlorinated solvents over the intended design life of the Hangar K application.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

The application at the Hangar K site did not encounter any difficult hydrogeological conditions. The application benefited from:

- High permeability that aided injection of neat vegetable oil.
- Low hydraulic gradient and rate of groundwater flow that limited contaminant and native electron acceptor flux.
- Calcareous sand that limited pH excursion.

COST ASSESSMENT

Cost Summary, Hangar K Site, CCAFS, Florida

Cost Element	Data to be Tracked	Project Cost
System Design/ Work Plan (Total = \$11,000)	- Labor for system design and work plan - Permitting costs	\$11,000 \$0
Capital Construction/ System Installation (Total = \$62,000)	- Recommended installation method - Mobilization (includes travel and per diem) - Site labor - Subcontractor - USACE CPT - Subcontractor - Surveyor - Construction material cost (well materials and injection equipment) - Substrate or amendment cost (including total cost and \$/lb)	- Direct Injection \$2,800 \$15,000 \$30,000 (estimated) \$1,500 \$7,000 \$5,700 (\$0.44 per pound delivered)
Baseline Characterization and Construction Completion Report (Total = \$24,000)	- Sampling labor - Reporting labor - Sampling equipment and supplies - Laboratory analytical costs	\$5,000 \$11,000 \$2,000 \$6,000
Operating Cost	Not Required – One time injection of neat vegetable	\$0
Long-Term Monitoring (per event) (Total for six events = \$144,000)	- Mobilization (includes travel and per diem) - Sampling labor - Sampling equipment and supplies - Analytical cost - Labor for project management and reporting - Number of events	\$2,500 \$7,500 \$2,000 \$6,000 \$6,000 - Six events
Total Application Cost		\$241,000

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** Hangar K, CCAFS, Florida

NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	60	1-10,000	feet	
Length (Parallel to predominant groundwater flow)	65	1-1,000	feet	
Saturated Thickness	10	1-100	feet	
Treatment Zone Cross Sectional Area	600	--	ft ²	
Treatment Zone Volume	39,000	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	102,129	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	72,950	--	gallons	
Design Period of Performance	5.0	.5 to 5	year	Not specified in initial design
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	

2. Treatment Zone Hydrogeologic Properties	Values	Range	Units	User Notes
Total Porosity	35%	.05-50	percent	
Effective Porosity	25%	.05-50	percent	
Average Aquifer Hydraulic Conductivity	10	.01-1000	ft/day	
Average Hydraulic Gradient	0.001	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.04	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	14.6	--	ft/yr	
Average Groundwater Flux through the Treatment Zone	16,386	--	gallons/year	
Soil Bulk Density	1.65	1.4-2.0	gm/cm ³	Sand
Soil Fraction Organic Carbon (foc)	0.50%	0.01-10	percent	Assumed default value

3. Native Electron Acceptors	Values	Range	Units	User Notes
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	0.5	0.01 to 10	mg/L	Ranged from <0.1 to 1.4 mg/L
Nitrate	0.05	0.1 to 20	mg/L	Less than 0.1 mg/L
Sulfate	40	10 to 5,000	mg/L	Ranged from 17 to 46 mg/L
Carbon Dioxide (estimated as the amount of Methane produced)	20	0.1 to 20	mg/L	Methane Produced - Max. 23 mg/L
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	15	0.1 to 20	mg/L	Manganese Produced - Max. 17 mg/L
Iron (III) (estimated as the amount of Fe (II) produced)	25	0.1 to 20	mg/L	Ferrous Iron Produced - Max 29 mg/L

4. Contaminant Electron Acceptors	Values	Range	Units	User Notes
Tetrachloroethene (PCE)	0.140	--	mg/L	HGRK-VEG1 on 7/11/00
Trichloroethene (TCE)	300.000	--	mg/L	HGRK-VEG1 on 7/11/00
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	121.790	--	mg/L	HGRK-VEG1 on 7/11/00
Vinyl Chloride (VC)	0.550	--	mg/L	HGRK-VEG1 on 7/11/00
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	

5. Aquifer Geochemistry (Optional Screening Parameters)	Values	Range	Units	User Notes
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	-140	-400 to +500	mV	Background -127 to -157 mV
Temperature	26	5.0 to 30	°C	Ranged from 24.4 to 31.2 °C
pH	7.1	4.0 to 10.0	su	Ranged from 6.05 to 7.35
Alkalinity	300	10 to 1,000	mg/L	Ranged from 280 to 360 mg/L
Total Dissolved Solids (TDS, or salinity)	NA	10 to 1,000	mg/L	Not analyzed
Specific Conductivity	600	100 to 10,000	µs/cm	Ranged from 384 to 920 µs/cm
Chloride	45	10 to 10,000	mg/L	Ranged from 6.0 to 85 mg/L
Sulfide - Pre injection	0.1	0.1 to 100	mg/L	Ranged from <0.1 to 0.1 mg/L
Sulfide - Post injection	1.0	0.1 to 100	mg/L	Maximum 2.0 mg/L
B. Aquifer Matrix				
Total Iron	NA	100 to 10,000	mg/kg	
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	
Neutralization Potential	NA	1.0 to 100	Percent as CaCO ₃	

NOTES:

Background data based on sampling in July/August 2000 at locations HGRK-VEG1, MP01, MP02, MP03, MP04, MP05, and MP06.
 Values for methane, manganese, and ferrous iron are post-injection.

Table S.2 Substrate Calculations in Hydrogen Equivalents**Site Name:** Hangar K, CCAFS, Florida

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
60	1-10,000	feet
65	1-1,000	feet
10	1-100	feet
600	--	ft ²
39,000	--	ft ³
72,950	--	gallons
5.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone 0
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.35	.05-50	
0.25	.05-50	
10	.01-1000	ft/day
0.001	0.1-0.0001	ft/ft
0.04	--	ft/day
14.6	--	ft/yr
16,386	--	gallons/year
1.65	1.4-2.0	gm/cm ³
0.005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.5	0.30	7.94	0.04	4
0.1	0.03	10.25	0.00	5
40	24.35	11.91	2.04	8
20.0	12.17	1.99	6.12	8
Soluble Competing Electron Acceptor Demand (lb.)			8.20	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
15.0	19.39	27.25	0.71	2
25.0	32.31	55.41	0.58	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			1.29	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.140	0.09	20.57	0.00	8
300.000	182.62	21.73	8.40	6
121.790	74.14	24.05	3.08	4
0.550	0.33	31.00	0.01	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.000	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			11.50	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x C_{gw})
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	0.18	0.74	20.57	0.04	8
107	160.50	644.89	21.73	29.68	6
45	27.40	110.10	24.05	4.58	4
3.0	0.01	0.03	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			34.29		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	0.5	0.07	7.94	0.01	4
Nitrate (denitrification)	0.1	0.01	10.25	0.00	5
Sulfate	40	5.47	11.91	0.46	8
Carbon Dioxide (estimated as the amount of Methane produced)	20	2.73	1.99	1.37	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				1.8	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.140	0.02	20.57	0.00	8
Trichloroethene (TCE)	300.000	41.02	21.73	1.89	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	121.790	16.65	24.05	0.69	4
Vinyl Chloride (VC)	0.550	0.08	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				2.58	

Initial Hydrogen Requirement First Year (lb)**59.7****Total Life-Cycle Hydrogen Requirement (lb)****77.4****5. Design Factors**

Microbial Efficiency Uncertainty Factor
Methane and Solid-Phase Electron Acceptor Uncertainty
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)

2X - 4X

2X - 4X

1X - 3X

Design Factor**1.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)****77.4****6. Acronyms and Abbreviations**

°C =degrees celsius

μS/cm = microsiemens per centimeter

cm/day = centimeters per day

cm/sec = centimeters per second

ft² = square feet

ft/day = feet per day

ft/ft = foot per foot

ft/yr = feet per year

gm/cm³ = grams per cubic centimeterkg of CaCO₃ per mg = kilograms of calcium carbonate per milligram

lb = pounds

meq/100 g = milliequivalents per 100 grams

mg/kg = milligrams per kilogram

mg/L = milligrams per liter

m/m = meters per meters

mV = millivolts

m/yr = meters per year

su = standard pH units

wt/wt H₂ = concentration molecular hydrogen, weight per weight

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

RESET DEFAULT

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 5

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	1,730	1,730	7.85E+08	1,338
Sodium Lactate Product (60 percent solution)	1.0	1,730	3,589	7.85E+08	1,338
Molasses (assuming 60 percent solution)	1.0	1,643	2,739	7.45E+08	1,271
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	1,730	2,163	7.85E+08	1,339
Ethanol Product (assuming 80% ethanol by weight)	1.0	885	1,106	4.01E+08	684
	1.0	1,194	1,706	5.42E+08	924
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	1,311	1,311	5.95E+08	812
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	673	673	3.05E+08	521
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	673	1,122	3.05E+08	521

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: **Hangar K, CCAFS, Florida**

1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	60	feet	18	meters
Length (parallel to groundwater flow)	65	feet	19.8	meters
Saturated Thickness	10	feet	3.0	meters
Design Period of Performance	5	years	5	years

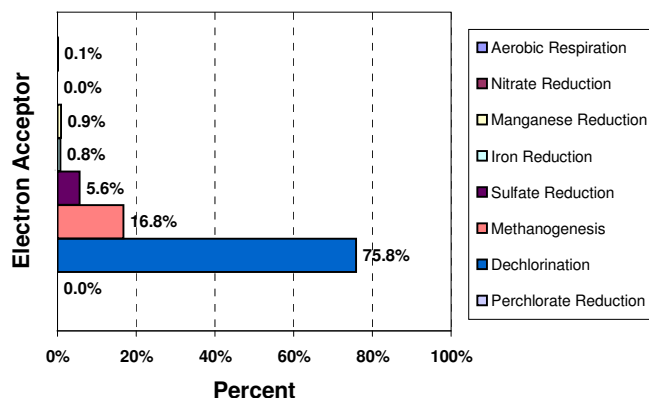
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.35	percent	0.35	percent
Effective Porosity	0.25	percent	0.25	percent
Average Aquifer Hydraulic Conductivity	10	ft/day	3.5E-03	cm/sec
Average Hydraulic Gradient	0.001	ft/ft	0.001	m/m
Average Groundwater Seepage Velocity	0.04	ft/day	1.4E-05	cm/sec
Average Groundwater Seepage Velocity	15	ft/yr	4.5	m/yr
Total Treatment Zone Pore Volume	72,950	gallons	276,136	liters
Groundwater Flux (per year)	16,386	gallons/year	62,024	liters/year
Total Groundwater Volume Treated (over entire design period)	154,877	gallons total	586,258	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	0.1%	0.081
Nitrate Reduction	0.0%	0.006
Sulfate Reduction	5.6%	4.340
Manganese Reduction	0.9%	0.711
Iron Reduction	0.8%	0.583
Methanogenesis	16.8%	12.989
Dechlorination	75.8%	58.711
Perchlorate Reduction	0.0%	0.000
Totals:	100.00%	77.42

Hydrogen demand in pounds/gallon:	5.00E-04
Hydrogen demand in grams per liter:	5.99E-02

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor =****1.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	3,589	326	1,338	as lactic acid
2. Molasses Product	2,739	228	1,271	as sucrose
3. Fructose Product	2,163	193	1,339	as fructose
4. Ethanol Product	1,106	160	684	as ethanol
5. Sweet Dry Whey (lactose)	1,706	sold by pound	924	as lactose
6. HRC®	1,311	sold by pound	812	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	673	86	521	as soybean oil
8. Emulsified Vegetable Oil	1,122	144	521	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

SITE SUMMARY

Area C, Alliant Techsystems, Inc. (ATK), Elkton, Maryland

For: Project Files for ESTCP Substrate Loading Study (Project No. 745255)

Revision: 08 July 2009

SITE IDENTIFICATION

Area C, Alliant Techsystems, Inc. (ATK), Elkton, MD (formerly Confidential Perchlorate Site) (ESTCP ER-0221)

CONTAMINANT SOURCE

<i>COC</i>	<i>Max. Conc.</i>	<i>DNAPL Present?</i>	<i>Notes</i>
Perchlorate	20,000 µg/L	No	Ref (1)
1,1,1-TCA	17,000 µg/L	No	Ref (1)
1,1-DCA	62 µg/L	No	Ref (1)
1,1-DCE	1,200 µg/L	No	Ref (1)
PCE	110 µg/L	No	Ref (1)
TCE	210 µg/L	No	Ref (1)
<i>cis</i> -1,2-DCE	10 µg/L	No	Ref (1)

Note: VC and *trans*-1,2-DCE were not detected at concentrations above 20 µg/L during the baseline sampling event.

SUBSTRATE DESIGN/INSTALLATION INFORMATION

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
Project Scale	Pilot	No change	
Substrate Type	EOS598	No change	EOS® concentrate consisted of approx 60% soybean oil, 24% water, 2% yeast extract, 10% emulsifier, 1% lactic acid, and 3% sodium lactate.
Number of Injection Points (IP)	10	No change	
IP Spacing Information	5 feet	No change	
Injection Date	October 2003	No change	
Injection Interval (depth bgs)	5-15 feet	No change	

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
Substrate Loading	110 gallons of EOS598 concentrate mixed with 422 gallons of water (532 gallons total), followed by a water chase.	No change	Mixed at a ration of 1:4 EOS [®] to water. Water supply was from an air stripper groundwater treatment system.
Injection Rate	1 gpm	No change	Injection pressure <5 psi.
Basis for Loading Rate	EOS [®] Bioremediation Design Software		
Injection amendment?	No	No change	
Pre-injection Specified?	Yes	No change	
Type of pre-injection	Sodium bromide tracer test	No change	500-mg/L solution
Post-injection Specified?	Yes	No change	
Type of post-injection	Water	No change	
Volume of post-injection	Average of 165 gallons per injection point, 1,648 gallons total	No change	

MONITORING INFORMATION

<i>Sample Collection Date (Reference)</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Reference</i>
April 2003	Yes	Yes	Yes	No	Ref (1,2)
September 2003	Yes	Yes	Yes	No	Ref (1,2)
October 2003	Yes	Yes	Yes	No	Ref (1,2)
November 2003	Yes	Yes	Yes	No	Ref (1,2)
December 2003	Yes	Yes	Yes	No	Ref (1,2)
February 2004	Yes	Yes	Yes	No	Ref (1,2)
July 2004	No	No	Yes	No	Ref (1,2)
September 2004	Yes	Yes	Yes	No	Ref (1,2)
April 2005	Yes	Yes	Yes	No	Ref (1,2)
October 2005	Yes	Yes	Yes	No	Ref (1,2)
March 2006	Yes	Yes	Yes	No	Ref (1,2)
November 2006	Yes	Yes	Yes	No	Ref (1,2)
April 2007	Yes	Yes	Yes	No	Ref (1,2)

REFERENCES

- (1) Solutions, IES. 2006. *Edible Oil Barriers for Treatment of Perchlorate Contaminated Groundwater*. Prepared for Environmental Security Technology Certification Program (ESTCP), Arlington, Virginia. 16 February. **(Final Report)**
- (2) Solutions, IES. 2008. *Technical Report Addendum, Edible Oil Barriers for Treatment of Perchlorate Contaminated Groundwater*. Prepared for Environmental Security Technology Certification Program (ESTCP), Arlington, Virginia. March. **(Technical Report Addendum)**

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates calculated or designed?

The calculations used for this demonstration were based on use of the EOS[®] Bioremediation design software (Appendix D and E of Solutions IES [2006]). Solutions-IES determined the amount of EOS[®] product to inject based on 1) the oil required for biodegradation (stoichiometric demand and organic carbon released), and 2) the oil retention by the aquifer sediment. The oil required for biodegradation was determined by first calculating the oil demand based on concentrations of native electron acceptors (dissolved oxygen, nitrate, and sulfate), concentrations of contaminants to be treated (primarily perchlorate and 1,1,1-TCA), the expected levels of organic carbon to be released from the barrier (typically 50 to 100 mg/L TOC), and estimated concentrations of reduced compounds produced (dissolved iron, manganese, methane). The oil requirement was then calculated by multiplying the groundwater flux through the barrier by the design life and the oil demand.

Data for the site were entered into the EOS[®] spreadsheet, and it was determined that 2 drums of EOS598 product were required for biodegradation based on a 3-year design life. The design life was limited to 3 years so that oil depletion and reduced treatment efficiency could be observed within the timeframe of the demonstration.

The second method evaluated the product requirement based on oil retention. To form a permeable biobarrier with emulsified oil, the sediments within the barrier should be uniformly coated with oil. The oil retention by the sediment was determined using the following equation (Solutions IES, 2006):

$$\text{Oil required} = x * y * z * \rho B * OR$$

Where, x = Treatment zone length parallel to groundwater flow (ft)

y = Design width perpendicular to groundwater flow (ft)

z = Effective height (ft)

ρB = Sediment bulk density (lb/ft³)

OR = Effective oil retention (lb oil/lb sediment)

The pilot test barrier was designed to be 50 feet wide perpendicular to groundwater flow (y). The effective height of the barrier was estimated to be between 5 and 10 feet (z). Although they injected into a 10-foot zone, the site lithology indicated 5 feet of higher permeability material where most of the injected material would likely be distributed. The length of the barrier parallel to groundwater flow was determined based on the desired contact time. The barrier was designed to provide a contact time of 30 days. Based on groundwater velocity data for the site, a design length of 5 feet (x) was used. The sediment bulk density was estimated to be 120 lb/ft³, and the effective oil retention was determined to be between 0.001 and 0.002 from laboratory column tests. Using these numbers, the oil required for retention by the sediment was calculated to be between 150 and 600 lbs, which is equivalent to between 1 and 3 drums of EOS[®] product.

Solutions-IES also calculated to the total volume of water and emulsion that needed to be injected to create the desired treatment zone to be one pore volume of the treatment zone. Based

on these calculations, two 55-gallon drums of EOS598 and 2,200 gallons total volume (water and emulsion) were injected.

2. What modifications to the substrate amendment protocol were required (e.g., concentration and frequency for soluble substrates; and depletion and additional injection of slow-release substrate types such as HRC[®] and EVO).

No modifications were required. The application had an effective life span of 2.5 to 3.5 years based on depletion of TOC, versus the design life of 3 years. The effective lifespan of the application may have been longer except that a higher rate of groundwater flow than anticipated was observed after injection.

3. Evaluation from Substrate Demand Tool

Site data were input into the substrate demand tool (attached). The substrate demand to treat 814,453 gallons (3,082,954 liters) of groundwater over the 3 year design life was calculated by the tool to be 53.9 pounds of molecular hydrogen, or 6.62E-05 pounds per gallon. (7.93E-03 grams per liter) of groundwater treated. This hydrogen demand could be met by 469 pounds of pure soybean oil, or by 100 gallons of emulsified vegetable oil product assuming the product is 60 percent oil by weight. Based on the quantity of substrate applied at the site (110 gallons of product), sufficient substrate was applied to meet the estimated hydrogen demand. This calculation may be biased high, as it assumes a constant rate of groundwater flow for the rate observed during operation of the extraction trench.

The primary electron accepting process was calculated to be sulfate reduction (29.3%), followed by methanogenesis (25.4%), nitrate reduction (11.7%), reduction of perchlorate (8.8%), manganese reduction (6.9%), iron reduction (6.8%), dechlorination of chlorinated solvents (6.7%), and aerobic respiration (4.3%).

In comparison, the EOS software for the initial design calculated a substrate demand of 28 pounds of molecular hydrogen, plus 176 pounds of dissolved organic carbon (DOC) released (Appendix D of Solutions IES, 2006). The primary difference in the estimated stoichiometric demand (28 pounds) was that a much lower rate of groundwater flow was estimated than measured during the demonstration. The EOS design tool also estimates that 0.18 pounds of hydrogen is produced per pound of soybean oil, while the substrate demand tool more conservatively estimates that 0.115 pounds of hydrogen is produced per pound of soybean oil.

PERFORMANCE OBJECTIVES

No. 1: Ability to Uniformly Distribute Substrate : Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

Substrate at the Area C Site was successfully distributed around the injection wells. Concentrations of TOC in the five injection wells that were monitored at 68 days after injection ranged from 24.8 to 96.9 mg/L, and averaged 57.2 mg/L. By approximately 2 years after injection, concentrations of TOC in the injection wells had consistently declined to a range of 12.3 to 62.6 mg/L, averaging 34.7 mg/L. Concentrations of TOC were also elevated in the

downgradient monitoring wells after injection. There were no apparent limitations to injection of the emulsified vegetable oil product.

No. 2: Achieving Optimal Geochemical Conditions

Successful geochemical conditions for stimulating anaerobic degradation of chlorinated solvents is defined as when the groundwater environment is highly anaerobic with DO less than 0.5 mg/L, ORP is less than -200 millivolts (mV), sulfate is reduced by more than 50 percent relative to background conditions, and methane is greater than 1.0 mg/L. These criteria may not apply in all cases.

Geochemical data collected at the site confirmed that anaerobic conditions were quickly established in the treatment area. In general, nitrate and sulfate concentrations decreased in the injection and downgradient wells, while ferrous iron and manganese concentrations increased. Methane concentrations increased to greater than 1 mg/L approximately 1 year after injection indicating methanogenic conditions were achieved within the biobarrier.

ORP in the injection wells was typically in the range from -50 to -150 mV, with the exception of anomalous data collected in February 2004 at 4 months post injection. It is unclear why lower redox levels could not be achieved, but lower ORP conditions were not necessary for effective treatment of perchlorate.

No. 3: Remediation Effectiveness: Evaluate efficiency in removal of VOCs based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Determine “threshold” concentrations of dissolved organic carbon that represent the minimum levels required to sustain complete reductive dechlorination.

The success of the application is evaluated by comparing concentrations to site-specific performance criteria, if established. Otherwise, a reduction in contaminant concentration of 99 percent or greater (over two orders of magnitude) is considered successful. For chlorinated aliphatic hydrocarbons (CAHs, or chlorinated solvents) where production of regulated intermediate dechlorination products may occur, a reduction in the total molar concentration of CAHs of greater than 90 percent is considered to be a success.

Perchlorate concentrations in the injection wells were reduced to below detection (<4 µg/L) within 5 days of injection, but increased to an average of 89 µg/L at 68 days post injection and remained above that level for the duration of the pilot test. However, removal efficiencies in the injection wells remained above 80 percent through 36 months of post-injection monitoring. Better overall reductions were observed in the downgradient wells, ranging from 97.1 to 99.9 percent from 1 to 42 months post injection. Maximum efficiencies were observed during both the first 4 months and during a period between year 2 and 3 when groundwater flow velocity slowed due to shutdown of the downgradient groundwater extraction system. After 3.5 years post-injection, residual TOC was limited and the resumption of pump and treat system operation resulted in a drop in perchlorate removal efficiency.

The emulsified oil substrate PRB was also effective in enhancing reductive dechlorination of 1,1,1-TCA, PCE, and TCE. Increases in the concentration of daughter products (1,2-DCA, CA, cis-1,2-DCE, VC and ethene) were observed. Dechlorination efficiency reached a maximum

between year 2 and 3, when groundwater flow velocity slowed and contact time in the biobarrier increased. Concentrations of chlorinated solvents did not approach regulatory drinking water criteria, although that was not a primary performance measure for the demonstration.

No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

Secondary water quality parameters that were evaluated for the Area C Site include pH and dissolved metals (iron, manganese, and arsenic).

Summary of Secondary Water Quality – Area C, ATK, Elkton, Maryland

Parameter	Comparison Criteria	Background (Upgradient)	Treatment Zone	Down-gradient	Issues?
pH	<6.5 or >8.5 (b)	5.5 to 6.9	5.2 to 7.0	5.4 to 7.7	None, remained similar to background
Dissolved Iron (mg/L)	0.3 (b)	<0.5 to 1.9	Up to 78 (7 or less at 42 months)	Up to 37 (7 or less at 42 months)	Potential – downgradient extraction system was shut down
Dissolved Manganese (mg/L)	0.05 (b)	0.13 to 0.36	Up to 16 (<2 at 42 months)	Up to 46 (4 or less at 42 months)	Potential – background above criteria and contributed to shut down of extraction system
Arsenic (mg/L)	0.01 (a)	<0.010 to 0.010	<0.010 to 0.021 (<0.010 at 42 months)	<0.010 to 0.040 (<0.010 at 42 months)	No – only a few isolated detections greater than criteria

Notes:

Background values for dissolved metals from upgradient well SMW-2.

Treatment zone values for dissolved metals from IW-3 and IW-7 (post-injection).

Downgradient values for dissolved metals from MW-6, SMW-4, and SMW-6 (post-injection).

mg/L = milligrams per liter.

Criteria based on (a) USEPA MCL; (b) USEPA Secondary Standard; or (c) USEPA Region 9 PRG.

pH. pH remained relatively stable from pre-injection to post-injection for upgradient, injection, and downgradient well locations, and an adverse decrease in pH was not observed.

Dissolved metals. Dissolved iron, manganese, and arsenic were analyzed for select upgradient, injection, and downgradient well locations. Arsenic was typically less than the regulator criterion of 0.010 mg/L, with only a few isolated detections exceeding the criterion.

Both upgradient and treatment zone concentrations of dissolved manganese and ferrous iron were typically above respective USEPA recommended secondary drinking water quality standards. After injection, a substantial increase in dissolved iron in the injection wells was observed, with a maximum concentration of 78 mg/L measured in IW-7 at Day 35. Increased levels of dissolved iron were also detected in the downgradient monitoring wells, but to a lesser extent than the changes observed in the injection wells. An increase in dissolved manganese was also observed in all of the injection and downgradient wells following injection. During the extended monitoring period, iron and manganese levels did decline as the substrate was depleted, but remained well above the comparison criteria.

More importantly, an interceptor trench for an air stripper treatment system at the site is located approximately 50 feet downgradient of the biobarrier. During the demonstration, increased fouling of the air stripper was observed and the stripper was shut down in early 2005. The increased fouling likely resulted from the increased levels of dissolved iron or from increased biofouling as a result of enhanced microbial activity in the groundwater and/or elevated biological oxygen demand (BOD) in the air-stripper influent.

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

A reduction of less than 50 percent in the average hydraulic conductivity within the reaction zone is considered to be acceptable. The impacts of the emulsified oil substrate injection on aquifer permeability were evaluated by comparing pre- and post-injection hydraulic conductivity values and pre- and post-injection bromide tracer test results. The average hydraulic conductivity in the upgradient well ranged from 0.91 to 8.80 ft/day, and in general increased towards the end of the demonstration. This may be due to repeated purging of the wells during sampling which acted to remove additional fines. The average hydraulic conductivity in the biobarrier decreased from 40.1 ft/day pre-injection to 8.53 ft/day at 18 months post-injection, then stabilized with an average hydraulic conductivity of 10.96 ft/day at 42 months post-injection. This represents a decrease in 72 percent from pre-injection to 42 months post-injection.

Similarly, the average hydraulic conductivity in the downgradient monitoring wells decreased from 31.59 ft/day pre-injection to 16.56 ft/day at 18 months post-injection, then increased with an average hydraulic conductivity of 24.09 ft/day at 42 months post-injection. This represents a decrease in 24 percent from pre-injection to 42 months post-injection. Although hydraulic conductivity in the injection wells decreased by greater than 50%, the average hydraulic conductivity downgradient of the biobarrier was typically higher than both the upgradient and injection wells. In general, hydraulic conductivity and groundwater flow was not thought to be adversely affected by injection of the emulsified oil.

No. 6: Substrate Persistence and Long-Term Effectiveness

Concentrations of TOC in groundwater increased immediately after EOS[®] injection as the oil-based substrate sorbed to aquifer sediments. Concentrations of TOC remained elevated for 24 months (2 years). By 30 months after injection, TOC levels in the injection wells dropped below 5 mg/L, a threshold that was used to suggest that the bioavailable organic carbon had been depleted. Results from a mass balance analysis indicates that 65% of the injected organic carbon

had been consumed prior to the decline in TOC, indicating relatively efficient use of the injected substrate. When the residence time in the biobarrier increased between 2 and 3 years post injection due to shut down of the groundwater extraction trench, some of the highest removal efficiencies for both perchlorate and chlorinated solvents were achieved. At 42 months after EOS[®] injection, 76% of the injected carbon had been accounted for. Therefore, monitoring over 42 months indicates that the biobarrier was effective in treating both perchlorate and chlorinated solvents for 2.5 to 3.5 years. Increased contact time in the PRB was shown to be desirable for both utilizing residual organic substrate and achieving regulatory cleanup goals.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

No modifications were required, and the effective life span of the application was approximately 2.5 to 3.5 years. For a full-scale biobarrier application, additional injections may be required to sustain effective treatment in the biobarrier for periods greater than approximately 3 years.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

The maximum efficiency of perchlorate removal was observed during the first 4 months of operation when concentrations of TOC were high, and during a period between 2 and 3 years post-injection when groundwater flow velocity slowed due to shutdown of the downgradient groundwater extraction system. After 3.5 years, residual TOC was limited and the resumption of groundwater extraction resulted in a drop in perchlorate removal efficiency. Perchlorate concentrations 20 feet downgradient of the biobarrier did remain one to two orders of magnitude less than the concentrations entering the biobarrier over the entire 42-month period. Dechlorination efficiency reached a maximum between 2 and 3 years post injection, also when groundwater flow velocity slowed and contact time in the treatment zone increased due to shut down the downgradient extraction trench.

Therefore, the effectiveness of the biobarrier was proportional to the rate of groundwater flow, which was higher than anticipated during operation of the groundwater extraction system. This could be compensated for by implementing a biobarrier with a longer effective contact time (e.g., adding an additional row of injection wells).

COST ASSESSMENT

Detailed cost data for this demonstration have not yet been published, although the technical reports indicate these data will be included in a future Cost and Performance Report. Some cost analysis was provided in the demonstration reports.

The pilot test biobarrier cost approximately \$23,200 to install and was effective in treating perchlorate and chlorinated solvent impacted groundwater for over 2 years. Over a 2 year effective life, the barrier treated 540,200 gallons of groundwater, or approximately 740 gallons per day. Therefore, the pilot-scale biobarrier cost \$0.043/gallon treated or \$46/square foot of barrier.

The costs associated with the extended monitoring period were \$12,000 for four additional sampling events during the 24-month period (\$48,000 total). There was no additional O&M, because the objective of the extended monitoring was to observe and evaluate substrate depletion. Some additional costs were incurred to prepare the technical report addendum.

The cost of a full-scale emulsified oil biobarrier at the Area C Site was estimated to be approximately \$38,000, which is equivalent to \$19/square-foot of barrier, or \$0.02/gallon of groundwater treated. The difference between the pilot test and a full-scale system is primarily due to an economy of scale.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** Area C, ATK Facility, Elkton, Maryland

NOTE: Unshaded boxes are user input.				
	Values	Range	Units	User Notes
1. Treatment Zone Physical Dimensions				
Width (Perpendicular to predominant groundwater flow direction)	50	1-10,000	feet	
Length (Parallel to predominant groundwater flow)	5	1-1,000	feet	
Saturated Thickness	10	1-100	feet	5 to 15 feet bgs
Treatment Zone Cross Sectional Area	500	--	ft ²	
Treatment Zone Volume	2,500	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	4,676	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	3,367	--	gallons	
Design Period of Performance	3.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	25%	.05-50	percent	
Effective Porosity	18%	.05-50	percent	From Table 4-1 of Solutions IES (2008)
Average Aquifer Hydraulic Conductivity	22	.01-1000	ft/day	From Table 4-1 of Solutions IES (2008)
Average Hydraulic Gradient	0.009	0.0001-0.1	ft/ft	Average first 18 months
Average Groundwater Seepage Velocity through the Treatment Zone	1.10	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	401.5	--	ft/yr	Initially estimated as 80 ft/yr
Average Groundwater Flux through the Treatment Zone	270,362	--	gallons/year	
Soil Bulk Density	1.65	1.4-2.0	gm/cm ³	silty sand and gravel
Soil Fraction Organic Carbon (foc)	0.01%	0.01-10	percent	Ranged from <1.0 to 920 mg/kg
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				From Table 3-5 of Solutions IES (2006)
Oxygen	2.7	0.01 to 10	mg/L	Ranged from 1.27 to 5.83
Nitrate	9.50	0.1 to 20	mg/L	Ranged from <0.5 to 13.9 mg/L
Sulfate	28	10 to 5,000	mg/L	Ranged from 18.3 to 34.4 mg/L
Carbon Dioxide (estimated as the amount of Methane produced)	4.0	0.1 to 20	mg/L	Methane Produced - Maximum 8.759 mg/L
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	15	0.1 to 20	mg/L	Manganese Produced - Maximum 46 mg/L
Iron (III) (estimated as the amount of Fe (II) produced)	30	0.1 to 20	mg/L	Ferrous Iron Produced - Maximum 78 mg/L
4. Contaminant Electron Acceptors				
				From Table 3-4 of Solutions IES (2006)
Tetrachloroethene (PCE)	0.053	--	mg/L	Ranged from 0.025 to 0.11 mg/L
Trichloroethene (TCE)	0.094	--	mg/L	Ranged from 0.028 to 0.21 mg/L
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.610	--	mg/L	Ranged from 0.276 to 1.21 mg/L total DCE
Vinyl Chloride (VC)	0.000	--	mg/L	Not detected
Carbon Tetrachloride (CT)	0.000	--	mg/L	Not reported
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	Not reported
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	Not reported
Chloromethane	0.000	--	mg/L	Not reported
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	Not reported
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	11.000	--	mg/L	Ranged from 5.7 to 17 mg/L
Dichloroethane (1,1-DCA and 1,2-DCA)	0.030	--	mg/L	Ranged from 0.007 to 0.062 mg/L
Chloroethane	0.000	--	mg/L	Not detected
Perchlorate	8.600	--	mg/L	Ranged from 3.1 to 20 mg/kg
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				From Tables 3-5 and 4-11 of Solutions IES (2006)
Oxidation-Reduction Potential (ORP)	132	-400 to +500	mV	Baseline ranged from +102 to +154 mV
Temperature	21	5.0 to 30	°C	Ranged from 19.2 to 23.4 °C
pH	5.9	4.0 to 10.0	su	Ranged from 5.4 to 6.2
Alkalinity	NA	10 to 1,000	mg/L	Not analyzed
Total Dissolved Solids (TDS, or salinity)	NA	10 to 1,000	µs/cm	Not analyzed
Specific Conductivity	220	100 to 10,000	µs/cm	Ranged from 145 to 342 µs/cm
Chloride	14	10 to 10,000	mg/L	Ranged from 6.6 to 18 mg/L
Sulfide - Pre injection	NA	0.1 to 100	mg/L	Not analyzed
Sulfide - Post injection	NA	0.1 to 100	mg/L	Not analyzed
B. Aquifer Matrix				
Total Iron	NA	100 to 10,000	mg/kg	Not analyzed
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	Not analyzed
Neutralization Potential	NA	1.0 to 100	Percent as CaCO ₃	Not analyzed

NOTES:

Baseline data from Tables 3-4, 3-5 and 4-11 of Solutions IES (2006)

Values for methane, manganese, and ferrous iron are post-injection from Table 4 of Appendix A of Solutions IES (2008).

Table S.2 Substrate Calculations in Hydrogen Equivalents**Site Name:** Area C, ATK Facility, Elkton, Maryland

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
50	1-10,000	feet
5	1-1,000	feet
10	1-100	feet
500	--	ft ²
2,500	--	ft ³
3,367	--	gallons
3.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.25	.05-50	
0.18	.05-50	
22	.01-1000	ft/day
0.009	0.1-0.0001	ft/ft
1.10	--	ft/day
401.5	--	ft/yr
270,362	--	gallons/year
1.65	1.4-2.0	gm/cm ³
0.0001	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
2.7	0.08	7.94	0.01	4
9.5	0.27	10.25	0.03	5
27.7	0.78	11.91	0.07	8
4.0	0.11	1.99	0.06	8
Soluble Competing Electron Acceptor Demand (lb.)			0.16	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
15.0	101.94	27.25	3.74	2
30.0	203.89	55.41	3.68	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			7.42	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.053	0.00	20.57	0.00	8
0.094	0.00	21.73	0.00	6
0.610	0.02	24.05	0.00	4
0.000	0.00	31.00	0.00	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
11.000	0.31	22.06	0.01	6
0.030	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
8.600	0.24	12.33	0.02	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			0.03	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x C_{gw})
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	0.00	0.00	20.57	0.00	8
107	0.00	0.00	21.73	0.00	6
45	0.00	0.00	24.05	0.00	4
3.0	0.00	0.00	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.12	0.03	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			0.00		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	2.7	6.16	7.94	0.78	4
Nitrate (denitrification)	9.5	21.43	10.25	2.09	5
Sulfate	27.7	62.49	11.91	5.25	8
Carbon Dioxide (estimated as the amount of Methane produced)	4	9.02	1.99	4.53	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				12.6	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.053	0.12	20.57	0.01	8
Trichloroethene (TCE)	0.094	0.21	21.73	0.01	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.610	1.38	24.05	0.06	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	11.000	24.82	22.06	1.12	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.030	0.07	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	8.600	19.40	12.33	1.57	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				2.77	

Initial Hydrogen Requirement First Year (lb)**23.0****Total Life-Cycle Hydrogen Requirement (lb)****53.9****5. Design Factors**

Microbial Efficiency Uncertainty Factor
Methane and Solid-Phase Electron Acceptor Uncertainty
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)

2X - 4X

2X - 4X

1X - 3X

Design Factor**1.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)****53.9****6. Acronyms and Abbreviations**

°C =degrees celsius

μS/cm = microsiemens per centimeter

cm/day = centimeters per day

cm/sec = centimeters per second

ft² = square feet

ft/day = feet per day

ft/ft = foot per foot

ft/yr = feet per year

gm/cm³ = grams per cubic centimeterkg of CaCO₃ per mg = kilograms of calcium carbonate per milligram

lb = pounds

meq/100 g = milliequivalents per 100 grams

mg/kg = milligrams per kilogram

mg/L = milligrams per liter

m/m = meters per meters

mV = millivolts

m/yr = meters per year

su = standard pH units

wt/wt H₂ = concentration molecular hydrogen, weight per weight

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

RESET DEFAULT

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 3

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	1,204	1,204	5.46E+08	177
Sodium Lactate Product (60 percent solution)	1.0	1,204	2,497	5.46E+08	177
Molasses (assuming 60 percent sucrose)	1.0	1,144	1,906	5.19E+08	168
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	1,204	1,505	5.46E+08	177
Ethanol Product (assuming 80% ethanol by weight)	1.0	616	770	2.79E+08	91
	1.0	831	1,187	3.77E+08	122
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	913	913	4.14E+08	107
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	469	469	2.13E+08	69
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	469	781	2.13E+08	69

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: **Area C, ATK Facility, Elkton, Maryland**

1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	50	feet	15	meters
Length (parallel to groundwater flow)	5	feet	1.5	meters
Saturated Thickness	10	feet	3.0	meters
Design Period of Performance	3	years	3	years

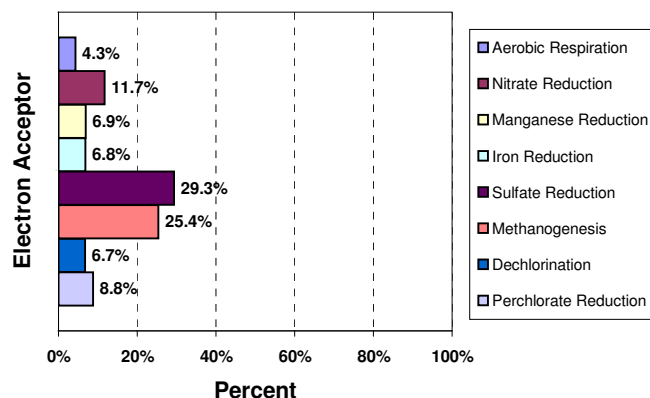
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.25	percent	0.25	percent
Effective Porosity	0.18	percent	0.18	percent
Average Aquifer Hydraulic Conductivity	22	ft/day	7.8E-03	cm/sec
Average Hydraulic Gradient	0.009	ft/ft	0.009	m/m
Average Groundwater Seepage Velocity	1.10	ft/day	3.9E-04	cm/sec
Average Groundwater Seepage Velocity	402	ft/yr	122.4	m/yr
Total Treatment Zone Pore Volume	3,367	gallons	12,745	liters
Groundwater Flux (per year)	270,362	gallons/year	1,023,403	liters/year
Total Groundwater Volume Treated (over entire design period)	814,453	gallons total	3,082,954	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	4.3%	2.337
Nitrate Reduction	11.7%	6.299
Sulfate Reduction	29.3%	15.807
Manganese Reduction	6.9%	3.741
Iron Reduction	6.8%	3.680
Methanogenesis	25.4%	13.661
Dechlorination	6.7%	3.618
Perchlorate Reduction	8.8%	4.740
Totals:	100.00%	53.88

Hydrogen demand in pounds/gallon:	6.62E-05
Hydrogen demand in grams per liter:	7.93E-03

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor =****1.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	2,497	227	177	as lactic acid
2. Molasses Product	1,906	159	168	as sucrose
3. Fructose Product	1,505	134	177	as fructose
4. Ethanol Product	770	112	91	as ethanol
5. Sweet Dry Whey (lactose)	1,187	sold by pound	122	as lactose
6. HRC®	913	sold by pound	107	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	469	60	69	as soybean oil
8. Emulsified Vegetable Oil	781	100	69	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

SITE SUMMARY DATA SHEET**SA 17, NTC Orlando, Florida**

For: Project Files for ESTCP Substrate Loading Study (Job No. 745255)

Revision: 01 May 2009

SITE IDENTIFICATION

SA-17, Naval Training Center Orlando, Florida

CONTAMINANT SOURCE

<i>COC</i>	<i>Max. Conc.</i>	<i>DNAPL Present?</i>	<i>Notes</i>
TCE	Up to 577,000 µg/L	Suspected	Ref (1)
<i>cis</i> -1,2-DCE	Below detection to 2460 µg/L	--	Ref (1)
VC	Below detection to 255 µg/L	--	Ref (1)

Notes: 1. ISCO used to reduce contaminant concentrations as interim remedial action prior to enhanced bioremediation being selected as a final remedy.
2. VC concentrations consistently reported as less than 5 µg/L, with many measurements below detection.

SUBSTRATE DESIGN/INSTALLATION INFORMATION

<i>Parameter</i>	<i>Original Design</i>	<i>Actual Installation</i>	<i>Notes/Reference</i>
Project Scale	Full Scale		
Substrate Type	EOS 598 B42		
Number of Injection Points (IP)	12 IPs (6 IPs in Zone A/B; 6 IPs in Zone C) With two 4-inch Extraction Wells		Recirculation system designed to enhance EOS distribution within treatment zone
IP Spacing Information	IPs: Ring w/ 30' spacing; Extraction Wells in center, 23' from IPs		
Injection Date	N/A		
Injection Interval (depth bgs)	5-25 feet bgs (Zone A/B) 30-50 feet bgs (Zone C)		2" Sch. 40 PVC Wells
Substrate Loading	18 drums EOS total (990 gal EOS total)		
Substrate Loading Rate	1:9 EOS:water (10% EOS solution)		Injection rate: 0.5 to 1 gpm
Basis for Loading Rate	Stoichiometry using EOS Remediation software		Adsorptive capacity of aquifer (oil retention) used for final determination

<i>Parameter</i>	<i>Original Design</i>	<i>Actual Installation</i>	<i>Notes/Reference</i>
Injection amendment?	NaBr (tracer) NaHCO ₃ (pH buffer)		
Pre-injection Specified?	Yes		Designed to test tightness of injection and recirculation system
Type of pre-injection	Hydrant Water		
Volume of pre-injection	Unspecified		
Post-injection Specified?	Yes		
Type of post-injection	Extracted groundwater remaining in frac tank after injection		
Volume of post-injection	Unspecified		

Notes: 1. Design intended to encompass entire area where TCE concentrations are greater than 10,000 µg/L.

MONITORING INFORMATION

<i>Sample Collection Date (Reference)</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Have Copy? ^{a/}</i>
<i>This information is pending</i>					

REFERENCES

- (1) AGVIQ-CH2M Hill JV II. 2006. *Remedial Action Work Plan Injection and Recirculation of Emulsified Oil Substrate (EOS®) at Study Area 17, Former Naval Training Center Orlando, Orlando, Florida*. Prepared for U.S. Naval Facilities Engineering Command Southern Division. May. (**Injection Work Plan**)

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates calculated or designed?

The substrate loading rate was based on calculations using the EOS Remediation spreadsheet tool, including estimates of native electron acceptor demand and groundwater flux through a treatment zone 50 feet wide, 20 feet deep, and 50 feet long for both the upper zone and lower zone applications (Appendix F of Ref [1]). Data for the site were entered into the EOS Remediation spreadsheet tool, and it was determined that 1 drum of EOS598 product was required for stoichiometric demand and carbon loss in the upper zone based on a 5-year design life, and that 9 drums of EOS were required based on the adsorptive capacity of the soil. For the lower zone, 2 drums were required for the stoichiometric demand and carbon loss, and 9 drums were required based on the adsorptive capacity of the soil.

Nine (9) drums of product were selected for injection into each zone. The product was to be diluted at a 9:1 water to product ratio, and injected using recirculation until breakthrough was observed at the extraction wells. Only one injection was planned, and subsequent injections were not anticipated.

2. What modifications to the substrate amendment protocol were required (e.g., concentration and frequency for soluble substrates; and depletion and additional injection of slow-release substrate types such as HRC[®] and EVO).

This information is pending.

3. Evaluation from Substrate Demand Tool

Site data were input into the substrate demand tool (attached) for the Upper Zone A/B and Lower Zone C using the same contaminant and geochemical input parameter used in the EOS Remediation design tool. Hydrogen demand calculations are summarized below:

Tool	Stoichiometric Demand (lb hydrogen)	DOC Released (lb organic carbon)	Gallons Treated	Notes
Upper Zone A/B				
EOS Design Tool	23 lb	104 lb	95,660	DOC released approx. 4X stoichiometric demand
Substrate Requirements Tool	25 lb	--	96,685	No design factor applied.
Lower Zone C				
EOS Design Tool	35 lb	150 lb	138,934	DOC released approx. 4X stoichiometric demand
Substrate Requirements Tool	37 lb	--	138,971	No design factor applied.

The differences between the two tools is due to minor variations in the calculations used for determining electron acceptor demand.

Upper Zone A/B

Based on the substrate requirements tool, the substrate required to treat 95,685 gallons (362,199 liters) of groundwater over 5 years was 25.4 pounds of molecular hydrogen, or 2.66E-04 pounds per gallon (3.19E-02 grams per liter) of groundwater treated. This hydrogen demand could be met by 221 pounds of soybean oil, or by 47 gallons of emulsified oil product assuming the product is 60% oil by weight.

Similar values were calculated by the EOS design tool, where the hydrogen demand was estimated to be 23 pounds of molecular hydrogen,. However, the tool also calculated the amount of dissolved organic carbon (DOC) released from the treatment zone to be 104 pounds of organic carbon (equivalent to approximately 13 gallons of pure soybean oil), and estimated that 1 drum (55 gallons) of emulsified oil product was necessary to meet both the electron acceptor demand

and the carbon loss. Based on application of 9 drums of product and the calculated stoichiometric demand, the effective design factor for this application was approximately 10 times.

The primary electron accepting process was calculated to be sulfate reduction (65.9%), followed by methanogenesis (15.8%), dechlorination of chlorinated solvents (9.9%), nitrate reduction (3.1%), iron reduction (2.8%), aerobic respiration (2.0%), and manganese reduction (0.6%).

Lower Zone C

Based on the substrate requirements tool, the substrate required to treat 138,971 gallons (526,047 liters) of groundwater over 5 years was 37.10 pounds of molecular hydrogen, or 2.67E-04 pounds per gallon (3.20E-02 grams per liter) of groundwater treated. This hydrogen demand could be met by 323 pounds of soybean oil, or by 69 gallons of emulsified oil product assuming the product is 60% oil by weight.

Similar values were calculated by the EOS design tool, where the hydrogen demand was estimated to be 35 pounds of molecular hydrogen,. However, the tool also calculated the amount of DOC released from the treatment zone to be 150 pounds of organic carbon (equivalent to approximately 19 gallons of pure soybean oil), and estimated that 2 drums (110 gallons) of emulsified oil product was necessary to meet both the electron acceptor demand and the carbon loss. Based on application of 9 drums of product and the calculated stoichiometric demand, the effective design factor for this application was approximately 7.2 times.

The primary electron accepting process for the lower zone was calculated to be sulfate reduction (65.6%), followed by methanogenesis (15.7%), dechlorination of chlorinated solvents (7.5%), iron reduction (5.6%), nitrate reduction (3.0%), aerobic respiration (2.0%), and manganese reduction (0.6%).

PHASE II EVALUATION

Soil sampling was conducted at the SA-17, OU-2, and OU-4 sites at NTC Orlando as part of this demonstration. The intent of the sampling was to evaluate methods for determining potential oil retention. The soil analytical protocol is listed on Table 1 below. Collection of additional post-injection samples was planned by the Navy contractor, but was not conducted due to lack of available sampling equipment.

Soil physical data are listed in Table 2. Samples from the OU-4 site exhibited the highest percentage of sand (96.5 to 98.7 percent), while samples from the OU-2 site had the highest percentage of silt and clay (9.8 to 20.2 percent). Permeameter tests were conducted by the Shaw Group geotechnical laboratory using a slightly modified version of the EOS Design Tool protocol. The range of pre-injection permeability was highly variable, ranging from 1.1E-04 to 4.6E-08 cm/sec for all samples. After the EOS598 product was pumped through the permeameter and flushed with water, the percent reductions in conductivity ranged from 39 to 99.9 percent, or by up to four orders of magnitude. There was no apparent correlation between the percent reduction and percentage of silt/clay in the soil samples.

Soil chemical data are listed in Table 3. Concentrations of total organic carbon (TOC, in triplicate) were measured both prior to and after injection of the EOS product in the permeameters. The difference in TOC is used to estimate the percentage of oil retention on a

weight TOC per weight soil basis. For the SA-17 site, oil retention ranged from 0.80 percent to 5.45 percent, averaging 3.33 percent. For the OU-2 site, oil retention ranged from 1.29 percent to 5.0 percent, and averaged 2.89 percent. For the OU-4 site, oil retention ranged from 0.89 percent to 1.25 percent, averaging 1.07 percent. As could be expected, oil retention was lowest in the soil samples with the least amount of silt/clay (i.e., samples from OU-4).

Soil pH for all samples ranged from 6.3 to 7.9 standard pH units (su), while neutralization potential ranged from 6.7 to 14 percent equivalent units of calcium carbonate by weight. The observed pH values do not suggest that pH excursion would be an issue at these sites, although groundwater pH (56.4 to 6.3 at SA-17) indicates that low pH may be an issue.

Hydraulic conductivity for the SA-17 sites has been reported to average 4.7 ft/day (1.7×10^{-3} cm/sec) in the upper zone and 6.9 ft/day (2.4×10^{-3} cm/sec) in the lower zone. It is unclear why the conductivity values measured in the laboratory were significantly lower than reported for field measurements. The reductions in permeability may have also been influenced by biodegradation and fouling of the aquifer material after injection of the substrate mixtures.

The oil retention values appear to be relatively high compared to values presented with the Edible Oil Design Tool. Values posted in the tool show measured values of oil retention that range from 0.0004 grams oil per gram soil (0.04 percent) for a coarse gravelly sand to 0.0095 gm/gm (0.95 percent) for a laboratory blended sand with 12 percent silt and clay. The higher oil retention measured in this study may be an artifact of the very low permeability measured in the permeameter tests. In addition, the target volume of post-injection water flush (five pore volumes) was not achieved for all tests.

It is evident that additional refinement of the laboratory protocol to evaluate oil retention is necessary. Different permeameter test methods may be required for soils that are expected to have low permeability. In addition, the tests must be run over a relatively short duration (within a couple days) to avoid degradation of the oil after injection. Alternatively, the soil could be sterilized to avoid biodegradation of the oil.

Table 1
Soil Analytical Protocol for NTC Orlando, Florida

Analyte	Method/ Reference	SA-17	OU-2	OU-4
		Pre-Injection	Pre-Injection	Pre-Injection
Percent Solids	E160.1	2	4	2
Total Organic Carbon	SW9060A modified for soil matrix (in triplicate)	2	4	2
Oil and Grease	SW9071B using n-hexane extraction	1	2	1
PLFA for Oil	Microbial Insights SOP	1	1	1
Permeameter Test	Per ER-0626 Protocol	2 + 1 (one split sample)	4 + 2 (two split samples)	2 + 1 (one split sample)
Grain Size Analysis	ASTM D-422	2	4	2
Bulk Density	ASTM C-29	2	4	2
Neutralization Potential	Microseeps SOP-WC41	2	4	2
Soil pH	ASTM D-4972	2	4	2

Table 2
Soil Analytical Results - Soil Physical Data

Site Location/ Sample ID	Percent Moisture ASTM D 2216 ^{a/} (percent)	Specific Gravity ASTM D 854 (unitless)	Bulk Density ASTM D 2937 (pcf) ^{b/}	Dry Density ASTM D 2937 (pcf)	Percent Sand ASTM D 422 (percent)	Pecent Silt/Clay ASTM D 422 (percent)	Pre-Injection Permeability ASTM D 5084 (cm/sec) ^{c/}	Post-Injection Permeability ASTM D 5084 (cm/sec)	Percent EOS Product Injected -- (percent)	Percent Reduction -- (percent)
OU-2, NTC Orlando										
NTC-OU2-SB1-22-25	23.1	2.6556	121.5	98.7	89.5	10.5	4.6E-08	2.8E-08	12%	39.1%
NTC-OU2-SB1-22-25 (SPLIT)	19.7	2.6505	123.0	102.8	89.7	10.3	1.9E-06	1.4E-07	5%	92.6%
NTC-OU2-SB1-32-35	34.2	2.6591	115.5	86.1	79.8	20.2	3.1E-07	1.9E-08	12%	93.9%
NTC-OU2-SB2-22-25	22.1	2.6591	123.3	101.0	84.3	15.7	1.5E-07	5.3E-08	12%	64.7%
NTC-OU2-SB2-32-35	23.2	2.6476	118.1	95.9	89.7	10.3	1.2E-05	6.4E-08	12%	99.5%
NTC-OU2-SB2-32-35 (SPLIT)	21.4	2.6550	117.0	96.3	90.2	9.8	2.4E-06	1.2E-07	5%	95.0%
SA-17, NTC Orlando										
NTC-SA17-SB1-15-25	18.9	2.6424	123.2	103.6	91.5	8.5	8.1E-06	6.9E-08	12%	99.1%
NTC-SA17-SB1-15-25	15.7	2.6547	123.2	106.6	91.4	8.6	4.9E-07	4.8E-08	5%	90.2%
NTC-SA17-SB1-30-40	21.0	2.6469	117.9	97.4	94.5	5.5	1.2E-06	2.0E-10	12%	100.0%
OU-4, NTC Orlando										
NTC-OU4-SB1-9-14	18.1	2.6641	119.1	100.9	98.5	1.5	1.1E-04	4.7E-06	12%	95.7%
NTC-OU4-SB1-9-14 (SPLIT)	18.8	2.6557	118.6	99.9	98.7	1.3	4.9E-07	8.0E-08	5%	83.7%
NTC-OU4-SB1-25-30	20.4	2.6505	122.2	101.5	96.5	3.5	5.5E-05	2.3E-05	12%	58.2%

^{a/} ASTM D 2216 results are based on dry sample weight.

^{b/} pcf = pounds per cubic foot.

Table 3
Soil Analytical Results - Soil Chemical Data

Site Location/ Sample ID	Percent EOS	Natural TOC (mg/kg)	Post EOS TOC (mg/kg)	Difference In TOC (% by wt)	Soil pH (su)	Neutralization Potential (CaCO ₃ Equiv. in %)	Oil and Grease (mg/kg)	TOC (mg/kg)	Percent Solids (percent)
SA-17, NTC Orlando									
NTC-SA17-SB1-15-25	12%	626 J+	37,100	3.65%	6.9	10	<290	<30	83
		769 J+	38,200	3.74%	--	--	--	--	--
		818 J+	39,000	3.82%	--	--	--	--	--
		738	38,100	3.74%					
NTC-SA17-SB1-15-25 (SPLIT)	5%	804 J+	9,350	0.85%	--	--	--	--	--
		1,030 J+	8,480	0.75%	--	--	--	--	--
		880 J+	8,780	0.79%	--	--	--	--	--
		905	8,870	0.80%					
NTC-SA17-SB1-30-40	12%	<592 J-	51,100	5.05%	7.9	8.1	NA	<33	75
		604 J+	54,400	5.38%	--	--	--	--	--
		<592 J-	59,700	5.91%	--	--	--	--	--
		596	55,067	5.45%					
Average Oil Retention for SA-17:				3.33%					

(continued)

Table 3
Soil Analytical Results - Soil Chemical Data

Site Location/ Sample ID	Percent EOS	Natural TOC (mg/kg)	Post EOS TOC (mg/kg)	Difference In TOC (% by wt)	Soil pH (su)	Neutralization Potential (CaCO ₃ Equiv. in %)	Oil and Grease (mg/kg)	TOC (mg/kg)	Percent Solids (percent)
OU-2, NTC Orlando									
NTC-OU2-SB1-22-25	12%	1,410	25,100	2.37%	7.5	14	<300	250	79
		1,450	25,800	2.44%	--	--	--	--	--
		975 J+	21,800	2.08%	--	--	--	--	--
		3,835	24,233	2.30 %					
NTC-OU2-SB1-22-25 (SPLIT)	5%	1,860	20,200	1.83%	--	--	--	--	--
		1,020 J+	16,400	1.54%	--	--	--	--	--
		1,440	17,800	1.64%	--	--	--	--	--
		1,440	18,133	1.67 %					
NTC-OU2-SB1-32-35	12%	2,380	28,200	2.58%	7.7	8.7	NA	<33	75
		2,380	28,200	2.58%	--	--	--	--	--
		2,130	27,000	2.49%	--	--	--	--	--
		2,297	27,800	2.55 %					
NTC-OU2-SB2-22-25	12%	2,190	15,400	1.32%	6.3	6.7	NA	240	82
		1,810	15,600	1.38%	--	--	--	--	--
		2,050	13,800	1.18%	--	--	--	--	--
		2,017	14,933	1.29 %					
NTC-OU2-SB2-32-35	12%	1,760	48,400	4.66%	6.9	11	<380	800	71
		1,910	51,100	4.92%	--	--	--	--	--
		1,860	55,900	5.40%	--	--	--	--	--
		1,843	51,800	5.00 %					
NTC-OU2-SB2-32-35 (SPLIT)	5%	2,070	52,000	4.99%	--	--	--	--	--
		1,740	38,600	3.69%	--	--	--	--	--
		1,440	51,600	5.02%	--	--	--	--	--
		1,750	47,400	4.57 %					
Average Oil Retention for OU-2:				2.89 %					

(continued)

Table 3
Soil Analytical Results - Soil Chemical Data

Site Location/ Sample ID	Percent EOS	Natural TOC (mg/kg)	Post EOS TOC (mg/kg)	Difference In TOC (% by wt)	Soil pH (su)	Neutralization Potential (CaCO ₃ Equiv. in %)	Oil and Grease (mg/kg)	TOC (mg/kg)	Percent Solids (percent)
OU-4, NTC Orlando									
NTC-OU4-SB1-9-14	12%	683 J+	9,600	0.89%	7.7	12	<280	920	82
		792 J+	9,350	0.86%	--	--	--	--	--
		704 J+	9,990	0.93%	--	--	--	--	--
		726	9,647	0.89%					
NTC-OU4-SB1-9-14 (SPLIT)	5%	1,370	13,600	1.22%	--	--	--	--	--
		<597 J-	13,400	1.28%	--	--	--	--	--
		2,310	14,700	1.24%	--	--	--	--	--
		4,277	13,900	1.25%					
NTC-OU4-SB1-25-30	12%	1,910	13,700	1.18%	7.3	11	NA	1800	84
		2,650	13,000	1.04%	--	--	--	--	--
		2,950	12,500	0.96%	--	--	--	--	--
		2,503	13,067	1.06%					
Average Oil Retention for OU-4:				1.07%					

b/ J+ indicates the result is an estimated quantity, but the result may be biased high.

b/ J- indicates the result is an estimated quantity, but the result may be biased low.

PERFORMANCE OBJECTIVES (PENDING)

No. 1: Ability to Uniformly Distribute Substrate : Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

This information is pending.

No. 2: Achieving Optimal Geochemical Conditions

This information is pending.

No. 3: Remediation Effectiveness: Evaluate efficiency in removal of VOCs based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Determine “threshold” concentrations of dissolved organic carbon that represent the minimum levels required to sustain complete reductive dechlorination.

This information is pending.

No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

This information is pending.

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

This information is pending.

No. 6: Substrate Persistence and Long-Term Effectiveness

This information is pending.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

This information is pending.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

This information is pending. Control of pH is a critical issue at this site.

COST ASSESSMENT

3. COST ASSESSMENT

Cost data are not available for this site.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** Upper Zone A/B, NTC Orlando**NOTE:** Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	50	1-10,000	feet	
Length (Parallel to predominant groundwater flow)	50	1-1,000	feet	
Saturated Thickness	20	1-100	feet	5 to 25 feet bgs
Treatment Zone Cross Sectional Area	1000	--	ft ²	
Treatment Zone Volume	50,000	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	108,489	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	63,597	--	gallons	
Design Period of Performance	5.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	29%	.05-50	percent	
Effective Porosity	17%	.05-50	percent	
Average Aquifer Hydraulic Conductivity	4.7	.01-1000	ft/day	
Average Hydraulic Gradient	0.0005	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.01	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	5.0	--	ft/yr	
Average Groundwater Flux through the Treatment Zone	6,418	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm ³	Silty sand
Soil Fraction Organic Carbon (foc)	0.50%	0.01-10	percent	Assumed default value
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				Values used in EOS Remediation Tool
Oxygen	5.0	0.01 to 10	mg/L	
Nitrate	10.00	0.1 to 20	mg/L	
Sulfate	250	10 to 5,000	mg/L	
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	
B. Solid-Phase Native Electron Acceptors				Values used in EOS Remediation Tool
Manganese (IV) (estimated as the amount of Mn (II) produced)	5	0.1 to 20	mg/L	
Iron (III) (estimated as the amount of Fe (II) produced)	50	0.1 to 20	mg/L	
4. Contaminant Electron Acceptors				
				Values used in EOS Remediation Tool
Tetrachloroethene (PCE)	0.010	--	mg/L	
Trichloroethene (TCE)	15.000	--	mg/L	
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.010	--	mg/L	
Vinyl Chloride (VC)	0.010	--	mg/L	
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	100	-400 to +500	mV	Generally reducing conditions
Temperature	NA	5.0 to 30	°C	Not available, likely above 20 degrees Celsius
pH	5.9	4.0 to 10.0	su	Ranged from 5.4 to 6.3, inpart due to ISCO treatment
Alkalinity	100	10 to 1,000	mg/L	Ranged from 8.6 to 111 mg/L
Total Dissolved Solids (TDS, or salinity)	NA	10 to 1,000	mg/L	Not available
Specific Conductivity	NA	100 to 10,000	µs/cm	Not available
Chloride	NA	10 to 10,000	mg/L	Not available
Sulfide - Pre injection	0.1	0.1 to 100	mg/L	Little sulfide detected at the site.
Sulfide - Post injection	NA	0.1 to 100	mg/L	Not available
B. Aquifer Matrix				
Total Iron	NA	100 to 10,000	mg/kg	Not analyzed
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	Not analyzed
Neutralization Potential	8.1%	1.0 to 100	Percent as CaCO ₃	Analyzed as part of ER-0627 Demonstration

NOTES:

Values used to calculate electron acceptor demand match those used in the EOS Remediation spreadsheet design tool (CH2M Hill, 2007).

Table S.2 Substrate Calculations in Hydrogen Equivalents**Site Name:** Upper Zone A/B, NTC Orlando

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
50	1-10,000	feet
50	1-1,000	feet
20	1-100	feet
1000	--	ft ²
50,000	--	ft ³
63,597	--	gallons
5.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone 0
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.29	.05-50	
0.17	.05-50	
4.7	.01-1000	ft/day
0.0005	0.1-0.0001	ft/ft
0.01	--	ft/day
5.0	--	ft/yr
6,418	--	gallons/year
1.7	1.4-2.0	gm/cm ³
0.005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
5.0	2.65	7.94	0.33	4
10.0	5.31	10.25	0.52	5
250	132.67	11.91	11.14	8
10.0	5.31	1.99	2.67	8
Soluble Competing Electron Acceptor Demand (lb.)			14.66	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
5.0	3.99	27.25	0.15	2
50.0	39.92	55.41	0.72	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			0.87	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.010	0.01	20.57	0.00	8
15.000	7.96	21.73	0.37	6
0.010	0.01	24.05	0.00	4
0.010	0.01	31.00	0.00	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.000	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			0.37	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x C_{gw})
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	0.01	0.07	20.57	0.00	8
107	8.03	42.59	21.73	1.96	6
45	0.00	0.01	24.05	0.00	4
3.0	0.00	0.00	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			1.96		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	5.0	0.27	7.94	0.03	4
Nitrate (denitrification)	10.0	0.54	10.25	0.05	5
Sulfate	250	13.39	11.91	1.12	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	0.54	1.99	0.27	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				1.5	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.010	0.00	20.57	0.00	8
Trichloroethene (TCE)	15.000	0.80	21.73	0.04	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.010	0.00	24.05	0.00	4
Vinyl Chloride (VC)	0.010	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				0.04	

Initial Hydrogen Requirement First Year (lb)**19.4****Total Life-Cycle Hydrogen Requirement (lb)****25.4****5. Design Factors**

Microbial Efficiency Uncertainty Factor
Methane and Solid-Phase Electron Acceptor Uncertainty
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)

2X - 4X

2X - 4X

1X - 3X

Design Factor**1.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)****25.4****6. Acronyms and Abbreviations**

°C =degrees celsius

μS/cm = microsiemens per centimeter

cm/day = centimeters per day

cm/sec = centimeters per second

ft² = square feet

ft/day = feet per day

ft/ft = foot per foot

ft/yr = feet per year

gm/cm³ = grams per cubic centimeterkg of CaCO₃ per mg = kilograms of calcium carbonate per milligram

lb = pounds

meq/100 g = milliequivalents per 100 grams

mg/kg = milligrams per kilogram

mg/L = milligrams per liter

m/m = meters per meters

mV = millivolts

m/yr = meters per year

su = standard pH units

wt/wt H₂ = concentration molecular hydrogen, weight per weight

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

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Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 5

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	568	568	2.58E+08	712
Sodium Lactate Product (60 percent solution)	1.0	568	1,179	2.58E+08	712
Molasses (assuming 60 percent sucrose)	1.0	540	900	2.45E+08	676
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	568	711	2.58E+08	712
Ethanol Product (assuming 80% ethanol by weight)	1.0	291	363	1.32E+08	364
	1.0	392	560	1.78E+08	491
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	431	431	1.95E+08	432
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	221	221	1.00E+08	277
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	221	369	1.00E+08	277

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: **Upper Zone A/B, NTC Orlando**

1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	50	feet	15	meters
Length (parallel to groundwater flow)	50	feet	15.2	meters
Saturated Thickness	20	feet	6.1	meters
Design Period of Performance	5	years	5	years

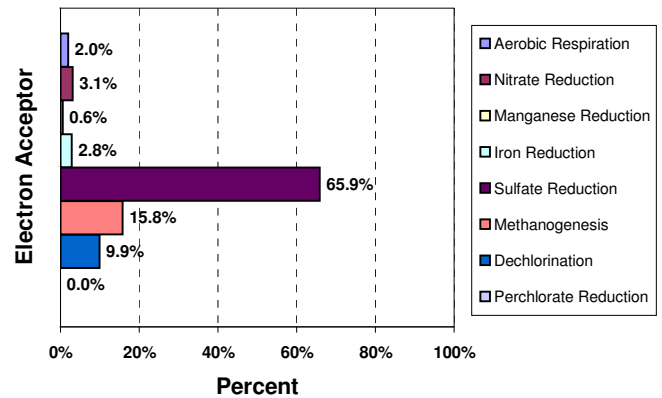
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.29	percent	0.29	percent
Effective Porosity	0.17	percent	0.17	percent
Average Aquifer Hydraulic Conductivity	4.7	ft/day	1.7E-03	cm/sec
Average Hydraulic Gradient	0.0005	ft/ft	0.0005	m/m
Average Groundwater Seepage Velocity	0.01	ft/day	4.2E-01	cm/day
Average Groundwater Seepage Velocity	5	ft/yr	1.5	m/yr
Total Treatment Zone Pore Volume	63,597	gallons	240,734	liters
Groundwater Flux (per year)	6,418	gallons/year	24,293	liters/year
Total Groundwater Volume Treated (over entire design period)	95,685	gallons total	362,199	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.0%	0.503
Nitrate Reduction	3.1%	0.779
Sulfate Reduction	65.9%	16.760
Manganese Reduction	0.6%	0.147
Iron Reduction	2.8%	0.720
Methanogenesis	15.8%	4.012
Dechlorination	9.9%	2.516
Perchlorate Reduction	0.0%	0.000
Totals:	100.00%	25.44

Hydrogen demand in pounds/gallon:	2.66E-04
Hydrogen demand in grams per liter:	3.19E-02

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor =****1.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	1,179	107	712	as lactic acid
2. Molasses Product	900	75	676	as sucrose
3. Fructose Product	711	63	712	as fructose
4. Ethanol Product	363	53	364	as ethanol
5. Sweet Dry Whey (lactose)	560	sold by pound	491	as lactose
6. HRC®	431	sold by pound	432	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	221	28	277	as soybean oil
8. Emulsified Vegetable Oil	369	47	277	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** Lower Zone C, NTC Orlando

NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	50	1-10,000	feet	
Length (Parallel to predominant groundwater flow)	50	1-1,000	feet	
Saturated Thickness	20	1-100	feet	30 to 50 feet bgs
Treatment Zone Cross Sectional Area	1000	--	ft ²	
Treatment Zone Volume	50,000	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	108,489	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	63,597	--	gallons	
Design Period of Performance	5.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	

2. Treatment Zone Hydrogeologic Properties	Values	Range	Units	User Notes
Total Porosity	29%	.05-50	percent	
Effective Porosity	17%	.05-50	percent	
Average Aquifer Hydraulic Conductivity	6.9	.01-1000	ft/day	
Average Hydraulic Gradient	0.0008	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.03	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	11.9	--	ft/yr	
Average Groundwater Flux through the Treatment Zone	15,075	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm ³	Silty sand
Soil Fraction Organic Carbon (foc)	0.50%	0.01-10	percent	Assumed default value

3. Native Electron Acceptors	Values	Range	Units	User Notes
A. Aqueous-Phase Native Electron Acceptors				Values used in EOS Remediation Tool
Oxygen	5.0	0.01 to 10	mg/L	
Nitrate	10.00	0.1 to 20	mg/L	
Sulfate	250	10 to 5,000	mg/L	
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	
B. Solid-Phase Native Electron Acceptors				Values used in EOS Remediation Tool
Manganese (IV) (estimated as the amount of Mn (II) produced)	5	0.1 to 20	mg/L	
Iron (III) (estimated as the amount of Fe (II) produced)	100	0.1 to 20	mg/L	Dissolved iron ranged up to 236 mg/L

4. Contaminant Electron Acceptors	Values	Range	Units	User Notes
				Values used in EOS Remediation Tool
Tetrachloroethene (PCE)	0.010	--	mg/L	
Trichloroethene (TCE)	15.000	--	mg/L	
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.010	--	mg/L	
Vinyl Chloride (VC)	0.010	--	mg/L	
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	

5. Aquifer Geochemistry (Optional Screening Parameters)	Values	Range	Units	User Notes
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	100	-400 to +500	mV	Generally reducing conditions
Temperature	NA	5.0 to 30	°C	Not available, likely above 20 degrees Celsius
pH	5.9	4.0 to 10.0	su	Ranged from 5.4 to 6.3, inpart due to ISCO treatment
Alkalinity	100	10 to 1,000	mg/L	Ranged from 8.6 to 111 mg/L
Total Dissolved Solids (TDS, or salinity)	NA	10 to 1,000	mg/L	Not available
Specific Conductivity	NA	100 to 10,000	µs/cm	Not available
Chloride	NA	10 to 10,000	mg/L	Not available
Sulfide - Pre injection	0.1	0.1 to 100	mg/L	Little sulfide detected at the site.
Sulfide - Post injection	NA	0.1 to 100	mg/L	Not available
B. Aquifer Matrix				
Total Iron	NA	100 to 10,000	mg/kg	Not analyzed
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	Not analyzed
Neutralization Potential	10.0%	1.0 to 100	Percent as CaCO ₃	Analyzed as part of ER-0627 Demonstration

NOTES:

Values used to calculate electron acceptor demand match those used in the EOS Remediation spreadsheet design tool (CH2M Hill, 2007).

Table S.2 Substrate Calculations in Hydrogen Equivalents**Site Name:** Lower Zone C, NTC Orlando

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
50	1-10,000	feet
50	1-1,000	feet
20	1-100	feet
1000	--	ft ²
50,000	--	ft ³
63,597	--	gallons
5.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.29	.05-50	
0.17	.05-50	
6.9	.01-1000	ft/day
0.0008	0.1-0.0001	ft/ft
0.03	--	ft/day
11.9	--	ft/yr
15,075	--	gallons/year
1.7	1.4-2.0	gm/cm ³
0.005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
5.0	2.65	7.94	0.33	4
10.0	5.31	10.25	0.52	5
250	132.67	11.91	11.14	8
10.0	5.31	1.99	2.67	8
Soluble Competing Electron Acceptor Demand (lb.)			14.66	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
5.0	5.80	27.25	0.21	2
100.0	115.96	55.41	2.09	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			2.31	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.010	0.01	20.57	0.00	8
15.000	7.96	21.73	0.37	6
0.010	0.01	24.05	0.00	4
0.010	0.01	31.00	0.00	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.000	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			0.37	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x Cgw)
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	0.01	0.07	20.57	0.00	8
107	8.03	42.59	21.73	1.96	6
45	0.00	0.01	24.05	0.00	4
3.0	0.00	0.00	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			1.96		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	5.0	0.63	7.94	0.08	4
Nitrate (denitrification)	10.0	1.26	10.25	0.12	5
Sulfate	250	31.45	11.91	2.64	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	1.26	1.99	0.63	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				3.5	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.010	0.00	20.57	0.00	8
Trichloroethene (TCE)	15.000	1.89	21.73	0.09	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.010	0.00	24.05	0.00	4
Vinyl Chloride (VC)	0.010	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				0.09	

Initial Hydrogen Requirement First Year (lb)**22.9****Total Life-Cycle Hydrogen Requirement (lb)****37.1****5. Design Factors**

Microbial Efficiency Uncertainty Factor
Methane and Solid-Phase Electron Acceptor Uncertainty
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)

2X - 4X

2X - 4X

1X - 3X

Design Factor**1.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)****37.1****6. Acronyms and Abbreviations**

°C =degrees celsius

μS/cm = microsiemens per centimeter

cm/day = centimeters per day

cm/sec = centimeters per second

ft² = square feet

ft/day = feet per day

ft/ft = foot per foot

ft/yr = feet per year

gm/cm³ = grams per cubic centimeterkg of CaCO₃ per mg = kilograms of calcium carbonate per milligram

lb = pounds

meq/100 g = milliequivalents per 100 grams

mg/kg = milligrams per kilogram

mg/L = milligrams per liter

m/m = meters per meters

mV = millivolts

m/yr = meters per year

su = standard pH units

wt/wt H₂ = concentration molecular hydrogen, weight per weight

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

RESET DEFAULT

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 5

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	829	829	3.76E+08	715
Sodium Lactate Product (60 percent solution)	1.0	829	1,720	3.76E+08	715
Molasses (assuming 60 percent sucrose)	1.0	787	1,312	3.57E+08	679
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	829	1,036	3.76E+08	715
Ethanol Product (assuming 80% ethanol by weight)	1.0	424	530	1.92E+08	366
	1.0	572	817	2.60E+08	493
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	628	628	2.85E+08	433
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	323	323	1.46E+08	278
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	323	538	1.46E+08	278

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: **Lower Zone C, NTC Orlando**

1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	50	feet	15	meters
Length (parallel to groundwater flow)	50	feet	15.2	meters
Saturated Thickness	20	feet	6.1	meters
Design Period of Performance	5	years	5	years

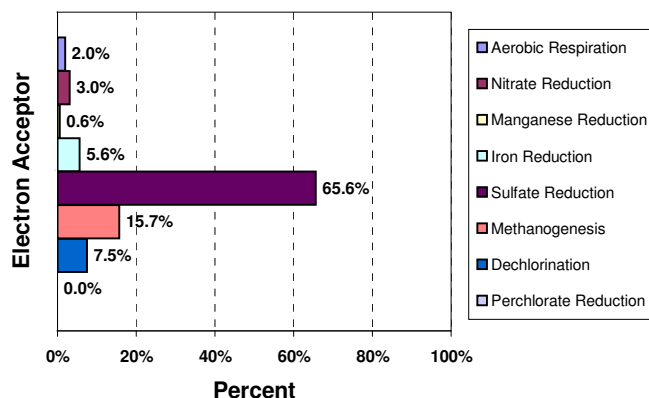
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.29	percent	0.29	percent
Effective Porosity	0.17	percent	0.17	percent
Average Aquifer Hydraulic Conductivity	6.9	ft/day	2.4E-03	cm/sec
Average Hydraulic Gradient	0.0008	ft/ft	0.0008	m/m
Average Groundwater Seepage Velocity	0.03	ft/day	9.9E-01	cm/day
Average Groundwater Seepage Velocity	12	ft/yr	3.6	m/yr
Total Treatment Zone Pore Volume	63,597	gallons	240,734	liters
Groundwater Flux (per year)	15,075	gallons/year	57,062	liters/year
Total Groundwater Volume Treated (over entire design period)	138,971	gallons total	526,047	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.0%	0.730
Nitrate Reduction	3.0%	1.131
Sulfate Reduction	65.6%	24.342
Manganese Reduction	0.6%	0.213
Iron Reduction	5.6%	2.093
Methanogenesis	15.7%	5.827
Dechlorination	7.5%	2.766
Perchlorate Reduction	0.0%	0.000
Totals:	100.00%	37.10

Hydrogen demand in pounds/gallon:	2.67E-04
Hydrogen demand in grams per liter:	3.20E-02

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor =****1.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	1,720	156	715	as lactic acid
2. Molasses Product	1,312	109	679	as sucrose
3. Fructose Product	1,036	93	715	as fructose
4. Ethanol Product	530	77	366	as ethanol
5. Sweet Dry Whey (lactose)	817	sold by pound	493	as lactose
6. HRC®	628	sold by pound	433	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	323	41	278	as soybean oil
8. Emulsified Vegetable Oil	538	69	278	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

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SITE SUMMARY

Elmendorf AFB DP98, Alaska

For: Project Files for ESTCP Substrate Loading Study (Job No. 745255)

Revision: 01 July 2009

SITE IDENTIFICATION

DP98 Site, Elmendorf AFB, Alaska

CONTAMINANT SOURCE: Maximum baseline concentrations

<i>COC</i>	<i>Max. Conc.</i>	<i>DNAPL Present?</i>	<i>Notes</i>
PCE	6,400 µg/L	No	Ref (1)
TCE	5,000 µg/L	No	Ref (1)
<i>cis</i> -1,2-DCE	8,030 µg/L	No	Ref (1)
VC	16 µg/L	No	Ref (1)

Notes: Primarily TCE and *cis*-1,2-DCE in treatment zone.**SUBSTRATE DESIGN/INSTALLATION INFORMATION**

<i>Parameter</i>	<i>Original Design</i>	<i>Modifications</i>	<i>Notes/Reference</i>
Project Scale	Pilot	No change	
Substrate Type	EOS®598 and Sodium Lactate (WilClear®)		Emulsified soybean oil product consisting of approx. 60% soybean oil, 5% food-grade emulsifiers (by weight), and 4% sodium lactate (by weight).
Number of Injection Points (IP)	3	No change	
IP Spacing Information	10	No change	
Injection Date	July 2005	No change	
Injection Interval (depth bgs)	21-31 feet	No change	
Substrate Mixture Volume	2,270 gal	2,275 gal	Approximately 1,900 gallons of make-up water from extraction and 1,200 gallons from potable water supply (including post-injection water push).

<i>Parameter</i>	<i>Original Design</i>	<i>Modifications</i>	<i>Notes/Reference</i>
Injection Rate	3 gpm	2-5 gpm	Injection pressure maintained below 10-15 psi.
Substrate Loading Rate	Average concentration of 14.9 g/L lactic acid and 15.8 g/L vegetable oil	Average concentration of 19.3 g/L lactic acid and 18.5 g/L vegetable oil	Includes post-injection water push. Lower than planned water push volume increased average concentrations.
Basis for Loading Rate	Stoichiometry with Design Factor of 15	No change	A high design factor was used based on prior experience using EVO.
Injection amendment?	WilClear® sodium lactate product	Increased from 90 gallons to 100 gallons	Rounded product quantity up to 2 drums.
Pre-injection Specified?	No	No change	
Post-injection Specified?	Yes	No change	
Type of post-injection	WilClear® + water	No change	
Volume of post-injection	1,560 gal	1,060 gal	

Notes: gpm = gallons per minute, psi = pounds per square inch

MONITORING INFORMATION

<i>Sample Collection Date (Reference)</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Have Copy? ^{a/}</i>
July 2005	Yes	Yes	Yes	Yes	Ref(2)
September 2005	Yes	Yes	Yes	Yes	Ref(2)
May/June 2006	Yes	Yes	Yes	Yes	Ref(2)
September 2006	Yes	Yes	Yes	Yes	Ref(2)
June 2008	Yes	Yes	Yes	Yes	Ref(3)

REFERENCES

- (1) United States Air Force (USAF). 2005. *Treatability Study Work Plan for Enhanced Monitored Natural Attenuation at DP98*. Elmendorf Air Force Base, Alaska. June. **(Final Work Plan)**
- (2) USAF. 2007. *Treatability Study Work Plan for Enhanced Monitored Natural Attenuation at DP98*. Elmendorf Air Force Base, Alaska. April. **(Final Report)**
- (3) Parsons. 2009. *Long-Term Monitoring Results for an Enhanced Monitored Natural Attenuation Treatability Study at the DP98 Site, Elmendorf AFB, Alaska*. Final Technical Memorandum from Parsons to Elmendorf AFB and ESTCP. 13 January 2009. **(Update)**

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates calculated or designed?

Stoichiometric calculations were used for this demonstration as a basis of comparison to prior applications. The calculation spreadsheet from Appendix C of AFCEE *et al.* (2004) was used to calculate the electron acceptor demand in hydrogen equivalents over a 3 year design life. The relatively high design factor (14 times) was based, in part, on past experiences where an effective residual oil concentration of less than 2 percent of the pore volume was not thought to be sufficient to sustain the reaction zone over a several year period. A residual oil saturation of 1.7 percent was used, and was thought to be close to the minimum acceptable concentration necessary to sustain the reaction zone.

For this application, approximately 30 percent of the substrate requirement was from lactic acid (i.e., the active ingredient in the sodium lactate product) and approximately 70 percent was from the oil in the EVO product. The objective of using a combined substrate was to rapidly induce highly anaerobic conditions with the sodium lactate substrate, and to sustain the reaction zone with the EVO product.

2. What modifications to the substrate amendment protocol were required (e.g., concentration and frequency for soluble substrates; and depletion and additional injection of slow-release substrate types such as HRC[®] and EVO).

No modifications were required, other than the water push after the EVO injection was reduced from approximately 1,500 gallons to 1,060 gallons (total for 3 wells). This was due to low extraction rates from nearby wells used to collect make up water, and this slightly increased the average substrate concentration in the overall substrate mixture.

The application had an effective life span of at least 3 years based on elevated levels of TOC present in June 2008 (Parsons, 2009). For June 2008, concentrations of TOC at the injection well locations ranged from 100 to 290 mg/L, with the highest concentration being measured at the center injection well location DP98INJ-02. At the downgradient locations (DP98MW-05 and DP98MW-06), levels of TOC decreased from over 90 mg/L in September 2006 to less than 20 mg/L in June 2008. While it appears elevated levels of organic carbon have been sustained through June 2008 (35 months post-injection) within the immediate injection zone, substrate levels are depleted within 15 to 30 feet downgradient of the injection wells.

This duration of sustained, elevated levels of substrate within the immediate injection zone (close to 3 years) is approximately the duration that was intended during design of the treatability study. It is likely the reaction zone will continue to be sustained for perhaps another year. This suggests that the design estimates of non-specific substrate demand were high. Alternatively, the substrate may persist due to slow rates of biodegradation in a cold weather environment. Groundwater temperatures at the DP98 site are less than 10 degrees Celsius.

3. Evaluation from Substrate Demand Tool

Site data were input into the substrate demand tool (attached). The substrate demand to treat 78.673 gallons (297,802 liters) of groundwater over 3 years was 5.76 pounds, or 7.32E-05 pounds per gallon (8.77E-03 grams per liter) of groundwater treated.

This hydrogen demand could be met by 50 pounds of soybean oil, or by 267 pounds of sodium lactate product. Based on the mass of substrate applied at the DP98 Site (509 pounds of oil and 1,100 pounds of sodium lactate product), the effective design factor applied at the site was 14 times the estimated hydrogen demand.

The primary electron accepting process was methanogenesis (57.3%), followed by manganese reduction (16.7%), sulfate reduction (9.6%), chlorinated solvents (8.7%), and iron reduction (6.2%). The site is naturally depleted in dissolved oxygen and nitrate.

PERFORMANCE OBJECTIVES

No. 1: Ability to Uniformly Distribute Substrate : Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

Substrate at the DP98 Site was successfully distributed around the injection wells and to downgradient monitoring well locations DP98MW-05 and DP98MW-06. Concentrations of TOC in September 2006 for these locations ranged from 130 to 460 milligrams per liter (mg/L), with the highest concentration at well location DP98MW-05.

The distribution of substrate, indicated by measurement of TOC, suggests that a relatively large proportion of the vegetable oil droplets may have migrated on the order of 10 to 15 feet before adsorbing to the aquifer matrix in the vicinity of well DP98MW-05. Lactic acid (from sodium lactate) also migrated through the reaction zone, presumably the source of elevated levels of TOC at well location DP98MW-06. It was also noted that an elevated level of TOC (50 mg/L) was measured at cross-gradient well location 41755-WL04 in September 2005, but not in May/June 2006. This suggests that the distribution of lactic acid (from dissolution of the sodium lactate) during injection and due to advection and dispersion with groundwater flow impacted a much larger area than anticipated.

No. 2: Achieving Optimal Geochemical Conditions

Successful geochemical conditions for stimulating anaerobic degradation of chlorinated solvents is defined as when the groundwater environment is highly anaerobic with DO less than 0.5 mg/L, ORP is less than -200 millivolts (mV), sulfate is reduced by more than 50 percent relative to background conditions, and methane is greater than 1.0 mg/L. Achieving optimal geochemical conditions at the DP98 site was successful with the exception of lowering ORP to less than -200 mV.

Iron and manganese reducing conditions were rapidly induced at the DP98 Site. Background sulfate concentrations are relatively low at the site (less than 15 mg/L), and were typically reduced by 50% or more within the reaction zone. The onset of methanogenesis was not observed in September 2005 (2 months after injection), but was observed in June 2006,

approximately 10 months after injection. Therefore, the addition of sodium lactate did not necessarily induce methanogenesis within a short period of time (within a couple months) as intended. Dechlorination of TCE to DCE did occur once methanogenesis was induced.

ORP was not reduced to below -200 mV (relative to a silver/silver chloride redox probe). It is unclear why lower redox levels could not be achieved. ORP measurements are consistently in the manganese and iron reduction range. Measurement of ORP depends on the coupled oxidation-reduction reactions that are occurring in the aquifer, and likely reflect a mixture of the TEAPs that are occurring. The occurrence of methanogenesis indicates the reaction zone is sufficiently reducing for fermentation reactions to occur. This includes the generation of molecular hydrogen - the primary electron donor for reductive dechlorination of CAHs. This suggests that measurements of ORP at this site may not be a good indication of the potential for reductive dechlorination of CAHs to occur.

No. 3: Remediation Effectiveness: Evaluate efficiency in removal of VOCs based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Determine “threshold” concentrations of dissolved organic carbon that represent the minimum levels required to sustain complete reductive dechlorination.

The success of the application is evaluated by comparing concentrations to site-specific performance criteria, if established. Otherwise, a reduction in contaminant concentration of 99 percent or greater (over two orders of magnitude) is considered successful. For chlorinated aliphatic hydrocarbons (CAHs, or chlorinated solvents) where production of regulated intermediate dechlorination products may occur, a reduction in the total molar concentration of CAHs of greater than 90 percent is considered to be a success.

The DP98 site was not successful at meeting all performance objectives. While concentrations of TCE were reduced to below detection within the injection zone, concentrations of *cis*-DCE remained highly elevated and concentrations of VC were observed to increase in June 2008 (approximately 3 years post-injection). As a result of incomplete dechlorination, substantial reductions in total molar concentrations of chlorinated ethenes were not observed.

The maximum initial concentration of TCE was detected at injection well DP98INJ-01 at 8,180 µg/L. The maximum initial concentration of *cis*-DCE was 6,340 µg/L at injection well location DP98INJ-02. VC was not detected in any well during the pre-injection sampling event.

In June 2008, approximately 35 months after injection, concentrations of TCE within the immediate reaction zone continued to be reduced to concentrations less than or equal to 15 µg/L, a reduction of over 99 percent relative to initial concentrations. Concentrations of TCE at downgradient wells DP98MW-05 and DP98MW-06 rebounded to 120 µg/L and 32 µg/L, respectively. This is a moderate rebound compared to initial concentrations of 2,000 µg/L and 140F µg/L at wells DP98MW-05 and DP98MW-06, respectively.

Concentrations of *cis*-DCE remain elevated in June 2008, with the highest concentration of *cis*-DCE being 18,000 µg/L at location DP98MW-05. VC was detected at all but one well (DP98INJ-01) within the treatment zone, at concentrations up to 200 µg/L at DP98MW-05. This indicates that the native microbial population is capable of dechlorinating *cis*-DCE to VC, but only to a limited extent. Further dechlorination of VC to ethene was not evident. Targeted gene

detection using the Bio-Dechlor Census analysis indicates that only very low concentrations (close to or below detection limits) of *Dehalococcoides* are present in groundwater at the site.

Total molar concentrations did not decrease by over 90 percent, but remained fairly stable for most wells from September 2006 to June 2008, with a substantial increase at well DP98MW-05. This suggests that a source of CAHs may persist at the site.

No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

Secondary water quality parameters that were evaluated for the DP98 site include pH, sulfide, dissolved metals or semi-metals (ferrous iron, manganese, arsenic, and selenium), and the fermentation products acetone and 2-butanone.

pH and Sulfide. With few exceptions, pH remained above 6.5 and an adverse decrease in pH was not observed. Only a few low level detections of sulfide were observed.

Dissolved metals. Filtered samples for arsenic, selenium, and manganese were analyzed in samples collected from wells along the axis of the treatment zone. Unfiltered samples for manganese and ferrous iron were measured in the field. For all samples, concentrations of selenium were below USEPA primary drinking water standards. Baseline levels of arsenic were less than or close to the USEPA primary drinking water standard, with a background higher concentration above the MCL at downgradient location DP98MW-06. Concentrations of arsenic were only slightly higher than the standard within the treatment zone after substrate injection. Background and treatment zone concentrations of manganese and ferrous iron are elevated above USEPA recommended secondary drinking water quality standard. The shallow groundwater at the DP98 is not a drinking water source, and the magnitude of the increase in concentrations does not appear to be an issue at this site.

Undesirable VOCs. Acetone and 2-butanone were detected at elevated concentrations at 2 months post-injection, but were not above the comparison criteria (USEPA Region 9 PRGs) and decreased to below detection within 10 months of injection.

Summary of Secondary Water Quality – DP98 Site

Parameter	Comparison Criteria	Background	Treatment Zone	Down-gradient	Issues?
pH	<6.5 or >8.5 (b)	6.44 to 7.00	6.52 to 6.86	6.18 to 6.91	No
Sulfide (mg/L)	NA	<0.10 to 0.11	<0.10 to 0.12	<0.10 to 1.0	No – only a few detections above 0.1 mg/L
Total Manganese (mg/L)	0.05 (b)	4.7 to 18	8.5 to 66	25 to 46	Potential – background above criteria
Total Ferrous Iron (mg/L)	0.3 (b)	0.3 to 8.7	1.8 to 29	5.9 to 45	Potential – background above criteria
Dissolved Manganese (mg/L)	0.05 (b)	4.2 to 6.2	9.3 to 25	19 to 44	Potential – background above criteria
Arsenic (mg/L)	0.01 (a)	<0.010 to 0.008F	0.012 to 0.036	0.025 to 0.037	Potential – background close to criteria and slightly elevated in treatment zone
Selenium (mg/L)	0.05 (a)	0.007F to 0.014F	0.013 to 0.022	0.015F to 0.035	No
Acetone (mg/L)	5.5 (c)	<0.01 to <0.165	Up to 0.346	Up to 0.296	No, low detections shortly after injection but not sustained
2-butanone (mg/L)	7.0 (c)	<0.05 to <0.140	<5.0 to <324	<5.0 to <324	No, low detections shortly after injection but not sustained

Notes:

Background values from wells DP98MW-04 (upgradient) and 41755-W104 (cross-gradient).

Treatment zone values from DP98INJ-01 through DP98INJ-03 (post-injection).

Downgradient values DP98MW-05 and DP98MW-06 (post-injection).

mg/L = milligrams per liter; µg/L = micrograms per liter. F-flag indicates concentration is estimated.

Criteria based on (a) USEPA MCL; (b) USEPA Secondary Standard; or (c) USEPA Region 9 PRG.

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

A reduction of less than 50 percent in the average hydraulic conductivity within the reaction zone is considered to be acceptable. The hydraulic conductivity measured for injection well DP98INJ-

02 decreased by approximately 30 percent over time from July 2005 to October 2006. One possible explanation is biofouling of the aquifer or well screen due to the high levels of organic carbon at this injection location. However, the hydraulic conductivity at DP98INJ-02 increased in June 2008, indicating any effects from the injection were not long-term. Hydraulic conductivity at downgradient well locations DP98MW-05 and DP98MW-06 remained relatively stable over time. Therefore, no adverse impacts on hydraulic conductivity were observed.

No. 6: Substrate Persistence and Long-Term Effectiveness

Concentrations of TOC remain elevated in the injection wells in June 2008, ranging from 100 to 290 mg/L. Concentrations of TOC were depleted close to initial concentrations in the downgradient wells. The average concentration of TOC and total VFAs in the injection wells increased from September 2006 to June 2008, so it is not possible to extrapolate when depletion of organic substrate will occur within the area of the injection wells. Based on decreasing concentrations of TOC and a moderate rebound in concentrations of TCE at downgradient wells DP98MW-05 and DP98-MW-6, the size of the effective reactive zone appears to have decreased to immediate area of the injection wells. The rebound in TCE at these wells occurred when TOC dropped from over 90 mg/L to less than 20 mg/L, suggesting that the threshold concentration to sustain dechlorination of TCE is between 20 and 90 mg/L at this site.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

No modifications were required. Additional injections were not necessary to sustain effective degradation of chlorinated solvents over the intended design life of the DP98 application.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

There were no apparent hydraulic limitations at the DP98 Site. While observation of sediments during borehole advancement indicated a moderate degree of heterogeneity, the range of hydraulic conductivity (0.09 to 1.7 feet per day) and rate of groundwater flow (up to 120 feet per year) were within ranges suitable for applying enhanced *in situ* bioremediation.

The presence of relatively high amounts of bioavailable iron and manganese may have influenced the ORP of groundwater the site, with ORP remaining in the range of iron reduction to manganese reduction over the duration of the treatability study. However, methanogenesis was induced and it appears that incomplete dechlorination is related to a lack of *Dehalococcoides* dechlorinating species and low groundwater temperatures.

COST ASSESSMENT

Cost Summary, DP98 Site, Elmendorf AFB, Alaska

[illegible]

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** DP98, Elmendorf AFB, Alaska

NOTE: Unshaded boxes are user input.				
1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	30	1-10,000	feet	
Length (Parallel to predominant groundwater flow)	10	1-1,000	feet	
Saturated Thickness	10	1-100	feet	
Treatment Zone Cross Sectional Area	300	--	ft ²	
Treatment Zone Volume	3,000	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	6,734	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	4,938	--	gallons	
Design Period of Performance	3	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	
Effective Porosity	22%	.05-50	percent	
Average Aquifer Hydraulic Conductivity	1.0	.01-1000	ft/day	
Average Hydraulic Gradient	0.030	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	49.8	--	ft/yr	
Average Groundwater Flux through the Treatment Zone	24,578	--	gallons/year	
Soil Bulk Density	1.65	1.4-2.0	gm/cm ³	Silty Sand and Gravel
Soil Fraction Organic Carbon (foc)	0.50%	0.01-10	percent	Assumed default value
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.0	0.01 to 10	mg/L	Ranged from 0.15 to 1.06 mg/L
Nitrate	0.05	0.1 to 20	mg/L	Less than 0.1 mg/L
Sulfate	10	10 to 5,000	mg/L	Ranged from 3.1 to 12 mg/L
Carbon Dioxide (estimated as the amount of Methane produced)	10	0.1 to 20	mg/L	Methane Produced - Max. 16 mg/L
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	40	0.1 to 20	mg/L	Manganese Produced - Max. 66 mg/L
Iron (III) (estimated as the amount of Fe (II) produced)	30	0.1 to 20	mg/L	Ferrous Iron Produced - Max 45 mg/L
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.000	--	mg/L	
Trichloroethene (TCE)	8.180	--	mg/L	DP98INJ-01 on 7/25/05
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	6.340	--	mg/L	DP98INJ-02 on 7/26/05
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	-60	-400 to +500	mV	Background +14 to -288 mV
Temperature	7.5	5.0 to 30	°C	Ranged from 6.2 to 8.7 °C
pH	6.5	4.0 to 10.0	su	Ranged from 6.18 to 6.86
Alkalinity	360	10 to 1,000	mg/L	Ranged from 340 to 391 mg/L
Total Dissolved Solids (TDS, or salinity)	NA	10 to 1,000	mg/L	Not analyzed
Specific Conductivity	1,000	100 to 10,000	µs/cm	Ranged from 921 to 1,039 µs/cm
Chloride	80	10 to 10,000	mg/L	Ranged from 47 to 110 mg/L
Sulfide - Pre injection	0.1	0.1 to 100	mg/L	Ranged from <0.1 to 0.2 mg/L
Sulfide - Post injection	0.1	0.1 to 100	mg/L	Maximum 1.0 mg/L
B. Aquifer Matrix				
Total Iron	NA	100 to 10,000	mg/kg	
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	
Neutralization Potential	NA	1.0 to 100	Percent as CaCO ₃	

NOTES:

Background data based on sampling in July 2005 at locations DP98INJ-01, DP98INJ-02, DP98INJ-03, DP98MW-04, DP98MW-05, DP98MW-06, and 41755-WL04. Values for methane, manganese, and ferrous iron are post-injection.

Table S.2 Substrate Calculations in Hydrogen Equivalents**Site Name:** DP98, Elmendorf AFB, Alaska

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
30	1-10,000	feet
10	1-1,000	feet
10	1-100	feet
300	--	ft ²
3,000	--	ft ³
4,938	--	gallons
3.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone 0
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.3	.05-50	
0.22	.05-50	
1	.01-1000	ft/day
0.03	0.1-0.0001	ft/ft
0.14	--	ft/day
49.8	--	ft/yr
24,578	--	gallons/year
1.65	1.4-2.0	gm/cm ³
0.005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
1.0	0.04	7.94	0.01	4
0.1	0.00	10.25	0.00	5
10	0.41	11.91	0.03	8
10.0	0.41	1.99	0.21	8
Soluble Competing Electron Acceptor Demand (lb.)			0.25	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
40.0	26.26	27.25	0.96	2
30.0	19.69	55.41	0.36	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			1.32	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.000	0.00	20.57	0.00	8
8.180	0.34	21.73	0.02	6
6.340	0.26	24.05	0.01	4
0.000	0.00	31.00	0.00	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.000	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			0.03	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x Cgw)
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	0.00	0.00	20.57	0.00	8
107	4.38	1.35	21.73	0.06	6
45	1.43	0.44	24.05	0.02	4
3.0	0.00	0.00	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			0.08		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.0	0.21	7.94	0.03	4
Nitrate (denitrification)	0.1	0.01	10.25	0.00	5
Sulfate	10	2.05	11.91	0.17	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	2.05	1.99	1.03	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				1.2	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	8.180	1.68	21.73	0.08	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	6.340	1.30	24.05	0.05	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				0.13	

Initial Hydrogen Requirement First Year (lb)**3.0****Total Life-Cycle Hydrogen Requirement (lb)****5.8****5. Design Factors**

Microbial Efficiency Uncertainty Factor
Methane and Solid-Phase Electron Acceptor Uncertainty
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)

2X - 4X

2X - 4X

1X - 3X

Design Factor**1.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)****5.8****6. Acronyms and Abbreviations**

°C =degrees celsius

μS/cm = microsiemens per centimeter

cm/day = centimeters per day

cm/sec = centimeters per second

ft² = square feet

ft/day = feet per day

ft/ft = foot per foot

ft/yr = feet per year

gm/cm³ = grams per cubic centimeterkg of CaCO₃ per mg = kilograms of calcium carbonate per milligram

lb = pounds

meq/100 g = milliequivalents per 100 grams

mg/kg = milligrams per kilogram

mg/L = milligrams per liter

m/m = meters per meters

mV = millivolts

m/yr = meters per year

su = standard pH units

wt/wt H₂ = concentration molecular hydrogen, weight per weight

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

RESET DEFAULT

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 3

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	129	129	5.83E+07	196
Sodium Lactate Product (60 percent solution)	1.0	129	267	5.83E+07	196
Molasses (assuming 60 percent sucrose)	1.0	122	204	5.54E+07	186
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	129	161	5.83E+07	196
Ethanol Product (assuming 80% ethanol by weight)	1.0	66	82	2.98E+07	100
	1.0	89	127	4.03E+07	135
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	97	97	4.42E+07	119
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	50	50	2.27E+07	76
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	50	83	2.27E+07	76

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: **DP98, Elmendorf AFB, Alaska**

1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	30	feet	9	meters
Length (parallel to groundwater flow)	10	feet	3.0	meters
Saturated Thickness	10	feet	3.0	meters
Design Period of Performance	3	years	3	years

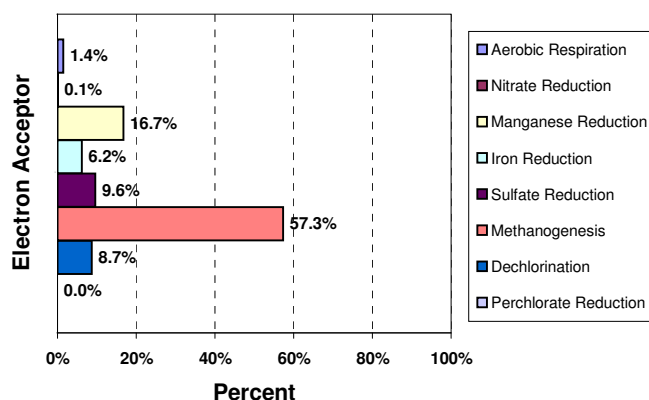
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.22	percent	0.22	percent
Average Aquifer Hydraulic Conductivity	1	ft/day	3.5E-04	cm/sec
Average Hydraulic Gradient	0.03	ft/ft	0.03	m/m
Average Groundwater Seepage Velocity	0.14	ft/day	4.2E+00	cm/day
Average Groundwater Seepage Velocity	50	ft/yr	15.2	m/yr
Total Treatment Zone Pore Volume	4,938	gallons	18,692	liters
Groundwater Flux (per year)	24,578	gallons/year	93,037	liters/year
Total Groundwater Volume Treated (over entire design period)	78,673	gallons total	297,802	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	1.4%	0.083
Nitrate Reduction	0.1%	0.003
Sulfate Reduction	9.6%	0.551
Manganese Reduction	16.7%	0.964
Iron Reduction	6.2%	0.355
Methanogenesis	57.3%	3.299
Dechlorination	8.7%	0.501
Perchlorate Reduction	0.0%	0.000
Totals:	100.00%	5.76

Hydrogen demand in pounds/gallon:	7.32E-05
Hydrogen demand in grams per liter:	8.77E-03

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor =****1.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	267	24	196	as lactic acid
2. Molasses Product	204	17	186	as sucrose
3. Fructose Product	161	14	196	as fructose
4. Ethanol Product	82	12	100	as ethanol
5. Sweet Dry Whey (lactose)	127	sold by pound	135	as lactose
6. HRC®	97	sold by pound	119	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	50	6	76	as soybean oil
8. Emulsified Vegetable Oil	83	11	76	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

SITE SUMMARY

Kenney Avenue Plume, Operable Unit 5, Elmendorf AFB, Alaska

For: Project Files for ESTCP Substrate Loading Study (Job No. 745255)

Review/Update: 10 July 2009

SITE IDENTIFICATION

Kenney Avenue Plume, OU5, Elmendorf AFB, Alaska

CONTAMINANT SOURCE

<i>COC</i>	<i>Max. Conc.</i>	<i>DNAPL Present?</i>	<i>Notes</i>
TCE	36.4 µg/L	No	Ref (2) - Well 403-WL-01 on 8/22/06
<i>cis</i> -1,2-DCE	0.21F µg/L	No	Ref (2) - Well OU5KMW-05 on 8/22/06
VC	0.13F µg/L	No	Ref (2) - Well OU5KMW-04 on 8/22/06

Notes: Max concentrations were obtained from baseline sampling results in August 2006. F-flag indicates an estimated concentration.

SUBSTRATE DESIGN/INSTALLATION INFORMATION

<i>Parameter</i>	<i>Original Design</i>	<i>Modifications?</i>	<i>Notes/Reference</i>
Project Scale	Pilot		
Substrate Type	Emulsified Soybean oil + sodium lactate (WilClear®)	Switched from EVO product (Newmans Zone®) to field mixed emulsion for the last of three injections.	EVO product dispersed too readily and would not sustain the reaction zone.
Number of Injection Wells	4 permanent wells on 20-foot spacing	Added five Geoprobe® direct injection points for the last injection.	Direct-push points were used to close a “gap” in the reaction zone.
IP Spacing Information	20 feet	Spacing had to be modified due to overhead power lines.	Adjustment of well locations in the field due to utilities caused a gap in the treatment zone.
Injection Date	August 2006, May 2007, July 2007 and September 2007	August 2006, June 2007, and September 2007	Reduced frequency from 4 events to 3 events.
Injection Interval (depth bgs)	43-53 feet	No change	

<i>Parameter</i>	<i>Original Design</i>	<i>Modifications?</i>	<i>Notes/Reference</i>
Initial Injection			
Substrate Mixture Volume (includes water push)	1,056 gallons EVO product, 880 gallons Wilclear product, and 27,600 gallons makeup water	1,056 gallons EVO product, 873 gallons Wilclear product, and 25,500 gallons makeup water.	Injected double volume in well OU5KINJ-03 and no injection in OU5KINJ-04 based on realignment of injection wells in the field.
Injection Rate	20-25 gpm	No Change	Injection pressures were maintained below approx 10 psi.
Substrate Mixture Loading Rate	20,100 mg/L lactic acid and 18,750 mg/L vegetable oil	21,472 mg/L lactic acid and 20,195 mg/L vegetable oil	Each injection was intended to sustain the reaction zone for 3 to 6 months at a time.
Basis for Loading Rate	Stoichiometry with a Design factor of 20X oil and 8X lactic acid.	No change	Substrate concentration slightly higher based on lower makeup water volume.
Interim Injections			
Substrate Mixture Volume (includes water push)	528 gallons EVO product, 440 gallons Wilclear product, and 27,200 gallons makeup water	760 gallons EVO product, 440 gallons Wilclear product, and 27,050 gallons makeup water.	Two interim injections were proposed, but this was reduced to one interim injection to limit the cost impact of using higher substrate quantities.
Injection Rate	20-25 gpm	No Change	Injection pressures were maintained below approx 10 psi.
Substrate Mixture Loading Rate	10,540 mg/L lactic acid and 9,830 mg/L vegetable oil	10,758 mg/L lactic acid and 14,112 mg/L vegetable oil	Each injection was intended to sustain the reaction zone for 3 to 6 months at a time.
Basis for Loading Rate	Stoichiometry with a Design factor of 14X (10X oil and 4X lactic acid)	No change	
Final Injection			
Substrate Mixture Volume (includes water push)	528 gallons EVO product, 440 gallons Wilclear product, and 27,200 gallons makeup water	1,042 gallons of neat soybean oil, 200 gallons Wilclear product, and 36,570 gallons makeup water.	Switched to field mixed emulsion.

<i>Parameter</i>	<i>Original Design</i>	<i>Modifications?</i>	<i>Notes/Reference</i>
Injection Rate	20-25 gpm	No Change	Injection pressures were maintained below approx 10 psi.
Substrate Mixture Loading Rate	10,540 mg/L lactic acid and 9,830 mg/L vegetable oil	2,374 mg/L lactic acid and 14,510 mg/L vegetable oil in injection wells; 5,821 mg/L lactic acid and 48,504 mg/L vegetable oil in five injection points.	Added five direct-push injection points to fill a gap in the reaction zone.
Basis for Loading Rate	Stoichiometry with a Design factor of 14X (10X oil and 4X lactic acid)	Increased substrate loading rate	
Injection amendment?	Calcium sulfate + bromide tracer	No change	Approximately 500 mg/L sulfate and 320 mg/L bromide added to emulsion.
Pre-injection Specified?	No	No change	
Post-injection Specified?	Yes	No change	
Type of post-injection	Sodium lactate + water	No change	
Volume of post-injection	1,200 gallons total with 10 gallons of sodium lactate product in 300 gallons of makeup water	Post injection water push ranged from 500 to 800 gallons per well to prevent biofouling.	

Notes: gpm = gallons per minute, psi = pounds per square inch

MONITORING INFORMATION

<i>Sample Collection Date (Reference)</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Reference</i>
June 2006	Yes	Yes	Yes	No	Ref (2)
August 2006	Yes	Yes	Yes	No	Ref (2)
September 2006	Yes	Yes	Yes	No	Ref (2)
May 2007	Yes	Yes	Yes	No	Ref (2)
September 2007	Yes	Yes	Yes	No	Ref(2)
June 2008 2006	Yes	Yes	Yes	Yes	Ref (2)

REFERENCES

- (1) United States Air Force. 2006. *Treatability Study Work Plan for Enhanced Bioremediation at the Kenney Plume, Operable Unit 5, Elmendorf AFB, Alaska*. Prepared by Parsons Infrastructure & Technology Group, Inc. August. **(Work Plan)**
- (2) United States Air Force. 2009. *Treatability Study for Enhanced Bioremediation at the Kenney Avenue Plume, Operable Unit 5, Elmendorf AFB, Alaska*. Prepared by Parsons Infrastructure & Technology Group, Inc. March. **(Final Report)**
- (3) Parsons. 2007. *Interim Results and Proposed Work Plan Modifications for an Enhanced Bioremediation Treatability Study at the Kenney Plume, Elmendorf AFB, Alaska*. Technical Memorandum submitted to Elmendorf AFB and AFCEE/Alaska. 22 August 2007. **(Work Plan Modification)**

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates calculated or designed?

The substrate loading rate was based on estimates of native electron acceptor demand and groundwater flux through a treatment zone of 80 feet wide, 10 feet deep, and 20 feet long. Subsequent injections were not anticipated to need as much substrate as the initial injection, and three additional injections were specified for O&M of the system (Appendix D of Ref [1]).

The calculation spreadsheet from Appendix C of AFCEE *et al.* (2004) was used to calculate the electron acceptor demand in hydrogen equivalents for a period of 6 months, for each of four proposed injections over a 2 year period. A design factor of 20 times the stoichiometric demand for vegetable oil was based, in part, on past experiences where an effective residual oil concentration of less than 2 percent of the pore volume was not thought to be sufficient to sustain the reaction zone. Subsequent injections were designed for a design factor of 10 times for vegetable oil to sustain the reaction zone. Sodium lactate was primarily used to condition the aquifer and to a broader downgradient anaerobic zone.

For this application, approximately 30 percent of the substrate requirement was from lactic acid (i.e., the active ingredient in the sodium lactate product) and approximately 70 percent was from the oil in the emulsified vegetable oil (EVO) product. The objective of using a combined substrate was to rapidly induce highly anaerobic conditions with the sodium lactate substrate, and to sustain the reaction zone with the EVO product.

2. What modifications to the substrate amendment protocol were required (e.g., concentration and frequency for soluble substrates; and depletion and additional injection of slow-release substrate types such as HRC[®] and EVO).

First Injection. Because of the re-location of injection wells OU5KINJ-03 and OU5KINJ-04 due to overhead power lines, a decision was made in the field to double the initial injection volume in OU5KINJ-03 and not to inject into OU5KINJ-04. This was done to create a larger radius of influence around well OU5KINJ-03, which is upgradient relative to OU5KINJ-04. Based on the quantities of each substrate and the total volume injected, the average concentration of lactic acid in the total volume of substrate mixture was approximately 21,500 mg/L, and the

average concentration of vegetable oil was approximately 20,200 mg/L. The effective oil saturation of the injected fluid was approximately 2.2 percent.

Second Injection. The same substrate products were procured as for the initial injection, and mixing was achieved using the same injection configuration. Substrate quantities were varied from the initial injection, with the average concentration of lactic acid in the total volume of substrate mixture being 10,800 mg/L, and the average concentration of vegetable oil being 14,100 mg/L. The effective oil saturation of the injected fluid was approximately 1.5 percent. These effective concentrations are less than the initial injection, as it was anticipated that the reaction zone would already be highly anaerobic from the initial injection and a lesser amount of substrate would be required to sustain the anaerobic reaction zone.

Third Injection. In September 2007, a total of approximately 35,300 gallons of an oil-in-water emulsion (containing vegetable oil and sodium lactate) and a water push of approximately 2,500 gallons was injected into four injection wells (OU5KINJ-01, OU5KINJ-02, OU5KINJ-03, and OU5KINJ-04) and five direct-push injection points (OU5KINJDP-01 through OU5KDPINJ-05). Due to dispersion of substrate observed during prior injections, a coarser substrate mixture was emulsified in the field using the Textrol BR™ soybean oil/lecithin product from the Solae Corporation. Mixing was achieved using the same injection equipment used previously, with a modification to emulsify the mixture using an in-line dosimeter and in-line mixer. For the four injection wells, the total volume injected, the average concentration of lactic acid in the total volume of substrate mixture was 2,374 mg/L, and the average concentration of vegetable oil was 14,510 mg/L. The effective oil saturation of the injected fluid was approximately 1.5 percent. These effective concentrations are less than the initial injection, as it was anticipated that a lesser amount of substrate would be required to sustain the anaerobic reaction zone.

Approximately 1,900 to 2,200 gallons of the substrate mixture were injected into the subsurface through five direct-push injection points over a 10-foot interval. For the direct push injection points, the average concentration of lactic acid in the total volume of the substrate mixture for the direct-push injection points was 5,820 mg/L, and the average concentration of vegetable oil was 48,500 mg/L. The effective oil saturation of the injected fluid was approximately 5.7 percent (versus the design concentration of 6.0 percent). These effective concentrations are greater than previous injections because the zone into which the substrate was injected had not previously been impacted by the first two substrate injections.

3. Evaluation from Substrate Demand Tool

Site data were input into the substrate demand tool (attached). The substrate demand to treat 3,225,640 gallons (12,210,034 liters) of groundwater over 2 years was 104.7 pounds of molecular hydrogen, or 3.25E-05 pounds per gallon (3.89E-03 grams per liter) of groundwater treated.

This hydrogen demand could be met by 911 pounds of soybean oil, or by 4,855 pounds of sodium lactate product. Based on the total weight of substrate applied at the Kenney Avenue Plume test site (15,603 pounds of oil and 16,643 pounds of sodium lactate product), the effective design factor applied at the site was approximately 20 times the estimated hydrogen demand over the 2 year design life. However, the substrate was dispersed over a much greater volume of the aquifer than the immediate reaction zone. Therefore, the effective design factor is not practical to quantify and is considerably less than calculated by the tool

The primary electron accepting process was calculated to be methanogenesis (50.4%), followed by sulfate reduction (32.4%), manganese reduction (14.4%), aerobic respiration (1.5%), iron reduction (0.8%), nitrate reduction (0.5%), and dechlorination of chlorinated solvents (<0.1%). Concentrations of TCE at the site are typically less than 30 to 40 micrograms per liter (µg/L).

PERFORMANCE OBJECTIVES

No. 1: Ability to Uniformly Distribute Substrate : Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

The three injections of organic substrate were readily accomplished, with the substrate mixture distributed over a broad area within the subsurface treatment zone. An exception was observed at monitoring location 403-WL-01, where levels of TOC were only 2.8 mg/L in September 2006 and 4.7 mg/L in May 2007. This resulted from a “gap” in the row of injection wells caused by the presence of an overhead electrical line, where injection wells could not be installed using a conventional hollow-stem auger rig. The use of direct-push injection points was deployed in September 2007 to cover this gap, although concentrations of TOC at well 403-WL-01 only increased to 17 mg/L (18 mg/L in a duplicate sample) in June 2008.

Following the first injection, elevated concentrations of lactic acid were observed at distances of 60 to 90 feet downgradient of the injection area within approximately one month. This confirmed that the soluble component of the substrate mixture was distributed over a broad portion of the Kenney Avenue Plume. However, the first two injections were unable to sustain concentrations of TOC greater than 30 to 40 mg/L at any location for more than 2 to 3 months. This is thought to be a result of high rates of groundwater flow and dispersion of both the sodium lactate and emulsified vegetable oil substrates.

The use of a field-mixed emulsion with a larger droplet size resulted in less dispersion of the vegetable oil substrate, with concentrations of TOC greater than 100 mg/L being sustained in the injection wells over a 9-month period from September 2007 to June 2008. These levels of TOC were sufficient to induce methanogenesis and the onset of dechlorination of TCE to *cis*-DCE. It appears the use of commercial vegetable oil microemulsions are not appropriate for the coarse grained deposits and high rates of groundwater flow present at the Kenney Avenue Plume.

No. 2: Achieving Optimal Geochemical Conditions

Successful geochemical conditions for stimulating anaerobic degradation of chlorinated solvents is defined as when the groundwater environment is highly anaerobic with DO less than 0.5 mg/L, ORP is less than -200 millivolts (mV), sulfate is reduced by more than 50 percent relative to background conditions, and methane is greater than 1.0 mg/L.

Following the first two injections, the primary terminal electron accepting processes (TEAPs) occurring at the site were manganese reduction, iron reduction, and sulfate reduction. Oxidation-reduction potential (ORP) measured at injection locations OU5KINJ-01 through OU5KINJ-03 ranged from -137 to -157 millivolts (mV), which provides supporting evidence that groundwater conditions were sufficiently reducing to support these processes.

It was not until after the third and final injection event in September 2007 using a field-mixed emulsion that methanogenesis was stimulated. This coincides with the onset of reductive dechlorination of TCE to *cis*-DCE. This also coincided with sustained concentrations of TOC of over 100 mg/L in the injection wells. It appears that these two conditions (TOC greater than 100 mg/L and methanogenesis) are required to stimulate reductive dechlorination of TCE at the Kenney Avenue Plume.

No. 3: Remediation Effectiveness: Evaluate efficiency in removal of VOCs based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Determine “threshold” concentrations of dissolved organic carbon that represent the minimum levels required to sustain complete reductive dechlorination.

The success of the application is evaluated by comparing concentrations to site-specific performance criteria, if established. Otherwise, a reduction in contaminant concentration of 99 percent or greater (over two orders of magnitude) is considered successful. For chlorinated aliphatic hydrocarbons (CAHs, or chlorinated solvents) where production of regulated intermediate dechlorination products may occur, a reduction in the total molar concentration of CAHs of greater than 90 percent is considered to be a success.

For the purposes of evaluating this treatability study, the target concentration of TCE in groundwater was the OU5 cleanup level for TCE of 5.0 µg/L within the pilot test cell. For *cis*-DCE and VC, the target concentrations were USEPA drinking water MCLs (<70 µg/L and <2.0 µg/L, respectively) at monitoring locations approximately 60 to 90 feet from the injection wells (e.g., OU5KMW-02 and OU5KMW-04). Concentrations of TCE did not change significantly following the first two injection events. No evidence of biodegradation of TCE was evident as there was a lack of any clear reduction in concentrations of TCE or a substantial increase in concentrations of dechlorination products such as *cis*-DCE.

As of June 2008, concentrations of TCE have been reduced to less than the target concentration 5.0 µg/L at injection locations OU5KINJ-01 and OU5KINJ-02. TCE was also reduced to below the target concentration at seep location OU5SP-09 in September 2008. TCE has been converted to *cis*-DCE, but concentrations of *cis*-DCE remain well below its MCL at all locations. Therefore, the performance objective was met with the exception of well locations 403-WL-01, OU5KMW-02, and OU5KMW-05.

In summary, the treatability study has been partially successful in reducing concentrations of TCE, without an adverse accumulation of *cis*-DCE or any production of VC. Biodegradation of TCE has been stimulated, but only after modifications to the injection design were made and methanogenesis was induced. Further biodegradation of *cis*-DCE is not apparent. This may be due to either 1) failure to achieve a groundwater redox state that is thermodynamically favorable for the transformation of *cis*-DCE to VC, or 2) a lack or slow growth of the appropriate dechlorinating bacteria (*Dehalococcoides* species).

No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

Secondary water quality parameters that were evaluated for the Kenney Avenue Plume include pH, sulfide, total and dissolved inorganics (ferrous iron, manganese, arsenic, and selenium), and the fermentation products acetone and 2-butanone.

Summary of Secondary Water Quality – Kenney Avenue Plume

Parameter	Comparison Criteria	Background	Treatment Zone	Down-gradient	Issues?
pH	<6.5 or >8.5 (b)	6.64 to 7.15	6.28 to 7.26	6.62 to 7.15	No
Sulfide (mg/L)	NA	0.01 to 0.04	<0.10 to 0.49	<0.10 to 0.14	No – all detections below 0.5 mg/L
Total Manganese (mg/L)	0.05 (b)	0.8 to 19.3	5.9 to 26.4	6.0 to 31.9	Potential – background above criteria
Total Ferrous Iron (mg/L)	0.3 (b)	<0.01 to 0.07	0.02 to >3.3	<0.01 to 1.1	Potential – Some detections above criteria
Dissolved Manganese (mg/L)	0.05 (b)	7.2 to 8.0	7.2 to 8.3	6.6 to 14	Potential – background above criteria
Arsenic (mg/L)	0.01 (a)	<0.030	0.0095F to <0.030	0.027F to <0.030	Potential – reporting limit greater than criteria
Selenium (mg/L)	0.05 (a)	<0.030	<0.030	<0.030	No
Acetone (mg/L)	5.5 (c)	<0.01	<0.01	<0.01	No
2-butanone (mg/L)	7.0 (c)	<0.01	<0.01	<0.01	No

Notes:

Background values from wells OU5KMW-01 and OU5KMW-03 (upgradient).

Treatment zone values from wells OU5KINJ-01 through OU5KINJ-04, and well 403-WL-01 (post-injection).

Downgradient values OU5KMW-02, OU5KMW-04, and OU5KMW-05 (post-injection).

mg/L = milligrams per liter; F-flag indicates concentration is estimated.

Criteria based on (a) USEPA MCL; (b) USEPA Secondary Standard; or (c) USEPA Region 9 PRG.

pH and Sulfide. With few exceptions, pH remained above 6.5 and an adverse decrease in pH was not observed. Only a few low level detections of sulfide (<0.5 mg/L) were observed, even though sulfate was added to the injection amendment.

Dissolved metals. Select groundwater samples from wells along the axis of the treatment zone were analyzed for dissolved inorganics (filtered samples for arsenic, selenium, and manganese) to determine the potential for mobilization of inorganics and degradation of secondary water

quality. The shallow groundwater at the Kenney Avenue Plume is not a drinking water source, but increases in manganese and iron above comparison criteria did occur.

Background concentrations of total ferrous iron ranged from <0.01 to 0.07 mg/L. Concentrations within the reaction zone were reported up to >3.3 mg/L. Concentrations of ferrous iron downgradient of the reaction zone ranged up to 1.1 mg/L. Background concentrations of total manganese ranged from 0.8 to 19.3 mg/L. Concentrations within the reaction zone were reported up to 26.4 mg/L. Concentrations of manganese downgradient of the reaction zone ranged up to 31.9 mg/L.

Background (baseline) concentrations of dissolved manganese ranged from 2.3 to 8.0 mg/L. Following injection, concentrations of dissolved manganese were slightly elevated, ranging from 3.5 to 14 mg/L. Manganese is naturally elevated at the Kenney Avenue Plume site. Both background and treatment zone concentrations of manganese are elevated above the USEPA recommended secondary drinking water quality standard.

Baseline levels of arsenic were all less than the reporting limit of 0.030 mg/L. After injection, detected concentrations of arsenic within the injection wells ranged from 0.0047F to 0.0095F mg/L, which are estimated concentrations (F-flag). Arsenic concentrations in the other monitoring wells were either not detected or were estimated concentrations ranging from 0.0047F mg/L to 0.027F mg/L. The laboratory reporting limit of 0.030 mg/L for arsenic exceeds the USEPA MCL. Only one sample (0.027F mg/L for OU5KMW-04 in June 2008) had an estimated concentration of arsenic that is higher than the USEPA MCL. Concentrations of selenium in all samples were below the USEPA MCL for this parameter of 0.050 mg/L.

Undesirable VOCs. Acetone and 2-butanone were only detected at low estimated concentrations less than 0.01 mg/L, and never approached the USEPA Region 9 PRGs comparison criteria of 5.5 mg/L and 7.0 mg/L, respectively.

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

A reduction of less than 50 percent in the average hydraulic conductivity within the reaction zone is considered to be acceptable. For the Kenney Avenue Plume application, the hydraulic conductivity at wells OU5KINJ-02 and OU5KINJ-03 appeared to decrease slightly over time. For example the hydraulic conductivity at OU5KINJ-02 was estimated to be 99 ft/day in August 2006 and 55 ft/day in June 2008, decreasing the most between September 2007 (87 ft/day) and June 2008. Similarly, the hydraulic conductivity at OU5KINJ-03 was estimated to be 94 ft/day in August 2006 and 74 ft/day in June 2008, with the lowest estimate of hydraulic conductivity occurring in September 2007 (57 ft/day). One possible explanation for the observed decreases is biofouling of the aquifer and/or well screen due to the high concentrations of organic substrate at these injection locations. The magnitude of the reduction is less than 50 percent. It is difficult to assess the impact of the decrease in hydraulic conductivity, but it may result in uneven distribution of substrate during subsequent injections.

No. 6: Substrate Persistence and Long-Term Effectiveness

The use of a field-mixed emulsion with a larger droplet size resulted in less dispersion of the vegetable oil substrate, with concentrations of TOC greater than 100 mg/L being sustained in the injection wells over a 9-month period from September 2007 to June 2008. Prior injections could only sustain concentrations of TCE at approximately 30 to 40 mg/L. The use of commercial vegetable oil microemulsions are not appropriate for the coarse grained deposits and high rates of groundwater flow present at the Kenney Avenue Plume. It is possible that future applications could be effective by applying a field mixed emulsion on an annual basis.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

Modifications to the injection plan were required, and monitoring of seep locations at the toe of the plume and a direct-push sampling event were added to the monitoring protocol. The cost of the modifications was controlled to a limited extent by reducing the number of injection events from four to three. However, the total cost of the demonstration escalated from a proposed cost of \$372,000 to a final cost of \$503,000, a difference of \$131,000. A portion of this increase was due to additional substrate requirements, increasing from a proposed cost of \$14,900 to a final cost of \$62,600, a difference of \$47,700. Other costs included \$33,600 for a microcosm study and \$32,000 for pre-injection site characterization.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

Application of enhanced *in situ* bioremediation at the Kenney Avenue Plume is limited by site-specific conditions. Conditions that contribute to the limited effectiveness of the treatability study include 1) high rates of groundwater flow that disperse the substrate and limit the ability to sustain highly reducing conditions, 2) low populations of microbes (*Dehalococcoides*) capable of sequential dechlorination of TCE all the way to ethene, and 3) slow rates of microbial activity due to low groundwater temperatures (less than 10 °C).

The range of groundwater flow (888 ft/yr) is close to an upper limit to the rate of groundwater flow suitable for applying enhanced *in situ* bioremediation. The high rate of groundwater flow was a primary reason for having to modify the substrate to a form that does not readily disperse.

The presence of relatively high amounts of bioavailable manganese may have influenced the ORP of groundwater the site, with ORP remaining in the range of manganese reduction to sulfate reduction over the duration of the treatability study. However, methanogenesis was induced after switching to a field mixed emulsion, and it appears that incomplete dechlorination is related to a lack of *Dehalococcoides* dechlorinating species and low groundwater temperatures.

COST ASSESSMENT

Cost Summary, Kenney Avenue Plume, Elmendorf AFB, Alaska

Cost Element	Cost Item	Project Cost
Project Management (Subtotal = \$35,000)	Project management and procurement	\$35,000
System Design/Work Plan/Meetings (Subtotal = \$36,000)	- Labor for system design and work plan - Kick off Meeting	\$33,500 \$2,500
Pre-injection Site Characterization (Subtotal = \$32,000)	- Mobilization/Demobilization - Labor - Driller - Analytical laboratory - Equipment and supplies	\$4,000 \$9,100 \$13,700 \$2,200 \$3,000
Microcosm Study (Subtotal = \$33,600)	Microcosm Study and Report	\$33,600
Capital Construction/ System Installation (Subtotal = \$140,400)	- Installation method - Mobilization/Permitting/Dig Permits (includes travel and per diem) - Site labor - Drilling subcontractor - Subcontractor - surveyor - Construction material cost (well materials and injection equipment) - Substrate or amendment cost (including \$/lb and total cost) - Waste Disposal	- Injection wells \$20,000 \$40,100 \$39,000 \$2,200 \$6,000 \$29,700 (\$ per pound delivered) \$3,400
Operating Cost - Two additional injections of EVO and sodium lactate (Subtotal = \$82,000)	- Mobilization/Demobilization - Site Labor - Direct-Push Services - Equipment and Supplies - Substrate or amendment cost (including \$/lb and total cost)	\$8,000 \$21,100 \$12,000 \$8,000 \$32,900 (\$ per pound delivered)
Process Monitoring (includes baseline sampling) (Subtotal = \$144,000)	- Mobilization (includes travel and per diem) - Sampling labor - Sampling equipment and supplies - Analytical cost - Labor for reporting - Final results meeting - Number of events	\$6,000 \$41,000 \$8,000 \$28,700 \$55,300 \$5,000 - Four events
Total Application Cost		\$503,000

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** Kenney Avenue Plume, Elmendorf AFB, Alaska

NOTE: Unshaded boxes are user input.				
	Values	Range	Units	Notes
1. Treatment Zone Physical Dimensions				
Width (Perpendicular to predominant groundwater flow direction)	80	1-10,000	feet	
Length (Parallel to predominant groundwater flow)	20	1-1,000	feet	
Saturated Thickness	10	1-100	feet	
Treatment Zone Cross Sectional Area	800	--	ft ²	
Treatment Zone Volume	16,000	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	41,899	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	35,914	--	gallons	
Design Period of Performance	2.0	.5 to 5	year	Three injections over 13 months
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	35%	.05-50	percent	Sand and gravel
Effective Porosity	30%	.05-50	percent	
Average Aquifer Hydraulic Conductivity	73	.01-1000	ft/day	
Average Hydraulic Gradient	0.010	0.0001-0.1	ft/ft	Average all events
Average Groundwater Seepage Velocity through the Treatment Zone	2.43	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	888	--	ft/yr	
Average Groundwater Flux through the Treatment Zone	1,594,863	--	gallons/year	
Soil Bulk Density	1.65	1.4-2.0	gm/cm ³	Sand
Soil Fraction Organic Carbon (foc)	0.50%	0.01-10	percent	Assumed default value
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				Average of baseline concentrations
Oxygen	0.5	0.01 to 10	mg/L	Ranged from 0.12 to 2.5 mg/L
Nitrate	0.20	0.1 to 20	mg/L	Less than 0.3 mg/L
Sulfate	15	10 to 5,000	mg/L	Ranged from 14 to 16 mg/L
Carbon Dioxide (estimated as the amount of Methane produced)	3.9	0.1 to 20	mg/L	Methane Produced - Max. 17 mg/L
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	15	0.1 to 20	mg/L	Manganese Produced - Max. 32 mg/L
Iron (III) (estimated as the amount of Fe (II) produced)	1.8	0.1 to 20	mg/L	Ferrous Iron Produced - Max 2.9 mg/L
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.000	--	mg/L	
Trichloroethene (TCE)	0.036	--	mg/L	Well 403-WL-01 on 8/22/06
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.0002	--	mg/L	Well OU5KMW-05 on 8/22/06
Vinyl Chloride (VC)	0.0001	--	mg/L	Well OU5KMW-04 on 8/22/06
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				Average of baseline concentrations
Oxidation-Reduction Potential (ORP)	105	-400 to +500	mV	Baseline ranged from +44 to +225 mV
Temperature	8.1	5.0 to 30	°C	Ranged from 7.6 to 8.6 °C
pH	7.0	4.0 to 10.0	su	Ranged from 6.90 to 7.03
Alkalinity	378	10 to 1,000	mg/L	Ranged from 305 to 770 mg/L
Total Dissolved Solids (TDS, or salinity)	NA	10 to 1,000	mg/L	Not analyzed
Specific Conductivity	581	100 to 10,000	µs/cm	Ranged from 427 to 666 µs/cm
Chloride	19	10 to 10,000	mg/L	Ranged from 18 to 22 mg/L
Sulfide - Pre injection	0.06	0.1 to 100	mg/L	Ranged from <0.01 to 0.15 mg/L
Sulfide - Post injection	0.2	0.1 to 100	mg/L	Maximum 0.49 mg/L
B. Aquifer Matrix				
Total Iron	15,675	100 to 10,000	mg/kg	Average of five samples Fe ³⁺ plus Fe ²⁺
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	
Neutralization Potential	NA	1.0 to 100	Percent as CaCO ₃	

NOTES:

Background data based on baseline sampling in August 2006.
 Values for methane, manganese, and ferrous iron are post-injection averages for the four injection wells.
 Sulfate was added as an amendment to the substrate mixture.

Table S.2 Substrate Calculations in Hydrogen Equivalents**Site Name:** Inney Avenue Plume, Elmendorf AFB, Alaska

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
80	1-10,000	feet
20	1-1,000	feet
10	1-100	feet
800	--	ft ²
16,000	--	ft ³
35,914	--	gallons
2.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.35	.05-50	
0.3	.05-50	
73	.01-1000	ft/day
0.01	0.1-0.0001	ft/ft
2.43	--	ft/day
888.2	--	ft/yr
1,594,863	--	gallons/year
1.65	1.4-2.0	gm/cm ³
0.005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.5	0.13	7.94	0.02	4
0.2	0.06	10.25	0.01	5
15	4.50	11.91	0.38	8
3.9	1.17	1.99	0.59	8
Soluble Competing Electron Acceptor Demand (lb.)			0.99	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
15.3	411.82	27.25	15.11	2
1.8	48.45	55.41	0.87	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			15.99	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.000	0.00	20.57	0.00	8
0.036	0.01	21.73	0.00	6
0.000	0.00	24.05	0.00	4
0.000	0.00	31.00	0.00	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.000	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			0.00	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x C_{gw})
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	0.00	0.00	20.57	0.00	8
107	0.02	0.03	21.73	0.00	6
45	0.00	0.00	24.05	0.00	4
3.0	0.00	0.00	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			0.00		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	0.5	5.99	7.94	0.75	4
Nitrate (denitrification)	0.2	2.66	10.25	0.26	5
Sulfate	15	199.63	11.91	16.76	8
Carbon Dioxide (estimated as the amount of Methane produced)	3.9	51.90	1.99	26.08	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				43.9	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	0.036	0.48	21.73	0.02	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	0.00	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				0.02	

Initial Hydrogen Requirement First Year (lb)**60.9****Total Life-Cycle Hydrogen Requirement (lb)****104.7****5. Design Factors**

Microbial Efficiency Uncertainty Factor
Methane and Solid-Phase Electron Acceptor Uncertainty
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)

2X - 4X

2X - 4X

1X - 3X

Design Factor**1.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)****104.7****6. Acronyms and Abbreviations**

°C =degrees celsius

μS/cm = microsiemens per centimeter

cm/day = centimeters per day

cm/sec = centimeters per second

ft² = square feet

ft/day = feet per day

ft/ft = foot per foot

ft/yr = feet per year

gm/cm³ = grams per cubic centimeterkg of CaCO₃ per mg = kilograms of calcium carbonate per milligram

lb = pounds

meq/100 g = milliequivalents per 100 grams

mg/kg = milligrams per kilogram

mg/L = milligrams per liter

m/m = meters per meters

mV = millivolts

m/yr = meters per year

su = standard pH units

wt/wt H₂ = concentration molecular hydrogen, weight per weight

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

RESET DEFAULT

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 2

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	2,340	2,340	1.06E+09	87
Sodium Lactate Product (60 percent solution)	1.0	2,340	4,855	1.06E+09	87
Molasses (assuming 60 percent sucrose)	1.0	2,223	3,705	1.01E+09	83
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	2,340	2,926	1.06E+09	87
Ethanol Product (assuming 80% ethanol by weight)	1.0	1,197	1,496	5.43E+08	44
	1.0	1,615	2,307	7.33E+08	60
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	1,774	1,774	8.05E+08	53
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	911	911	4.13E+08	34
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	911	1,518	4.13E+08	34

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents**Site Name:** Kenney Avenue Plume, Elmendorf AFB, Alaska**1. Treatment Zone Physical Dimensions**

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	80	feet	24	meters
Length (parallel to groundwater flow)	20	feet	6.1	meters
Saturated Thickness	10	feet	3.0	meters
Design Period of Performance	2	years	2	years

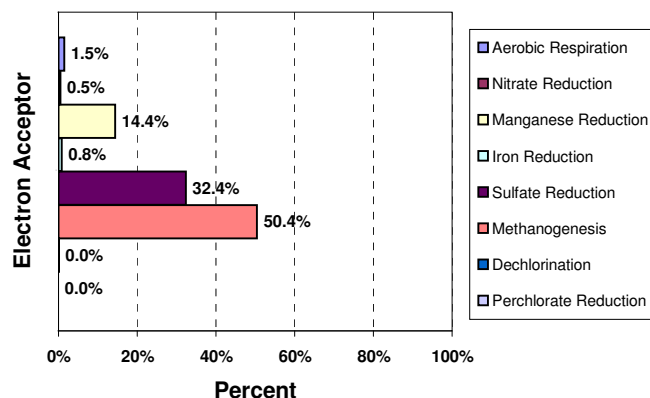
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.35	percent	0.35	percent
Effective Porosity	0.3	percent	0.3	percent
Average Aquifer Hydraulic Conductivity	73	ft/day	2.6E-02	cm/sec
Average Hydraulic Gradient	0.01	ft/ft	0.01	m/m
Average Groundwater Seepage Velocity	2.43	ft/day	7.4E+01	cm/day
Average Groundwater Seepage Velocity	888	ft/yr	270.7	m/yr
Total Treatment Zone Pore Volume	35,914	gallons	135,944	liters
Groundwater Flux (per year)	1,594,863	gallons/year	6,037,045	liters/year
Total Groundwater Volume Treated (over entire design period)	3,225,640	gallons total	12,210,034	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	1.5%	1.525
Nitrate Reduction	0.5%	0.525
Sulfate Reduction	32.4%	33.900
Manganese Reduction	14.4%	15.113
Iron Reduction	0.8%	0.874
Methanogenesis	50.4%	52.751
Dechlorination	0.0%	0.046
Perchlorate Reduction	0.0%	0.000
Totals:	100.00%	104.73

Hydrogen demand in pounds/gallon:	3.25E-05
Hydrogen demand in grams per liter:	3.89E-03

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor =****1.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	4,855	441	87	as lactic acid
2. Molasses Product	3,705	309	83	as sucrose
3. Fructose Product	2,926	261	87	as fructose
4. Ethanol Product	1,496	217	44	as ethanol
5. Sweet Dry Whey (lactose)	2,307	sold by pound	60	as lactose
6. HRC®	1,774	sold by pound	53	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	911	117	34	as soybean oil
8. Emulsified Vegetable Oil	1,518	195	34	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

SITE SUMMARY**Contemporary Cleaners Site, Orlando, Florida**

For: Project Files for ESTCP Substrate Loading Study (Job No. 745255)

Review/Update: 17 August 2009

SITE IDENTIFICATION

Contemporary Cleaners Site, Orlando, Florida

CONTAMINANT SOURCE

<i>COC</i>	<i>Maximum Concentration</i>	<i>DNAPL Present?</i>	<i>Notes</i>
PCE	12,100 µg/L	No	Ref (1) - MW019 on 3/4/99 (upper aquifer)
TCE	4,980 µg/L	No	Ref (1) – DP002 on 11/14/97 (lower aquifer)
<i>cis</i> -1,2-DCE	4,000 µg/L	No	Ref (1) – DP012 on 3/28/97 (upper aquifer)
<i>trans</i> -1,2-DCE	130 µg/L	No	Ref (1) – DP012 on 3/28/97 (upper aquifer)
VC	2,900 µg/L	No	Ref (1) – DP003 on 3/26/97 (upper aquifer)

SUBSTRATE DESIGN/INSTALLATION INFORMATION

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
Phase I – Full-scale Upper Surficial Aquifer and Pilot-Scale Lower Surficial Aquifer			
Project Scale	Full-Scale Upper Surficial Aquifer and Pilot-Scale Lower Surficial Aquifer	No change	0 to 30 feet = Upper Surficial Aquifer 30 to 50 feet = Lower Surficial Aquifer
Substrate Type	HRC®	No change	
Number of Injection Points (IP)	144 (upper aquifer) 7 (lower aquifer)	No change	A second injection was performed 18 months later targeting the lower surficial aquifer (Ref [4]).
IP Spacing Information	10 feet	No change	
Injection Date	January-February 1999	No change	
Injection Interval (depth bgs)	5-30 feet (upper aquifer) 40-55 feet (lower aquifer)	No change	
Substrate Loading - Upper	Total of 3,240 lbs into 144 points, or 0.9 lb per vertical foot.	Total of 6,800 lbs injected into 147 points, or approx. 1.9 lb per vertical foot.	REF (1). Varied between 1.5 and 6.0 gallons per point based on estimated concentration of VOCs.

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
Substrate Loading - Lower	Total of 158 lbs into 7 points, or 0.9 lb per vertical foot.	No change	REF (1)
Basis for Loading Rate	Vendor Recommendation	Vendor diluted product for ease of injection, resulting in a greater weight of product.	
Injection amendment?	No	No change	
Pre-injection Specified?	No	No change	
Post-injection Specified?	No	No change	
Phase II – Expanded Upper Surficial Aquifer and Full-scale Lower Surficial Aquifer			
Project Scale	Full-Scale Upper Surficial Aquifer (Zone 1) and Full-Scale Lower Surficial Aquifer (Zone 2)	Changes made based on field conditions during injection. Primarily fewer injection points due to presence of utilities or direct-push refusal.	The second injection was performed 18 months after initial injection, targeting the upper and lower surficial aquifers. Some discrepancies exist between installation reports by IT Corp. (Ref [1,4]). and papers presented by Kean <i>et al.</i> (Ref [2,3]).
Substrate Type	HRC®	No change	
Number of Injection Points (IP) – Upper Surficial Aquifer (Zone 1)	50 IP	47 IP from 5 to 30 feet bls (starting July 2000)	Ref (4). Covered an area approximately 45 by 112 feet.
Number of Injection Points (IP) – Lower Surficial Aquifer (Zone 2)	128 IP	99 IP from 35 to 55 feet bls (Starting August 2000)	Ref (4). Covered an area of approximately 90 by 150 feet.
IP Spacing Information	10 feet	No change	
Injection Date	July-August 2000	No change	
Injection Interval (depth bgs)	5-30 feet (upper surficial aquifer) 35-55 feet (lower surficial aquifer)	No change. Some points encountered refusal at less depth.	Some injections in the lower surficial aquifer extended into the underlying upper intermediate aquifer.
Substrate Loading – Zone 1	1,250 lbs into 50 points, 25 lbs per point at 1.25 lb per vertical foot.	Injected 1,410 pounds into 47 points, 30 lbs per point or 1.2 lb per vertical foot.	Ref 4)
Substrate Loading – Zone 2	2,600 lbs – Proposed at 1.0 lb per vertical foot	Injected 2,475 lbs total. 25 lbs per point at 1.25 lbs per vertical foot.	Ref (4)
Basis for Loading Rate	Vendor	Changes based on	

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
	Recommendation	field conditions	
Injection amendment?	No	No change	
Pre-injection Specified?	No	No change	
Post-injection Specified?	No	No change	

MONITORING INFORMATION

<i>Sample Collection Date</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Reference</i>
January 1999	Yes	No	Yes	No	Ref(1)
March 1999	Yes	No	Yes	No	Ref(1)
April 1999	No ^{a/}	Yes ^{b/}	Yes	Yes – no date	Ref(2,3)
May 1999	No	Yes	Yes	“	Ref(2,3)
June 1999	No	Yes	Yes	“	Ref(2,3)
July 1999	No	Yes	Yes	“	Ref(2,3)
February 2001	No	Yes	Yes	“	Ref(2,3)
May 2001	No	Yes	Yes	“	Ref(2,3)
August 2001	No	Yes	Yes	“	Ref(2,3)

^{a/} Charts and graphs but no tabulated data. Data through march 1999 tabulated in Ref(1).

^{b/} Total organic acids.

REFERENCES

- (1) IT Corporation. 1999. *HRC™ Pilot Test Installation Report*. Contemporary Cleaners Site, Orlando, Florida. March. (**Installation Report, includes proposed plan from Regenesis**).
- (2) Kean, J. A., D. Graves, and M. Lodato. 2003. Enhanced Reductive Dechlorination and the Relationship between *cis*-1,2-DCE Accumulation and Methanogenesis. Paper A-05. *Proceedings of the Seventh International Symposium of In Situ and On-Site Bioremediation*. Orlando, Florida, June 2003. Battelle Press, Columbus, Ohio. (**Case Study Paper**)
- (3) Kean, J. A., D. Graves, K. Bishop, E. Mott-Smith, and M. Lodato. 2002. Obstacles to Complete PCE Degradation During Reductive Dechlorination. In: A.R. Gavaskar and A.S.C. Chen (Eds.), *Remediation of Chlorinated and Recalcitrant Compounds – 2002*, Proceedings of the Third International Conference on Remediation of Chlorinated and Recalcitrant Compounds (Monterey, CA; May 2002). Paper 2B-48. Battelle Press, Columbus, Ohio. (**Case Study Paper**)
- (4) IT Corporation. 2000. *HRC™ Completion Report*. Contemporary Cleaners Site, Orlando, Florida. September 8. (**Variance to Phase II Installation**).
- (5) Kean, J.A., Lodato, M.N., Graves, D. 2000. Enhanced Biological Reductive Dechlorination at a Dry Cleaning Facility. *Ground Water Currents*, No. 37, September 2000. (**Case Study Paper**)

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates calculated or designed?

Substrate loading rates were based on recommendations from Regenesis Bioremediation Products (Appendix A in Ref [1]), specified in pounds of product per vertical foot with specification of injection point spacing. It is assumed that Regenesis used an in-house spreadsheet tool based on stoichiometric demand to determine the loading rate. Changes were made by the vendor prior to the injection. IT Corporation (REF [1]) indicates this was a result of Regenesis reformulating the product by diluting it to a more readily injected form.

2. What modifications to the substrate amendment protocol were required (e.g., concentration and frequency for soluble substrates; and depletion and additional injection of slow-release substrate types such as HRC[®] and EVO).

Modification were mostly a result of field conditions encountered. Additional applications of substrate were not performed. Kean *et al.* (2002 and 2003) interpret a temporal stall in dechlorination of DCE to be due to methanogens out competing *Dehalococcoides* species, and interpret this to be due to too much substrate being applied. This interpretation is inconsistent with observations at other enhanced *in situ* bioremediation applications where rapid and complete dechlorination often occurs under methanogenic conditions.

3. Evaluation from Substrate Demand Tool

Site data were input into the substrate demand tool for both the upper and lower surficial aquifers for the Phase 1 injection only (attached). For the upper surficial aquifer, the substrate demand to treat 794,087 gallons (3,005,863 liters) of groundwater over 2.0 years was 82.29 pounds of molecular hydrogen, or 1.04E-04 pounds per gallon (1.24E-02 grams per liter) of groundwater treated. This hydrogen demand could be met by 1,394 pounds of HRC[®] product, assuming the product is 40 percent lactic acid and 40 percent glycerol by weight. Based on the mass of substrate applied at the Contemporary Cleaners dissolved plume (approximately 6,600 pounds of HRC[®]), the effective design factor applied at the site was 4.7 times the estimated hydrogen demand.

For the lower surficial aquifer Phase 1 pilot test, the substrate demand to treat 10,388 gallons (39,322 liters) of groundwater over 2.0 years was 0.98 pounds of molecular hydrogen, or 9.43E-05 pounds per gallon (1.13E-02 grams per liter) of groundwater treated. This hydrogen demand could be met by 17 pounds of HRC[®] product, assuming the product is 40 percent lactic acid and 40 percent glycerol by weight. Based on the mass of substrate applied in the lower surficial zone (approximately 160 pounds of HRC[®]), the effective design factor applied in this zone was 9.4 times the estimated hydrogen demand. Much closer injection point spacing (3 feet) was used for the lower surficial aquifer pilot test.

The primary electron accepting process in the upper surficial aquifer was methanogenesis (60.7%), followed by dechlorination of chlorinated solvents (18.2%), sulfate reduction (13.5%), iron reduction (2.9%), aerobic respiration (2.0%), manganese reduction (1.5%), and nitrate reduction (1.2%).

The primary electron accepting process in the lower surficial aquifer was methanogenesis (66.7%), followed by sulfate reduction (14.9%), dechlorination of chlorinated solvents (11.3%), iron reduction (3.2%), manganese reduction (1.6%), nitrate reduction (1.3%), and aerobic respiration (1.1%).

PERFORMANCE OBJECTIVES

No. 1: Ability to Uniformly Distribute Substrate : Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

The presence and persistence of organic acids in both the upper and lower surficial aquifers was highly variable. For three wells in the upper surficial aquifer, total organic acids ranged from below detection to as high as 410 mg/L over a period of 27 months (monitoring data from March 1999 to May 2001, following the first injection in February 1999). Organic acids were still elevated (40 mg/L or higher) in two of the three wells in the upper surficial aquifer in July 1999, but all concentrations were below 30 mg/L in subsequent monitoring events starting in February 2001. This suggests that the effective duration of the HRC[®] product was on the order of 7 to 27 months.

For the lower surficial aquifer (intermediate zone), the concentrations of total organic acids were also highly variable in the two wells monitored, ranging from below detection up to 833 mg/L. Concentrations at the two wells in August 2001 were 29 and 69 mg/L, indicating the substrate still persisted for at least 12 months following the August 2000 injection; although it should be noted that concentration of total organic acids in the two lower aquifer wells were 1.0 mg/L or less in the previous sampling event in May 2001.

In summary, the HRC product released elevated levels of organic acids for up to 12 months, but the distribution was not uniform or consistent from one monitoring event to another. The slow rate of groundwater flow at this site (estimated to be 16 feet per year in the upper surficial aquifer and 2.6 feet per year in the lower surficial aquifer) may have limited the dispersion of organic acids.

No. 2: Achieving Optimal Geochemical Conditions

Successful geochemical conditions for stimulating anaerobic degradation of chlorinated solvents is defined as when the groundwater environment is highly anaerobic with DO less than 0.5 mg/L, ORP is less than -200 mV, sulfate is reduced by more than 50 percent relative to background conditions, and methane is greater than 1.0 mg/L. These criteria may not apply in all cases.

Only limited geochemical data is available for the Contemporary Cleaners Site. Elevated concentrations of sulfide (> 5 mg/L), dissolved iron (up to 20.6 mg/L), and methane (up to 54 mg/L) indicate that highly reducing geochemical conditions were achieved. ORP data are only available through March 1999 (1 to 2 months following the first injection, Ref[1]), and were typically in the range of -100 to -200 mV.

Data for pH through March 1999 indicates that pH was low for effective dechlorination of chlorinated ethenes. Pre-injection measurements of pH for the upper surficial aquifer typically

ranged from 5.0 to 6.0, and ranged from 4.15 to 5.97 (typically below 5.0) in March 1999 after the first injection. This site may have benefited from the use of amendments to control pH.

No. 3: Remediation Effectiveness: Evaluate efficiency in removal of VOCs based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Determine “threshold” concentrations of dissolved organic carbon that represent the minimum levels required to sustain complete reductive dechlorination.

The success of the application is evaluated by comparing concentrations to site-specific performance criteria, if established. Otherwise, a reduction in contaminant concentration of 99 percent or greater (over two orders of magnitude) is considered successful. For chlorinated aliphatic hydrocarbons (CAHs, or chlorinated solvents) where production of regulated intermediate dechlorination products may occur, a reduction in the total molar concentration of CAHs of greater than 90 percent is considered to be a success.

The initial injection into the upper surficial aquifer was considered successful based on a rapid removal of PCE with limited production of DCE and VC. The second injection into the lower surficial aquifer resulted in dechlorination of PCE, but also in a significant increase in *cis*-DCE. Some reduction in *cis*-DCE was eventually observed, but the persistence and increase in concentrations of *cis*-DCE through August 2002 shows that performance criteria were not achieved. There is insufficient data available to make a quantitative analysis of reductions in total molar concentrations, but total VOCS in the lower surficial aquifer were higher in August 2002 (2 years post injection) than during any previous monitoring event (Figure 4 in Kean *et al.*, 2003).

No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

Secondary water quality parameters that were evaluated for the Contemporary Cleaners Site include sulfide and dissolved iron. Data for other potential secondary water quality parameters post-injection were not reported. The values used in this evaluation are from a table of select monitoring well geochemical data from within the treatment zones. The well locations from which the values were derived were not specified.

A pre-injection sulfide concentration of 0.08 mg/L was reported, with post injection concentrations of sulfide ranging from 0.08 to >5.0 mg/L. The pre-injection sulfate concentration for sulfate was reported to be below detection, and it is difficult to correlate the elevated sulfide concentrations to reductions in sulfate. Sulfide concentrations greater than 5 mg/L are likely to cause an odor issue.

A pre-injection concentration for filtered iron was reported to be 3.49 mg/L, which is above the USEPA recommended secondary drinking water quality standard. Post injection concentrations of dissolved iron were reported to range from 0.98 to 20.6 mg/L. The magnitude of the increase in dissolved iron concentration could be a potential issue at this site.

Summary of Secondary Water Quality – Contemporary Cleaners Site

Parameter	Comparison Criteria	Background	Treatment Zone	Down-gradient	Issues?
Sulfide (mg/L)	NA	0.08	0.08 to >5.0	Not Reported	Potential – elevated concentrations >5.0 mg/L
Total Iron (mg/L)	0.3 (b)	3.49	0.98 to 20.6	Not Reported	Potential – background above criteria

Notes:

Background values from pre-injection monitoring event.

Monitoring well locations not specified.

mg/L = milligrams per liter.

Criteria based on (a) USEPA MCL; (b) USEPA Secondary Standard; or (c) USEPA Region 9 PRG.

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

Data on groundwater hydraulics are not sufficient to evaluate impacts on hydraulic conductivity. Based on the relatively low application rate of HRC[®] product (less than 2 pounds per vertical foot), there is no reason to suspect that an adverse impact occurred. Hydraulic conductivity in the upper surficial aquifer was reported to range from 0.01 ft/day to 12.6 ft/day (averaging 1.3 ft/day), and from 0.1 to 0.8 ft/day (averaging 0.6 ft/day) in the lower surficial aquifer. Hydraulic conductivity in the lower surficial aquifer may be less than optimal for injection of a viscous fluid.

No. 6: Substrate Persistence and Long-Term Effectiveness

Concentrations of total organic acids in the upper surficial aquifer remained elevated in two of three monitoring wells through 7 months post injection, but declined to less than 30 mg/L at 24 months post injection. There also appears to be a rebound in total concentration of VOCs in July 1999 (7 months post injection) and May 2001 (27 months post injection), with the total VOC concentration in May 2001 comprised mostly of *cis*-DCE. Therefore, the effective duration of the HRC application in the upper surficial aquifer is in the range of 7 to 27 months. The rebound appears to correlate to total organic acid concentrations falling below 30 to 40 mg/L.

Concentrations at the two wells in the lower surficial aquifer in August 2001 were 29 and 69 mg/L, indicating the substrate still persisted for at least 12 months following the August 2000 injection; although it should be noted that concentration of total organic acids in the two lower aquifer wells were 1.0 mg/L or less in the previous sampling event in May 2001. Total VOCs (mostly *cis*-DCE) in the lower aquifer increased for four out of the five monitoring events following the Phase II injection in August 2000. Therefore, the HRC[®] application in the lower surficial aquifer was not effective in lowering concentrations of total VOCs.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

No post-injection modifications were performed. Additional injections were not necessary to sustain degradation of PCE over the intended design life of the Contemporary Cleaners application. Additional injections would likely be required to further reduce concentrations of DCE and VC.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

There were no apparent hydraulic limitations to injection of HRC[®] at the Contemporary Cleaners Site. The rate of groundwater flow was estimated to be 16 feet per year in the upper surficial aquifer and 2.6 feet per year in the lower surficial aquifer. These rates of groundwater flow are less than optimal for a passive application of enhanced *in situ* bioremediation. An accumulation of *cis*-DCE in the lower surficial aquifer was initially thought to be influenced by drought conditions from 1999 to 2001, which lowered the water table and increased the vertical hydraulic gradient (Kean *et al.*, 2003). However, site wide correlation between DCE concentrations and groundwater elevation could not be made.

Kean *et al.* (2003) attributed the stall in dechlorination of *cis*-DCE to excessive methanogenesis. They report a correlation between the accumulation of *cis*-DCE and methanogenesis, such that dechlorination of *cis*-DCE began to occur after methanogenesis subsided. This suggested to the authors that methanogens were out competing the halo-respiring bacteria. An alternative explanation may be that pH was less than optimal, with pH of less than 5.0 in many locations shortly after the first injection. An evaluation of the impact of low pH was not mentioned in any result documents or case study papers.

3. COST ASSESSMENT

Cost Summary, Contemporary Cleaners, Orlando Florida

Cost data for the Contemporary Cleaners Site are not available.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** Contemporary Cleaners, Orlando, Florida

NOTE: Unshaded boxes are user input.				
1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	80	1-10,000	feet	Upper Surficial Aquifer - Phase 1
Length (Parallel to predominant groundwater flow)	180	1-1,000	feet	144 points on 10-foot centers
Saturated Thickness	25	1-100	feet	Injected from 30 to 5 ft bgs
Treatment Zone Cross Sectional Area	2000	--	ft ²	
Treatment Zone Volume	360,000	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	808,056	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	673,380	--	gallons	
Design Period of Performance	2.0	.5 to 5	year	Not Specified - Assume 24 months
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	Estimated
Effective Porosity	25%	.05-50	percent	Estimated from flow rate
Average Aquifer Hydraulic Conductivity	1.3	.01-1000	ft/day	
Average Hydraulic Gradient	0.009	0.0001-0.1	ft/ft	Mounded - Flow generally to West
Average Groundwater Seepage Velocity through the Treatment Zone	0.04	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	16.1	--	ft/yr	Estimated to be 16 ft/yr
Average Groundwater Flux through the Treatment Zone	60,354	--	gallons/year	
Soil Bulk Density	1.65	1.4-2.0	gm/cm ³	Silty fine-grained Sand to 30 ft bgs
Soil Fraction Organic Carbon (foc)	0.50%	0.01-10	percent	Assumed default value
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	2.0	0.01 to 10	mg/L	Ranged from 0.3 to 3.0 mg/L
Nitrate	1.50	0.1 to 20	mg/L	Maximum of 1.5 mg/L
Sulfate	20	10 to 5,000	mg/L	Background not reported, assumed
Carbon Dioxide (estimated as the amount of Methane produced)	15	0.1 to 20	mg/L	Methane Produced - Max. 23 mg/L
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	5.0	0.1 to 20	mg/L	Not Analyzed - Assumed 5 mg/L
Iron (III) (estimated as the amount of Fe (II) produced)	20.0	0.1 to 20	mg/L	Ferrous Iron Produced - Max 21 mg/L
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	3.300	--	mg/L	DP005 in 1997
Trichloroethene (TCE)	2.400	--	mg/L	DP012 in 1997
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	4.000	--	mg/L	DP012 in 1997
Vinyl Chloride (VC)	2.900	--	mg/L	DP003 in 1997
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	-96	-400 to +500	mV	Background -196 to -32 mV
Temperature	27	5.0 to 30	°C	Ranged from 77.5 to 82.9 °F
pH	5.1	4.0 to 10.0	su	Ranged from 4.59 to 5.80
Alkalinity	NA	10 to 1,000	mg/L	Not analyzed
Total Dissolved Solids (TDS, or salinity)	NA	10 to 1,000	µs/cm	Not analyzed
Specific Conductivity	150	100 to 10,000	µs/cm	Ranged from 100 to 200 µs/cm
Chloride	NA	10 to 10,000	mg/L	Not analyzed
Sulfide - Pre injection	NA	0.1 to 100	mg/L	Not analyzed or not reported
Sulfide - Post injection	>5.0	0.1 to 100	mg/L	Maximum >5.0 mg/L
B. Aquifer Matrix				
Total Iron	NA	100 to 10,000	mg/kg	
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	
Neutralization Potential	NA	1.0 to 100	Percent as CaCO ₃	

NOTES:

Background data based on sampling in January 1998 and January 1999 at locations MW002 through MW006, MW011, MW012, and MW019 through MW022.
 Values for methane, manganese, and ferrous iron are post-injection.
 Injected 2.45 gallon per point, or 0.9 pounds per vertical foot on average; actual ranged from 1.5 to 6.0 gallons per point.

Table S.2 Substrate Calculations in Hydrogen Equivalents
Site Name: **Contemporary Cleaners, Orlando, Florida**

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
80	1-10,000	feet
180	1-1,000	feet
25	1-100	feet
2000	--	ft ²
360,000	--	ft ³
673,380	--	gallons
2.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.3	.05-50	
0.25	.05-50	
1.3	.01-1000	ft/day
0.0085	0.1-0.0001	ft/ft
0.04	--	ft/day
16.1	--	ft/yr
60,354	--	gallons/year
1.65	1.4-2.0	gm/cm ³
0.005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
2.0	11.24	7.94	1.42	4
1.5	8.43	10.25	0.82	5
20	112.38	11.91	9.44	8
15.0	84.29	1.99	42.35	8
Soluble Competing Electron Acceptor Demand (lb.)			54.03	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
5.0	33.13	27.25	1.22	2
20.0	132.53	55.41	2.39	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			3.61	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
3.300	18.54	20.57	0.90	8
2.400	13.49	21.73	0.62	6
4.000	22.48	24.05	0.93	4
2.900	16.30	31.00	0.53	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.000	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			2.98	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x C_{gw})
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	4.34	160.95	20.57	7.82	8
107	1.28	47.62	21.73	2.19	6
45	0.90	33.38	24.05	1.39	4
3.0	0.04	1.61	31.00	0.05	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			11.46		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	2.0	1.01	7.94	0.13	4
Nitrate (denitrification)	1.5	0.76	10.25	0.07	5
Sulfate	20	10.07	11.91	0.85	8
Carbon Dioxide (estimated as the amount of Methane produced)	15	7.55	1.99	3.80	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				4.8	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	3.300	1.66	20.57	0.08	8
Trichloroethene (TCE)	2.400	1.21	21.73	0.06	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	4.000	2.01	24.05	0.08	4
Vinyl Chloride (VC)	2.900	1.46	31.00	0.05	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				0.27	

Initial Hydrogen Requirement First Year (lb)	77.2

Total Life-Cycle Hydrogen Requirement (lb)	82.3

5. Design Factors

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X

Design Factor	1.0

Total Life-Cycle Hydrogen Requirement with Design Factor (lb)	82.3

6. Acronyms and Abbreviations

°C =degrees celsius	meq/100 g = milliequivalents per 100 grams
μs/cm = microsiemens per centimeter	mg/kg = milligrams per kilogram
cm/day = centimeters per day	mg/L = milligrams per liter
cm/sec = centimeters per second	m/m = meters per meters
ft ² = square feet	mV = millivolts
ft/day = feet per day	m/yr = meters per year
ft/ft = foot per foot	su = standard pH units
ft/yr = feet per year	wt/wt H ₂ = concentration molecular hydrogen, weight per weight
gm/cm ³ = grams per cubic centimeter	
kg of CaCO ₃ per mg = kilograms of calcium carbonate per milligram	
lb = pounds	

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

RESET DEFAULT

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 2

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	1,839	1,839	8.34E+08	277
Sodium Lactate Product (60 percent solution)	1.0	1,839	3,814	8.34E+08	277
Molasses (assuming 60 percent sucrose)	1.0	1,747	2,911	7.92E+08	264
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	1,839	2,299	8.34E+08	278
Ethanol Product (assuming 80% ethanol by weight)	1.0	940	1,175	4.27E+08	142
Whey (assuming 100% lactose)	1.0	1,269	1,813	5.76E+08	192
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	1,394	1,394	6.32E+08	168
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	716	716	3.25E+08	108
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	716	1,193	3.25E+08	108

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Contemporary Cleaners, Orlando, Florida

1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	80	feet	24	meters
Length (parallel to groundwater flow)	180	feet	54.9	meters
Saturated Thickness	25	feet	7.6	meters
Design Period of Performance	2	years	2	years

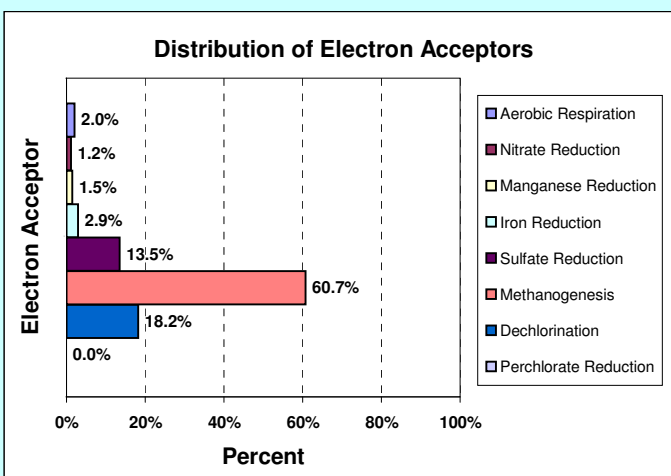
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.25	percent	0.25	percent
Average Aquifer Hydraulic Conductivity	1.3	ft/day	4.6E-04	cm/sec
Average Hydraulic Gradient	0.0085	ft/ft	0.0085	m/m
Average Groundwater Seepage Velocity	0.04	ft/day	1.3E+00	cm/day
Average Groundwater Seepage Velocity	16	ft/yr	4.9	m/yr
Total Treatment Zone Pore Volume	673,380	gallons	2,548,949	liters
Groundwater Flux (per year)	60,354	gallons/year	228,457	liters/year
Total Groundwater Volume Treated (over entire design period)	794,087	gallons total	3,005,863	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.0%	1.669
Nitrate Reduction	1.2%	0.970
Sulfate Reduction	13.5%	11.127
Manganese Reduction	1.5%	1.216
Iron Reduction	2.9%	2.392
Methanogenesis	60.7%	49.947
Dechlorination	18.2%	14.973
Perchlorate Reduction	0.0%	0.000
Totals:	100.00%	82.29

Hydrogen demand in pounds/gallon:	1.04E-04
Hydrogen demand in grams per liter:	1.24E-02

**4. Substrate Equivalents: Design Factor =****1.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	3,814	347	277	as lactic acid
2. Molasses Product	2,911	243	264	as sucrose
3. Fructose Product	2,299	205	278	as fructose
4. Ethanol Product	1,175	170	142	as ethanol
5. Sweet Dry Whey (lactose)	1,813	sold by pound	192	as lactose
6. HRC®	1,394	sold by pound	168	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	716	92	108	as soybean oil
8. Emulsified Vegetable Oil	1,193	153	108	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** Contemporary Cleaners, Orlando, Florida

NOTE: Unshaded boxes are user input.				
1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	24	1-10,000	feet	Lower Surficial Aquifer - Phase 1
Length (Parallel to predominant groundwater flow)	4	1-1,000	feet	7 points in row on 3- to 4-foot centers
Saturated Thickness	25	1-100	feet	Injected from 55 to 30 ft bgs
Treatment Zone Cross Sectional Area	600	--	ft ²	
Treatment Zone Volume	2,400	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	5,387	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	4,489	--	gallons	
Design Period of Performance	2.0	.5 to 5	year	Not Specified - Assume 24 months
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	Estimated
Effective Porosity	25%	.05-50	percent	Estimated from flow rate
Average Aquifer Hydraulic Conductivity	0.3	.01-1000	ft/day	
Average Hydraulic Gradient	0.006	0.0001-0.1	ft/ft	Flow to South
Average Groundwater Seepage Velocity through the Treatment Zone	0.01	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	2.63	--	ft/yr	Estimated to be 2.6 ft/yr
Average Groundwater Flux through the Treatment Zone	2,949	--	gallons/year	
Soil Bulk Density	1.65	1.4-2.0	gm/cm ³	Silty Clayey Sand and Sandy Clay
Soil Fraction Organic Carbon (foc)	0.50%	0.01-10	percent	Assumed default value
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.0	0.01 to 10	mg/L	Ranged from 0.4 to 1.1 mg/L
Nitrate	1.50	0.1 to 20	mg/L	Maximum of 1.5 mg/L
Sulfate	20	10 to 5,000	mg/L	Background not reported, assumed
Carbon Dioxide (estimated as the amount of Methane produced)	15	0.1 to 20	mg/L	Methane Produced - Max. 23 mg/L
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	5	0.1 to 20	mg/L	Not Analyzed - Assumed 5 mg/L
Iron (III) (estimated as the amount of Fe (II) produced)	20.0	0.1 to 20	mg/L	Ferrous Iron Produced - Max 21 mg/L
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	2.706	--	mg/L	DP011 in 1997
Trichloroethene (TCE)	4.980	--	mg/L	DP002 in 1997
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	1.000	--	mg/L	DP017 in 1997
Vinyl Chloride (VC)	0.000	--	mg/L	ND in 1997
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	10	-400 to +500	mV	Background -100 to +277 mV
Temperature	27	5.0 to 30	°C	Ranged from 77.5 to 81.1 °F
pH	5.6	4.0 to 10.0	su	Ranged from 4.57 to 6.50
Alkalinity	NA	10 to 1,000	mg/L	Not analyzed
Total Dissolved Solids (TDS, or salinity)	NA	10 to 1,000	µs/cm	Not analyzed
Specific Conductivity	220	100 to 10,000	µs/cm	Ranged from 130 to 310 µs/cm
Chloride	NA	10 to 10,000	mg/L	Not analyzed
Sulfide - Pre injection	NA	0.1 to 100	mg/L	Not analyzed
Sulfide - Post injection		0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	NA	100 to 10,000	mg/kg	
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	
Neutralization Potential	NA	1.0 to 100	Percent as CaCO ₃	

NOTES:

Background data based on sampling in January 1998 and January 1999 at locations MW007 through MW009, MW013, MW014, MW017, MW018, and MW023.
 Values for methane, manganese, and ferrous iron are post-injection.
 Injected 2.45 gallon per point, or 0.9 pounds per vertical foot

Table S.2 Substrate Calculations in Hydrogen Equivalents
Site Name: **Contemporary Cleaners, Orlando, Florida**

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
24	1-10,000	feet
4	1-1,000	feet
25	1-100	feet
600	--	ft ²
2,400	--	ft ³
4,489	--	gallons
2.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.3	.05-50	
0.25	.05-50	
0.3	.01-1000	ft/day
0.006	0.1-0.0001	ft/ft
0.01	--	ft/day
2.6	--	ft/yr
2,949	--	gallons/year
1.65	1.4-2.0	gm/cm ³
0.005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
1.0	0.04	7.94	0.00	4
1.5	0.06	10.25	0.01	5
20	0.75	11.91	0.06	8
15.0	0.56	1.99	0.28	8
Soluble Competing Electron Acceptor Demand (lb.)			0.36	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
5.0	0.43	27.25	0.02	2
20.0	1.73	55.41	0.03	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			0.05	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
2.706	0.10	20.57	0.00	8
4.980	0.19	21.73	0.01	6
1.000	0.04	24.05	0.00	4
0.000	0.00	31.00	0.00	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.000	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			0.02	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x Cgw)
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	3.56	0.88	20.57	0.04	8
107	2.66	0.66	21.73	0.03	6
45	0.23	0.06	24.05	0.00	4
3.0	0.00	0.00	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			0.08		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

Oxygen	1.0	0.02	7.94	0.00	4
Nitrate (denitrification)	1.5	0.04	10.25	0.00	5
Sulfate	20	0.49	11.91	0.04	8
Carbon Dioxide (estimated as the amount of Methane produced)	15	0.37	1.99	0.19	8

Total Competing Electron Acceptor Demand Flux (lb/yr)**0.2****B. Soluble Contaminant Electron Acceptors**

Tetrachloroethene (PCE)	2.706	0.07	20.57	0.00	8
Trichloroethene (TCE)	4.980	0.12	21.73	0.01	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	1.000	0.02	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6

Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)**0.01****Initial Hydrogen Requirement First Year (lb)****0.7****Total Life-Cycle Hydrogen Requirement (lb)****1.0****5. Design Factors**

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X

Design Factor**1.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)****1.0****6. Acronyms and Abbreviations**

°C =degrees celsius	meq/100 g = milliequivalents per 100 grams
μs/cm = microsiemens per centimeter	mg/kg = milligrams per kilogram
cm/day = centimeters per day	mg/L = milligrams per liter
cm/sec = centimeters per second	m/m = meters per meters
ft ² = square feet	mV = millivolts
ft/day = feet per day	m/yr = meters per year
ft/ft = foot per foot	su = standard pH units
ft/yr = feet per year	wt/wt H ₂ = concentration molecular hydrogen, weight per weight
gm/cm ³ = grams per cubic centimeter	
kg of CaCO ₃ per mg = kilograms of calcium carbonate per milligram	
lb = pounds	

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

RESET DEFAULT

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 2

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	22	22	9.93E+06	253
Sodium Lactate Product (60 percent solution)	1.0	22	45	9.93E+06	253
Molasses (assuming 60 percent sucrose)	1.0	21	35	9.43E+06	240
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	22	27	9.93E+06	253
Ethanol Product (assuming 80% ethanol by weight)	1.0	11	14	5.08E+06	129
Whey (assuming 100% lactose)	1.0	15	22	6.86E+06	174
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	17	17	7.53E+06	153
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	9	9	3.87E+06	98
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	9	14	3.87E+06	98

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Contemporary Cleaners, Orlando, Florida

1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	24	feet	7	meters
Length (parallel to groundwater flow)	4	feet	1.2	meters
Saturated Thickness	25	feet	7.6	meters
Design Period of Performance	2	years	2	years

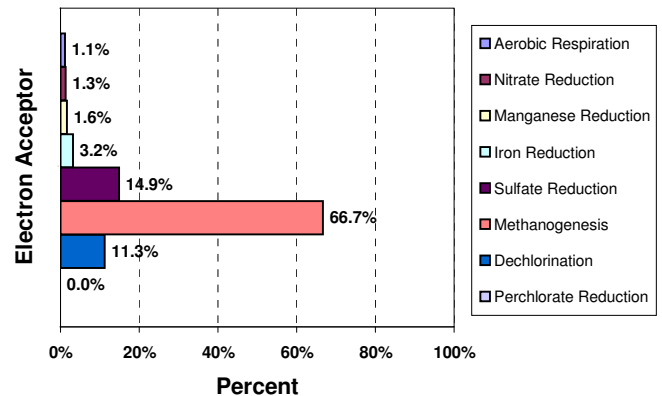
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.25	percent	0.25	percent
Average Aquifer Hydraulic Conductivity	0.3	ft/day	1.1E-04	cm/sec
Average Hydraulic Gradient	0.006	ft/ft	0.006	m/m
Average Groundwater Seepage Velocity	0.01	ft/day	2.2E-01	cm/day
Average Groundwater Seepage Velocity	3	ft/yr	0.8	m/yr
Total Treatment Zone Pore Volume	4,489	gallons	16,993	liters
Groundwater Flux (per year)	2,949	gallons/year	11,164	liters/year
Total Groundwater Volume Treated (over entire design period)	10,388	gallons total	39,322	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	1.1%	0.011
Nitrate Reduction	1.3%	0.013
Sulfate Reduction	14.9%	0.146
Manganese Reduction	1.6%	0.016
Iron Reduction	3.2%	0.031
Methanogenesis	66.7%	0.653
Dechlorination	11.3%	0.110
Perchlorate Reduction	0.0%	0.000
Totals:	100.00%	0.98

Hydrogen demand in pounds/gallon:	9.43E-05
Hydrogen demand in grams per liter:	1.13E-02

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor =****1.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	45	4	253	as lactic acid
2. Molasses Product	35	3	240	as sucrose
3. Fructose Product	27	2	253	as fructose
4. Ethanol Product	14	2	129	as ethanol
5. Sweet Dry Whey (lactose)	22	sold by pound	174	as lactose
6. HRC®	17	sold by pound	153	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	9	1	98	as soybean oil
8. Emulsified Vegetable Oil	14	2	98	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

SITE SUMMARY**Springdale Cleaners, Portland, Oregon**

For: Project Files for ESTCP Substrate Loading Study (Job No. 745255)

Review/Update: 17 August 2009

SITE IDENTIFICATION

Springdale Cleaners, Portland, Oregon

CONTAMINANT SOURCE

<i>COC</i>	<i>Max. Conc.</i>	<i>DNAPL Present?</i>	<i>Notes</i>
PCE	120,000 µg/L	Inferred	Ref (2,3)
TCE	8,300 µg/L	--	Ref (2,3)
<i>cis</i> -1,2-DCE	740 µg/L	--	Ref (2,3)
VC	ND	--	Ref (2,3)

Notes: Maximum concentrations are pre-injection at cross-gradient well JEMW-5.

SUBSTRATE DESIGN/INSTALLATION INFORMATION

<i>Parameter</i>	<i>Original Design</i>	<i>Modifications?</i>	<i>Notes/Reference</i>
Project Scale	Pilot		R(1,2)
Substrate Type	HRC [®] and HRC-X [™]	No change	
Number of Injection Points (IP)	Dissolved Plume: 22 Source Zone: 5		
IP Spacing Information	Dissolved Plume: 6 – 12 feet Source Zone: 5 feet		Dissolved plume pints covered approximately 1200 sq ft.
Injection Date	December 1999		
Injection Interval (depth bgs)	Dissolved Plume: 5 to 22 feet bgs Source Zone: 8 to 22 feet bgs (approximately)		
Substrate Loading	Dissolved Plume: 1,900 lbs HRC [®] Source Zone: 700 HRC-X [™]		
Substrate Loading Rate	Dissolved Plume: 4 lbs per foot Source Zone: 10 lbs per foot		Pounds of product per vertical foot
Basis for Loading Rate	Assume Regeneration Software		Calculations not provided
Injection amendment?	None		
Pre-injection Specified?	None		

<i>Parameter</i>	<i>Original Design</i>	<i>Modifications?</i>	<i>Notes/Reference</i>
Post-injection Specified?	None		

MONITORING INFORMATION

<i>Sample Collection Date</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Reference</i>
5/28/99 (186 days prior)	Yes	No	No	No	Ref (2,3)
12/8/99 (day 8)	Yes	Yes	Limited	No	Ref (2,3)
1/6/00 (day 37)	Yes	Yes	Limited	No	Ref (2,3)
2/8/00 (day 70)	Yes	Yes	Limited	No	Ref (2,3)
3/7/00 (day 98)	Yes	Yes	Limited	No	Ref (2,3)
6/15/00 (day 198)	Yes	Yes	Limited	No	Ref (2,3)
9/12/00 (day 287)	Yes	Yes	Limited	No	Ref (2,3)
12/6/00 (day 372)	Yes	Yes	Limited	No	Ref (2,3)
6/5/01 (day 553)	Yes	Yes	Limited	No	Ref (2,3)
3/6/02 (day 827)	Yes	Yes	Limited	No	Ref (2,3)
8/29/02 (day 1003)	Yes	Yes	Limited	No	Ref (2,3)
4/30/03 (day 1247)	Yes	Yes	Limited	No	Ref (2,3)

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- (2) Norris, R.D. 2004. HRC® and HRC-XTM Pilot Test at Portland, Oregon Dry Cleaner Site. In: *Principles and Practices of Enhanced Anaerobic Bioremediation of Chlorinated Solvents* (AFCEE et al., 2004). Appendix E.5. **(Case Study)**
- (3) ITRC (Interstate Technology & Regulatory Council). 2007. *In Situ Bioremediation of Chlorinated Ethene DNAPL Source Zones: Case Studies*. BioDNAPL-2. Washington, D.C.: Interstate Technology & Regulatory Council, Bioremediation of DNAPLs Team. April. pp. 79-98. Available at www.itrcweb.org. **(Case Study)**
- (4) Jacobs Engineering. 2000. *Expanded Site Investigation Report – Springdale Cleaners Site*. **(not available)**

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates calculated or designed?

No-fee design services were provided by Regenesys, and a formal work plan does not appear to have been produced. It is unclear whether the vendors used its proprietary software that utilizes stoichiometric calculations. The loading rates were either based on prior experience and/or on the vendors design software.

2. What modifications to the substrate amendment protocol were required (e.g., concentration and frequency for soluble substrates; and depletion and additional injection of slow-release substrate types such as HRC[®] and EVO).

No modifications were required for this one-time injection. The HRC[®] product in the dissolved plume was able to maintain elevated concentrations of total organic acids for a minimum period of 18 months (1.5 years). The HRC-X[™] product applied in the source zone was able to maintain a total organic acid concentration of 64 to 4,230 mg/L at 1,247 days, an effective period of 3.4 years.

3. Evaluation from Substrate Demand Tool

Site data were input into the substrate demand tool for both the dissolved plume and source zone treatments (attached). For the dissolved plume, the substrate demand to treat 151,859 gallons (574,834 liters) of groundwater over 1.5 years was 15.07 pounds of molecular hydrogen, or 9.92E-05 pounds per gallon. (1.19E-02 grams per liter) of groundwater treated. This hydrogen demand could be met by 255 pounds of HRC[®] product, assuming the product is 40 percent lactic acid and 40 percent glycerol by weight. Based on the mass of substrate applied at the Springdale Cleaners dissolved plume site (1,900 pounds of HRC[®]), the effective design factor applied at the site was 7.5 times the estimated hydrogen demand.

The primary electron accepting process in the dissolved plume was methanogenesis (42.3%), followed by sulfate reduction (30.4%), iron reduction (11.7%), chlorinated solvents (11.5%), manganese reduction (3.1%), aerobic respiration (1.1%) and nitrate reduction (0.1%). Concentrations of dissolved oxygen and nitrate were not reported, and it was assumed that the site is naturally depleted in these electron acceptors (DO assumed to be 1.0 mg/L and nitrate assumed to be 0.1 mg/L). Methane was also estimated at 10 mg/L for this exercise.

For the source zone, the substrate demand to treat 102,229 gallons (386,968 liters) of groundwater over 3.0 years was 16.06 pounds of molecular hydrogen, or 1.57E-04 pounds per gallon. (1.88E-02 grams per liter) of groundwater treated. This hydrogen demand could be met by 272 pounds of HRC[®] product, assuming the product is 40 percent lactic acid and 40 percent glycerol by weight. Based on the mass of substrate applied at the Springdale Cleaners dissolved plume site (700 pounds of HRC-X[™], and assuming HRC-X[™] is similar in content to HRC[®]), the effective design factor applied at the site was 2.6 times the estimated hydrogen demand.

The primary electron accepting process in the source zone was chlorinated solvents (44.0%), followed by methanogenesis (26.7%), sulfate reduction (19.2%), iron reduction (8.4%), and manganese reduction (1.0%). Concentrations of dissolved oxygen and nitrate were not reported, and it was assumed that the site is naturally depleted in these electron acceptors (DO assumed to be 1.0 mg/L and nitrate assumed to be 0.1 mg/L). Methane was also estimated at 10 mg/L for this exercise.

The primary difference between the dissolved plume application and the source zone application is the demand exerted by chlorinated solvents, being much higher in the source zone application.

PERFORMANCE OBJECTIVES

No. 1: Ability to Uniformly Distribute Substrate : Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

There was a very limited monitoring network for the Springdale Cleaners site, with only two wells monitoring the dissolved plume application and only one well in the source zone treatment. The monitoring wells within the injection grids have consistently exhibited elevated levels of organic acids, but there is insufficient data to evaluate the distribution of substrate.

No. 2: Achieving Optimal Geochemical Conditions

Successful geochemical conditions for stimulating anaerobic degradation of chlorinated solvents is defined as when the groundwater environment is highly anaerobic with DO less than 0.5 mg/L, ORP is less than -200 mV, sulfate is reduced by more than 50 percent relative to background conditions, and methane is greater than 1.0 mg/L. Based on these criteria, achieving optimal geochemical conditions at the Springdale Cleaners was successful with the exception of lowering ORP to less than -200 mV. Methane was not analyzed at this site.

Iron and manganese reducing conditions were induced within 37 days of injection at the Site. For the dissolved plume, sulfate concentration increased at well MW-2, from 43 mg/L during baseline sampling to 98 mg/L at 70 days post-injection. Sulfate concentrations decreased at MW-2 after 70 days post injection, generally at 50% or lower than background. Sulfate concentrations in the source zone appear to have been reduced prior to injection. Methane was not measured at this site.

ORP was not measured consistently during the application. In the dissolved plume at MW-2, the lowest ORP measurement was -84.1 mV at 8 days after injection. For the source zone application, the lowest ORP measurement at well JEMW-4 was -43 mV at 98 days post injection. It is unclear why lower redox levels could not be achieved. ORP measurements are consistently in the manganese and iron reduction range, which appear to be predominant terminal electron accepting processes at this site.

No. 3: Remediation Effectiveness: Evaluate efficiency in removal of VOCs based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Determine “threshold” concentrations of dissolved organic carbon that represent the minimum levels required to sustain complete reductive dechlorination.

The success of the application is evaluated by comparing concentrations to site-specific performance criteria, if established. Otherwise, a reduction in contaminant concentration of 99 percent or greater (over two orders of magnitude) is considered successful. For chlorinated aliphatic hydrocarbons (CAHs, or chlorinated solvents) where production of regulated intermediate dechlorination products may occur, a reduction in the total molar concentration of CAHs of greater than 90 percent is considered to be a success.

An objective of the pilot test was to extend monitoring past the commonly-accepted end points to determine length of performance, effectiveness over varying conditions, and cost of treatment.

For PCE and TCE, the Oregon Department of Environmental Quality (ODEQ) is 5.0 µg/L for both compounds.

The concentration of PCE at location MW-2 within the dissolved plume decreased from 7,000 µg/L during baseline sampling to <10 µg/L at day 1003 post injection, but rebounded to 101 µg/L at day 1,247. Concentrations of TCE, cis-DCE, trans-DCE, and VC all increased after injection as higher chlorinated compounds were reduced. At day 1,247, the concentration of TCE was 488 µg/L (versus baseline of 480 µg/L), cis-DCE was 486 µg/L (versus baseline of 130 µg/L), trans-DCE was 140 µg/L (versus baseline of 93 µg/L), and VC was 110 µg/L (baseline not analyzed, but non-detect through 98 days post injection).

Similarly, the concentration of PCE at location JEMW-4 within the source zone decreased from 7,000 µg/L during baseline sampling to <200 µg/L at day 287 post injection, and was also <200 µg/L at day 1,247. Concentrations of TCE also decreased from 8,300 µg/L during baseline sampling to <200 µg/L at day 827 through 1,247. However, concentrations of cis-DCE, trans-DCE, and VC all increased after injection as higher chlorinated compounds were reduced. At day 1,247, the concentration of cis-DCE was 53,500 µg/L (versus baseline of 740 µg/L), trans-DCE was 558 µg/L (versus baseline of 170 µg/L), and VC was 4,900 µg/L (baseline not analyzed, but below detection through 287 days post injection).

Total molar concentrations did not decrease by over 90 percent for either the dissolved plume or source zone. The reduction in total molar concentration of chlorinated ethenes in the dissolved plume decreased from 48,164 nmol/L to 7,590 nmol/L, a reduction of 84.2 percent. The reduction in total molar concentration of chlorinated ethenes in the source area decreased from 66,3510 nmol/L to 63,1631 nmol/L, a reduction of 4.8 percent assuming that concentrations of PCE and TCE were one-half the detection limit of 200 µg/L.

While the Springdale Cleaners application was effective at reducing the concentrations of the PCE at the site, both site-specific performance objectives and the performance objective of this demonstration were not achieved. The threshold concentration to stimulate effective dechlorination was reported to be from 80 to 100 µg/L. Therefore, additional injections and longer term operation and monitoring are likely required to meet the site-specific remedial objectives.

No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

Secondary water quality parameters that were evaluated for the Springdale Cleaners Site include sulfide, ferrous iron, and manganese. The maximum concentration of sulfide was 1.4 mg/L at well MW-2 at 553 days post injection. Otherwise concentrations were less than 1.0 mg/L. For well JEMW-4 in the source zone, sulfide was less than detection (typically less than 0.1 mg/L). Therefore, sulfide generation was not an issue at this site.

Dissolved iron was measured throughout the pilot test, while manganese was measured through 372 days post injection. Neither were measured during baseline sampling. With the exception of the monitoring event at 98 days post injection, concentrations of dissolved iron at cross gradient location JEMW-5 ranged from 0.48 mg/L to 6.4 mg/L and concentrations of manganese ranged from 0.57 to 0.75 mg/L.

The treatment zone concentrations of manganese and ferrous iron are elevated above USEPA recommended secondary drinking water quality standards. At MW-2 in the dissolved plume, dissolved ferrous iron increased to as high as 197 mg/L at 372 days post injection, and was measured at a concentration of 61.1 mg/L at 1,247 days post injection. Manganese at well MW-2 increased to 18.6 mg/L at 372 days post injection, at which time manganese was dropped from the analyte list. For well JEMW-4 in the source zone treatment area, dissolved ferrous iron increased to as high as 410 mg/L at 1,247 days post injection, and manganese increased to as high as 17.9 mg/L at 372 days post injection. The magnitude of the increase in concentrations of dissolved iron and manganese may be an issue at this site, but has not been addressed in any case study documents.

Summary of Secondary Water Quality – Springdale Cleaners Site

Parameter	Comparison Criteria	Background	Treatment Zone	Down-gradient	Issues?
Sulfide (mg/L)	NA	<0.1	<0.10 to 1.4	No Data	No – only few detections above 0.5 mg/L
Total Manganese (mg/L)	0.05 (b)	0.57 to 0.75	8.5 to 66	No Data	Potential – background above criteria
Total Iron (mg/L) (assumed to be ferrous iron)	0.3 (b)	0.48 to 6.4	1.8 to 29	No Data	Potential – background above criteria

Notes:

Background values assumed from cross gradient well JEMW-5, with the exception of anomalous readings at 98 days post injection.

Treatment zone values from MW-2 in dissolved plume and JEMW-4 in source zone.

mg/L = milligrams per liter.

Criteria based on (a) USEPA MCL; (b) USEPA Secondary Standard; or (c) USEPA Region 9 PRG.

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

A reduction of less than 50 percent in the average hydraulic conductivity within the reaction zone is considered to be acceptable. No impacts on hydraulic conductivity or groundwater flow were noted. The HRC product is only physically distributed within a couple feet of the injection point, so only a very limited portion of the aquifer is impacted by physical product. The reported groundwater velocity is 0.3 ft/day (110 ft/yr), which is suitable for applying enhanced *in situ* bioremediation.

No. 6: Substrate Persistence and Long-Term Effectiveness

Concentrations of organic acids (acetic, butyric, lactic, propionic, and pyruvic) remained elevated at dissolved plume treatment well MW-2 through 553 days (approximately 18 months post

injection), with a total organic acid concentration of 906 mg/L at day 553. The total organic acid concentration dropped to only 3.8 mg/L at day 827 and was 85 mg/L at day 1247 (40 months post injection). The threshold concentration for total organic acids was interpreted to be from 80 to 100 mg/L, and it was concluded that the effective life span for the dissolved plume application using HRC[®] was a minimum of 18 months. Concentrations of chlorinated ethenes in the dissolved plume at 1,247 days post injection did not meet performance objectives, therefore additional injections would be required to meet performance objectives.

Concentrations of organic acids in the source zone remained elevated at well JEMW-4 through 1247 days (40 months) post injection, with a total organic acid concentration of 4,230 mg/L at day 1247. Therefore, the HRC-X application has a minimum effective lifespan of approximately 41 months, or 3.4 years. Concentrations of chlorinated ethenes in the source area at 1,247 days post injection did not meet performance objectives, and additional monitoring would be required to determine whether performance objectives could be achieved without additional injections.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

No modifications were required. Additional injections were not necessary to sustain effective degradation of chlorinated solvents over the intended design life of the Springdale Cleaners application.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

There were no apparent hydraulic limitations at the Springdale Cleaners Site. The reported rate of groundwater flow (110 ft/yr) is within a range suitable for applying enhanced *in situ* bioremediation.

The presence of relatively high amounts of bioavailable iron and manganese may have influenced the ORP of groundwater the site, with ORP remaining in the range of iron reduction to manganese reduction during the pilot test. However, the production of ethene measured at wells MW-2 and JEMW-4 indicates that geochemical conditions were sufficient to stimulate complete dechlorination.

3. COST ASSESSMENT

Cost Summary, Springdale Cleaners, Portland Oregon

Cost Element	Data to be Tracked	Project Cost
System Design/ Work Plan (Total = Not provided)	- Labor for system design and work plan - Permitting costs and procurement	- Not provided - Not provided
Capital Construction/ System Installation (Total = \$34,000 excluding installation of monitoring system)	- Installation method - Mobilization (includes travel and per diem) - Site Labor - Drilling Subcontractor - Subcontractor - Surveyor - Construction material cost (well materials and injection equipment) - Substrate or amendment cost (including shipping)	- Injection points - Not provided \$4,000 \$8,000 \$1,000 - Not provided \$21,000 (\$8.08 per pound delivered)
Baseline Characterization and Construction Completion Report (Total = \$10,000)	- Baseline Sampling - Completion Report	\$5,000 \$5,000
Operating Cost	Not Required – One time injection of HRC[®] and HRC-X[™]	\$0
Long-Term Monitoring (per year) (Total = \$35,300 per year)	- Mobilization (includes travel and per diem) - Sampling labor - Sampling equipment and supplies - Analytical cost - Labor for project management and reporting - Number of events	\$2,000 \$6,500 \$2,000 \$12,800 \$12,000 - Eleven events total
	Total Application Cost - Assume two years of monitoring - Assumes \$10,000 for work plan and mobilization (costs not provided)	\$124,6000

Note: No fee design costs were provided by Regenesi.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** Springdale Drycleaners, Portland, OR (Dissolved)

NOTE: Unshaded boxes are user input.				
1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	30	1-10,000	feet	Dissolved Plume Application
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet	
Saturated Thickness	22	1-100	feet	
Treatment Zone Cross Sectional Area	660	--	ft ²	
Treatment Zone Volume	26,400	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	39,505	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	29,629	--	gallons	
Design Period of Performance	1.5	.5 to 5	year	Not Specified
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	20%	.05-50	percent	Silty clay and silty sand
Effective Porosity	15%	.05-50	percent	Estimated
Average Aquifer Hydraulic Conductivity	4.5	.01-1000	ft/day	Estimated to match reported
Average Hydraulic Gradient	0.01	0.0001-0.1	ft/ft	rate of groundwater flow
Average Groundwater Seepage Velocity through the Treatment Zone	0.30	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	110.0	--	ft/yr	
Average Groundwater Flux through the Treatment Zone	81,487	--	gallons/year	
Soil Bulk Density	1.65	1.4-2.0	gm/cm ³	Sand
Soil Fraction Organic Carbon (foc)	0.50%	0.01-10	percent	Assumed default value
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.0	0.01 to 10	mg/L	Not reported - assumed based on redox state
Nitrate	0.10	0.1 to 20	mg/L	Not reported - assumed to be low
Sulfate	43	10 to 5,000	mg/L	Post injection ranged up to 98 mg/L
Carbon Dioxide (estimated as the amount of Methane produced)	10	0.1 to 20	mg/L	Not reported - assumed value
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	10	0.1 to 20	mg/L	Average Mn MW-2 (Max. of 18.6 mg/L)
Iron (III) (estimated as the amount of Fe (II) produced)	77	0.1 to 20	mg/L	Average Fe MW-2 (Max. of 197 mg/L)
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	7.000	--	mg/L	MW-2 on 5/28/99
Trichloroethene (TCE)	0.480	--	mg/L	MW-2 on 5/28/99
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.223	--	mg/L	MW-2 on 5/28/99 (cis and trans-DCE)
Vinyl Chloride (VC)	0.000	--	mg/L	MW-2 on 5/28/99
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	-20	-400 to +500	mV	Avg. Post injection: Range -108 to +120 mV
Temperature	Not Reported	5.0 to 30	°C	
pH	Not Reported	4.0 to 10.0	su	
Alkalinity	Not Reported	10 to 1,000	mg/L	
Total Dissolved Solids (TDS, or salinity)	Not Reported	10 to 1,000	mg/L	
Specific Conductivity	Not Reported	100 to 10,000	µs/cm	
Chloride	15	10 to 10,000	mg/L	Ranged from 8.9 to 28 mg/L
Sulfide - Pre injection	<0.2	0.1 to 100	mg/L	MW-2
Sulfide - Post injection	0.5	0.1 to 100	mg/L	Average MW-2: Ranged from <0.1 to 1.4
B. Aquifer Matrix				
Total Iron	NA	100 to 10,000	mg/kg	
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	
Neutralization Potential	NA	1.0 to 100	Percent as CaCO ₃	

NOTES:

Background data based on sampling of wells MW-2 and MW-4 before or after injection as noted.
 Values for manganese and ferrous iron are post-injection.

Table S.2 Substrate Calculations in Hydrogen Equivalents**Site Name:** Springdale Drycleaners, Portland, OR (Dissolved)

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
30	1-10,000	feet
40	1-1,000	feet
22	1-100	feet
660	--	ft ²
26,400	--	ft ³
29,629	--	gallons
1.5	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.2	.05-50	
0.15	.05-50	
4.521	.01-1000	ft/day
0.01	0.1-0.0001	ft/ft
0.30	--	ft/day
110.0	--	ft/yr
81,487	--	gallons/year
1.65	1.4-2.0	gm/cm ³
0.005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
1.0	0.25	7.94	0.03	4
0.1	0.02	10.25	0.00	5
43	10.63	11.91	0.89	8
10.0	2.47	1.99	1.24	8
Soluble Competing Electron Acceptor Demand (lb.)			2.17	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
10.0	12.67	27.25	0.47	2
77.0	97.57	55.41	1.76	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			2.23	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
7.000	1.73	20.57	0.08	8
0.480	0.12	21.73	0.01	6
0.223	0.06	24.05	0.00	4
0.000	0.00	31.00	0.00	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.000	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			0.09	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x C_{gw})
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	9.21	25.04	20.57	1.22	8
107	0.26	0.70	21.73	0.03	6
45	0.05	0.14	24.05	0.01	4
3.0	0.00	0.00	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			1.25		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.0	0.68	7.94	0.09	4
Nitrate (denitrification)	0.1	0.07	10.25	0.01	5
Sulfate	43	29.24	11.91	2.45	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	6.80	1.99	3.42	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				6.0	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	7.000	4.76	20.57	0.23	8
Trichloroethene (TCE)	0.480	0.33	21.73	0.02	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.223	0.15	24.05	0.01	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				0.25	

Initial Hydrogen Requirement First Year (lb)**12.0****Total Life-Cycle Hydrogen Requirement (lb)****15.1****5. Design Factors**

Microbial Efficiency Uncertainty Factor
Methane and Solid-Phase Electron Acceptor Uncertainty
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)

2X - 4X

2X - 4X

1X - 3X

Design Factor**1.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)****15.1****6. Acronyms and Abbreviations**

°C =degrees celsius

μS/cm = microsiemens per centimeter

cm/day = centimeters per day

cm/sec = centimeters per second

ft² = square feet

ft/day = feet per day

ft/ft = foot per foot

ft/yr = feet per year

gm/cm³ = grams per cubic centimeterkg of CaCO₃ per mg = kilograms of calcium carbonate per milligram

lb = pounds

meq/100 g = milliequivalents per 100 grams

mg/kg = milligrams per kilogram

mg/L = milligrams per liter

m/m = meters per meters

mV = millivolts

m/yr = meters per year

su = standard pH units

wt/wt H₂ = concentration molecular hydrogen, weight per weight

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

RESET DEFAULT

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 1.5

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	337	337	1.53E+08	266
Sodium Lactate Product (60 percent solution)	1.0	337	698	1.53E+08	266
Molasses (assuming 60 percent sucrose)	1.0	320	533	1.45E+08	252
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	337	421	1.53E+08	266
Ethanol Product (assuming 80% ethanol by weight)	1.0	172	215	7.81E+07	136
Whey (assuming 100% lactose)	1.0	232	332	1.05E+08	183
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	255	255	1.16E+08	161
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	131	131	5.94E+07	103
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	131	218	5.94E+07	103

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents**Site Name:** Springdale Drycleaners, Portland, OR (Dissolved)**1. Treatment Zone Physical Dimensions**

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	30	feet	9	meters
Length (parallel to groundwater flow)	40	feet	12.2	meters
Saturated Thickness	22	feet	6.7	meters
Design Period of Performance	1.5	years	1.5	years

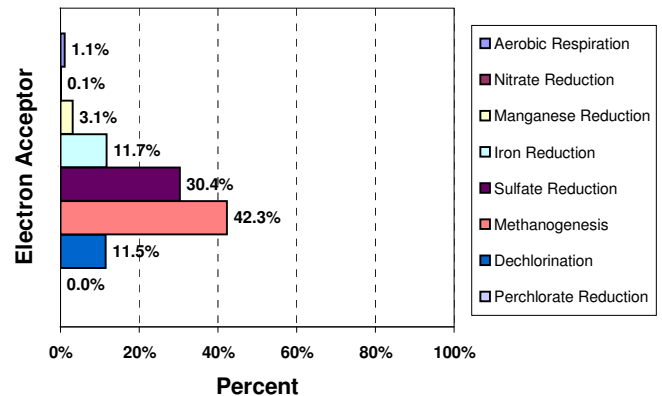
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.2	percent	0.2	percent
Effective Porosity	0.15	percent	0.15	percent
Average Aquifer Hydraulic Conductivity	4.521	ft/day	1.6E-03	cm/sec
Average Hydraulic Gradient	0.01	ft/ft	0.01	m/m
Average Groundwater Seepage Velocity	0.30	ft/day	9.2E+00	cm/day
Average Groundwater Seepage Velocity	110	ft/yr	33.5	m/yr
Total Treatment Zone Pore Volume	29,629	gallons	112,154	liters
Groundwater Flux (per year)	81,487	gallons/year	308,454	liters/year
Total Groundwater Volume Treated (over entire design period)	151,859	gallons total	574,834	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	1.1%	0.160
Nitrate Reduction	0.1%	0.012
Sulfate Reduction	30.4%	4.575
Manganese Reduction	3.1%	0.465
Iron Reduction	11.7%	1.761
Methanogenesis	42.3%	6.368
Dechlorination	11.5%	1.726
Perchlorate Reduction	0.0%	0.000
Totals:	100.00%	15.07

Hydrogen demand in pounds/gallon:	9.92E-05
Hydrogen demand in grams per liter:	1.19E-02

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor =****1.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	698	63	266	as lactic acid
2. Molasses Product	533	44	252	as sucrose
3. Fructose Product	421	38	266	as fructose
4. Ethanol Product	215	31	136	as ethanol
5. Sweet Dry Whey (lactose)	332	sold by pound	183	as lactose
6. HRC®	255	sold by pound	161	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	131	17	103	as soybean oil
8. Emulsified Vegetable Oil	218	28	103	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** Springdale Drycleaners, Portland, OR (Source)

NOTE: Unshaded boxes are user input.				
1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	12	1-10,000	feet	Source Zone Application
Length (Parallel to predominant groundwater flow)	15	1-1,000	feet	
Saturated Thickness	22	1-100	feet	
Treatment Zone Cross Sectional Area	264	--	ft ²	
Treatment Zone Volume	3,960	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	5,926	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	4,444	--	gallons	
Design Period of Performance	3.0	.5 to 5	year	Not Specified
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	20%	.05-50	percent	Silty clay and silty sand
Effective Porosity	15%	.05-50	percent	Estimated
Average Aquifer Hydraulic Conductivity	4.5	.01-1000	ft/day	Estimated to match reported
Average Hydraulic Gradient	0.01	0.0001-0.1	ft/ft	rate of groundwater flow
Average Groundwater Seepage Velocity through the Treatment Zone	0.30	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	110.0	--	ft/yr	
Average Groundwater Flux through the Treatment Zone	32,595	--	gallons/year	
Soil Bulk Density	1.65	1.4-2.0	gm/cm ³	Sand
Soil Fraction Organic Carbon (foc)	0.50%	0.01-10	percent	Assumed default value
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.0	0.01 to 10	mg/L	Not reported - assumed based on redox state
Nitrate	0.10	0.1 to 20	mg/L	Not reported - assumed to be low
Sulfate	43	10 to 5,000	mg/L	Assumed from baseline at MW-2
Carbon Dioxide (estimated as the amount of Methane produced)	10	0.1 to 20	mg/L	Not reported - assumed value
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	5	0.1 to 20	mg/L	Average Mn JEMW-4 (Max. of 17.9 mg/L)
Iron (III) (estimated as the amount of Fe (II) produced)	88	0.1 to 20	mg/L	Average Fe JEMW-4 (Max. of 410 mg/L)
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	98.000	--	mg/L	JEMW-4 on 5/28/99
Trichloroethene (TCE)	8.300	--	mg/L	JEMW-4 on 5/28/99
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.910	--	mg/L	JEMW-4 on 5/28/99 (cis- + trans-DCE)
Vinyl Chloride (VC)	0.000	--	mg/L	Baseline not analyzed
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	8	-400 to +500	mV	Avg. Post injection: Range -43 to +44 mV
Temperature	Not Reported	5.0 to 30	°C	
pH	Not Reported	4.0 to 10.0	su	
Alkalinity	Not Reported	10 to 1,000	mg/L	
Total Dissolved Solids (TDS, or salinity)	Not Reported	10 to 1,000	mg/L	
Specific Conductivity	Not Reported	100 to 10,000	µs/cm	
Chloride	56	10 to 10,000	mg/L	Avg. post injection: Ranged from 20 to 120 mg/L
Sulfide - Pre injection	Not Reported	0.1 to 100	mg/L	Not reported
Sulfide - Post injection	<0.1	0.1 to 100	mg/L	JEMW-4
B. Aquifer Matrix				
Total Iron	NA	100 to 10,000	mg/kg	
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	
Neutralization Potential	NA	1.0 to 100	Percent as CaCO ₃	

NOTES:

Background data based on sampling of well JEMW-4 before or after injection as noted.
 Values for manganese and ferrous iron are post-injection.

Table S.2 Substrate Calculations in Hydrogen Equivalents**Site Name:** Springdale Drycleaners, Portland, OR (Source)

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
12	1-10,000	feet
15	1-1,000	feet
22	1-100	feet
264	--	ft ²
3,960	--	ft ³
4,444	--	gallons
3.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.2	.05-50	
0.15	.05-50	
4.521	.01-1000	ft/day
0.01	0.1-0.0001	ft/ft
0.30	--	ft/day
110.0	--	ft/yr
32,595	--	gallons/year
1.65	1.4-2.0	gm/cm ³
0.005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
1.0	0.04	7.94	0.00	4
0.1	0.00	10.25	0.00	5
43	1.59	11.91	0.13	8
10.0	0.37	1.99	0.19	8
Soluble Competing Electron Acceptor Demand (lb.)			0.33	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
5.2	4.44	27.25	0.16	2
88.0	75.07	55.41	1.35	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			1.52	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
98.000	3.63	20.57	0.18	8
8.300	0.31	21.73	0.01	6
0.910	0.03	24.05	0.00	4
0.000	0.00	31.00	0.00	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.000	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			0.19	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x C_{gw})
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	128.87	52.58	20.57	2.56	8
107	4.44	1.81	21.73	0.08	6
45	0.20	0.08	24.05	0.00	4
3.0	0.00	0.00	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			2.64		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.0	0.27	7.94	0.03	4
Nitrate (denitrification)	0.1	0.03	10.25	0.00	5
Sulfate	43	11.70	11.91	0.98	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	2.72	1.99	1.37	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				2.4	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	98.000	26.65	20.57	1.30	8
Trichloroethene (TCE)	8.300	2.26	21.73	0.10	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.910	0.25	24.05	0.01	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				1.41	

Initial Hydrogen Requirement First Year (lb)**8.5****Total Life-Cycle Hydrogen Requirement (lb)****16.1****5. Design Factors**

Microbial Efficiency Uncertainty Factor
Methane and Solid-Phase Electron Acceptor Uncertainty
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)

2X - 4X

2X - 4X

1X - 3X

Design Factor**1.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)****16.1****6. Acronyms and Abbreviations**

°C =degrees celsius

μS/cm = microsiemens per centimeter

cm/day = centimeters per day

cm/sec = centimeters per second

ft² = square feet

ft/day = feet per day

ft/ft = foot per foot

ft/yr = feet per year

gm/cm³ = grams per cubic centimeterkg of CaCO₃ per mg = kilograms of calcium carbonate per milligram

lb = pounds

meq/100 g = milliequivalents per 100 grams

mg/kg = milligrams per kilogram

mg/L = milligrams per liter

m/m = meters per meters

mV = millivolts

m/yr = meters per year

su = standard pH units

wt/wt H₂ = concentration molecular hydrogen, weight per weight

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

RESET DEFAULT

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 3

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	359	359	1.63E+08	421
Sodium Lactate Product (60 percent solution)	1.0	359	745	1.63E+08	421
Molasses (assuming 60 percent sucrose)	1.0	341	568	1.55E+08	400
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	359	449	1.63E+08	421
Ethanol Product (assuming 80% ethanol by weight)	1.0	184	229	8.33E+07	215
Whey (assuming 100% lactose)	1.0	248	354	1.12E+08	290
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	272	272	1.23E+08	255
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	140	140	6.34E+07	164
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	140	233	6.34E+07	164

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Springdale Drycleaners, Portland, OR (Source)

1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	12	feet	4	meters
Length (parallel to groundwater flow)	15	feet	4.6	meters
Saturated Thickness	22	feet	6.7	meters
Design Period of Performance	3	years	3	years

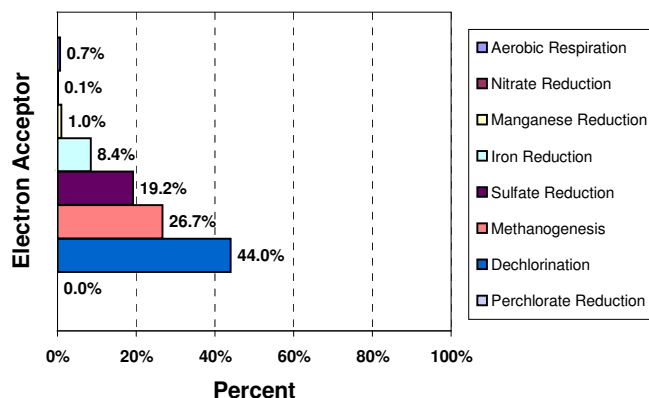
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.2	percent	0.2	percent
Effective Porosity	0.15	percent	0.15	percent
Average Aquifer Hydraulic Conductivity	4.521	ft/day	1.6E-03	cm/sec
Average Hydraulic Gradient	0.01	ft/ft	0.01	m/m
Average Groundwater Seepage Velocity	0.30	ft/day	9.2E+00	cm/day
Average Groundwater Seepage Velocity	110	ft/yr	33.5	m/yr
Total Treatment Zone Pore Volume	4,444	gallons	16,823	liters
Groundwater Flux (per year)	32,595	gallons/year	123,381	liters/year
Total Groundwater Volume Treated (over entire design period)	102,229	gallons total	386,968	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	0.7%	0.107
Nitrate Reduction	0.1%	0.008
Sulfate Reduction	19.2%	3.080
Manganese Reduction	1.0%	0.163
Iron Reduction	8.4%	1.355
Methanogenesis	26.7%	4.287
Dechlorination	44.0%	7.065
Perchlorate Reduction	0.0%	0.000
Totals:	100.00%	16.06

Hydrogen demand in pounds/gallon:	1.57E-04
Hydrogen demand in grams per liter:	1.88E-02

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor = 1.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	745	68	421	as lactic acid
2. Molasses Product	568	47	400	as sucrose
3. Fructose Product	449	40	421	as fructose
4. Ethanol Product	229	33	215	as ethanol
5. Sweet Dry Whey (lactose)	354	sold by pound	290	as lactose
6. HRC®	272	sold by pound	255	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	140	18	164	as soybean oil
8. Emulsified Vegetable Oil	233	30	164	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

SITE SUMMARY

East Gate Disposal Yard (EGDY), Fort Lewis Logistics Center, Washington

For: Project Files for ESTCP Substrate Loading Study (Job No. 745255)

Revision: 21 September 2009

SITE IDENTIFICATION

East Gate Disposal Yard (EGDY), Fort Lewis Logistics Center, Washington

CONTAMINANT SOURCE

<i>COC</i>	<i>Max. Conc.</i>	<i>DNAPL Present?</i>	<i>Notes</i>
TCE	Up to 35,000 µg/L	Inferred	Ref (2): Baseline at MW2A1 on 3/22/05
<i>cis</i> -DCE	Up to 13,000 µg/L	--	Ref (2): Baseline at MW2D1 on 3/9/05
VC	ND during baseline	--	Ref (2)

SUBSTRATE DESIGN/INSTALLATION INFORMATION

<i>Parameter</i>	<i>Original Design</i>	<i>Modifications?</i>	<i>Notes/Reference</i>
Project Scale	Two Pilot Test Cells	None	Ref (1, 2)
Substrate Type	Sodium Lactate	Whey	Ref (1, 2)
Number of Injection Points (IP)	One injection and one extraction well per test cell.	None	Ref (1, 2)
IP Spacing Information	50 feet from injection to extraction well	No change	Ref (1, 2)
Injection Date	Delayed due to re-installation of injection and extraction wells	Phase 3 – June 2005 to February 2006	Ref (1, 2)
Injection Interval (depth bgs)	15 to 30 feet below land surface (bls)	<i>For re-installation:</i> 15 to 20 feet bls for injection; 15 to 35 feet bls for extraction.	Ref (1, 2)
Substrate Loading	Recirculation with addition of 0.1% and 6.0% sodium lactate solutions	Recirculation with addition of 1% and 10% whey solutions.	Ref (1, 2)

<i>Parameter</i>	<i>Original Design</i>	<i>Modifications?</i>	<i>Notes/Reference</i>
Basis for Loading Rate		Bench-scale tests between a concentration that stimulates biological reductive dechlorination (1% whey) and a concentration that enhances mass transfer by physiochemical interactions (10% whey solution).	Ref (1, 2)
Injection Strategy	Test Cell 1: 0.1% sodium lactate solution only. Test Cell 2: 6% solution of sodium and ethyl lactate solution (proprietary blend). An initial injection to uniformly distribute substrate, then monthly injections.	Test Cell 1: 10% whey solution then 1% whey solution. Test Cell 2: 1% whey solution then 10% whey solution	Ref (1, 2)
Injection Amendments	None	Yes – bioaugmentation was performed on July 17, 2005.	Ref (1, 2)
Injection Volumes	Initial injection at discretion of field team leader to get an initial uniform distribution. Monthly operational injections with a total of 4614 gallons per month per test cell	Two initial injections in June 2005, and monthly injections from July 1005 to February 2006 (see table below). Monthly injections ranged from 1,700 to 4,000 gallons each.	Ref (1, 2)
Injection Frequency	Monthly	Monthly - see summary table below	Ref (1, 2)
Injection Rate/Pressure	5 gpm for approximately 15 hours, pressure not specified	5 to 12 gpm	Ref (1, 2)
Pre-injection Specified?	No – but a steady state tracer test was conducted	Tracer tests and baseline recirculation.	Ref (1, 2)
Post-injection Specified?	Potable water for 60 minutes at 5 gpm after each injection event	Not reported	Ref (1, 2)

Phase 3 Whey Injection Summaries (from Table 3.3 in Ref [2]).

Date	Treatment Cell 1		Treatment Cell 2	
	Volume of Water (gal)	Concentration of Whey (%)	Volume of Water (gal)	Concentration of Whey (%)
June 2005	3,200	4	3,900	3
June 2005	3,200	3	3,200	3
July 2005	1,700	10	4,000	1
August 2005	0*	0*	1,800	1
September 2005	1,700	10	4,000	1
October 2005	1,900	10	1,800	1
November 2005	1,800	1	1,800	10
December 2005	1,800	1	1,800	10
January 2006	1,800	1	1,800	10
February 2006	1,800	1	1,800	10
* No recirculation or injection of whey due to equipment difficulties. Note: Scenario 2 areas are shaded; Scenario 1 areas are left un-shaded.				

MONITORING INFORMATION

<i>Sample Collection Date (Reference)</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Have Copy?</i>
Phase 2 Baseline Sampling – Multiple events from 3/05 to 4/05	Yes	Yes	Yes	Yes	Ref (2)
Phase 3A. Whey Injection – Multiple events from 7/05 to 10/05	Yes	Yes	Yes	Yes	Ref (2)
Phase 3B – Whey injection – Multiple events from 11/05 to 2/06	Yes	Yes	Yes	Yes	Ref (2)
Post Whey Injection – Two events in 3/06 and 4/06	Yes	Yes	Yes	Yes	Ref (2)

REFERENCES

- (1) North Wind Environmental. 2003. *Demonstration Plan for In Situ Bioremediation of Chlorinated Solvents with Enhanced Mass Transfer at the Fort Lewis East Gate Disposal Yard*. Prepared for the Environmental Security Technology Certification Program, Arlington, Virginia. January. (**Work Plan**)
- (2) Macbeth, T.W. and K. Sorenson. 2008. *Final Report, In Situ Bioremediation of Chlorinated Solvent Source Zones with Enhanced Mass Transfer*. Prepared for the Environmental Security Technology Certification Program, Arlington, Virginia. September. (**Final Report**)
- (3) Macbeth, T. W., L. Nelson, J. S. Rothermel, R. A. Wymore, and K. S. Sorenson. 2006. Evaluation of Whey for Bioremediation of Trichloroethene Source Zones. *Bioremediation Journal*, Vol. 10(3):115-128.

- (4) Macbeth, T. W. 2008. *Optimization of Enhanced in situ Bioremediation of a TCE Residual Source Area Derived from Integration of Laboratory Studies with Field Operations*. Ph.D. Dissertation, University of Idaho, Moscow, Idaho.

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates were calculated or designed?

Because the objective of this demonstration was to evaluate enhanced mass transfer from a DNAPL to a soluble phase, stoichiometric calculations were not used for this demonstration. The initial injection called for solutions of 0.1% sodium lactate (by volume) and a 6% sodium lactate/ethyl lactate mixture (by volume). An initial injection to uniformly distribute the solutions in the two test cells was left to the discretion of the field team leader, with monthly injections scheduled thereafter.

The solution strengths for sodium lactate were based on laboratory studies for the TAN INEEL site where a 0.1% sodium lactate solution was thought to sufficient to stimulate reductive dechlorination without increasing the interfacial tension and solubilization of DNAPL, and where a 6% solution of sodium lactate and ethyl lactate (proprietary "Solution B") would reduce the interfacial tension of pure phase TCE and enhance mass transfer to the aqueous phase.

2. What modifications to the substrate amendment protocol were required (e.g., concentration and frequency of substrate; and depletion and additional injection of substrate).

The injection scenario was changed substantially from the demonstration plan based on laboratory studies conducted just prior to the demonstration. There was better potential to achieve enhanced mass transfer with whey solutions less than or equal to 10% by weight, versus sodium lactate solutions approaching 30 to 60% by weight.

Laboratory studies demonstrated that whey solutions increased effective solubility of TCE as a linear function of the dissolved organic matter concentration in the range from 0% to 6% by weight (Macbeth et al., 2006; Macbeth, 2008). From 6% to 10% whey powder concentrations, the solubility of TCE increases at a slower rate. It was expected that at low concentrations of whey powder (1% by weight), enhanced mass transfer would be due primarily to mechanisms associated with biological anaerobic dechlorination. At a high whey powder concentration (10% by weight), it was thought that mass transfer of TCE from DNAPL would be enhanced to a greater extent due to physiochemical interactions between the electron donor solution and TCE mass occurring as DNAPL or sorbed to the aquifer matrix.

After construction, one test cell was found to be at the fringe of the DNAPL source area (Cell No. 1) and the other within the DNAPL source area (Cell No. 2). A series of four tracer studies were conducted to ensure that the vertical and horizontal distribution of electron donor solution would be adequate. New injection and extraction wells were installed based on early tracer tests to improve the ability to distribute injected fluids.

Two injection strategies were applied to each test cell. For Cell No. 1, the first substrate injection was changed to a high concentration of whey powder (10% by weight) in solution followed by a low concentration of whey powder (1.0% by weight). For Cell No. 2, the injections were reversed with a low concentration of whey powder (1.0% by weight) in solution followed by a high concentration of whey powder (10% by weight).

3. Evaluation from Substrate Demand Tool

Site data were input into the substrate demand tool (attached) for Treatment Cell No. 2. A significant assumption was that the net flux of groundwater into and out of the treatment cell was equal to zero, in other words the groundwater flowing into and out of the treatment cell during recirculation was equal to the overall flux of groundwater under a natural gradient. The substrate demand to treat 484,497 gallons (1,833,969 liters) of groundwater over 8 months was 29.22 pounds of molecular hydrogen, or 6.03E-05 pounds per gallon (7.22E-03 grams per liter) of groundwater treated. This hydrogen demand could be met by 644 pounds of sweet dairy whey (assuming the whey is 70% lactose by weight), or 111 mg/L of lactose on a time-weighted average concentration.

The primary electron accepting process was methanogenesis (41.7%), followed by chlorinated solvents (31.4%), sulfate reduction (22.1%), aerobic respiration (2.1%), nitrate reduction (1.5%), iron reduction (0.7%), and manganese reduction (0.5%, estimated). The site is naturally low in background concentrations of dissolved oxygen and nitrate.

PERFORMANCE OBJECTIVES

No. 1: Ability to Uniformly Distribute Substrate: Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

An application is considered successful when the targeted concentrations of soluble organic carbon are achieved in all monitoring locations within the intended reaction zone. A series of four tracer studies were conducted to ensure that the vertical and horizontal distribution of electron donor solution would be adequate. New injection and extraction wells were installed based on the tracer tests to improve the ability to distribute injected fluids.

Concentrations of chemical oxygen demand (COD) were measured as a surrogate for soluble organic carbon. Average baseline concentrations of COD ranged from 32 to 53 mg/L for the eight monitoring points used for sampling. Increases in COD concentrations during the Phase 3 injections ranged up to 25,320 mg/L compared to baseline, while in only a few cases did COD not increase following an injection event. Concentrations of COD post-injection (April 2006) ranged from 183 to 821 mg/L. Overall the distribution of substrate was reasonably uniform.

No. 2: Achieving Optimal Geochemical Conditions

Successful geochemical conditions for stimulating anaerobic degradation of chlorinated solvents is defined as when the groundwater environment is highly anaerobic with DO less than 0.5 mg/L, ORP is less than -200 mV, sulfate is reduced by more than 50 percent relative to background conditions, and methane is greater than 1.0 mg/L. Although these specific objectives were not

met for this demonstration, appropriate reducing conditions were achieved throughout the test cells.

DO concentrations were depleted following injection of substrate relative to baseline conditions. In Cell No. 2, baseline DO concentrations averaged 1.2 mg/L. Following 1% w/w whey injections, the total average DO concentration was reduced to 1.0 mg/L, and was reduced further to 0.8 mg/L following 10% whey injections. DO concentrations remained low for the 2-month post injection samplings with an average DO concentration of 0.7 mg/L.

ORP values decreased considerably after injection of substrate. For Cell No. 2, average ORP values during baseline (Phase 2) ranged from 104 mV to 195 mV, and following 1% whey injections dropped to an average of -137 to -23 mV, and decreased again following 10% w/w whey injections to an average of -155 to -106 mV. After whey injections were complete, post-injection ORP values increased to an average range of -79 to 81 mV. Similar trends were observed in Cell No. 1.

Iron and sulfate conditions were rapidly induced at the EGDY Site, with ferrous iron concentrations increasing from below detection to greater than 3 mg/L. Baseline sulfate concentrations typically ranged from 15 to 30 mg/L, and were typically reduced to less than 10 to 12 mg/L during substrate injection.

Methane concentrations were generally non-detect prior to substrate injection. Significant methane production was not observed until approximately 5 months after whey injections in both treatment cells, irrespective of the whey injection strategy. The highest concentrations of methane were observed during post-injection sampling with average concentrations of 6.0 mg/L. The lag in the onset of significant methanogenesis can be attributed to one or more factors including: 1) lag in the period of achieving reducing conditions, 2) slow growth of methanogens, and/or 3) the low pH following the onset of whey injections. In any case, methane-producing conditions were achieved within both test cells approximately 4 months after whey injections began.

No. 3: Remediation Effectiveness: Evaluate efficiency in removal of VOCs based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Determine “threshold” concentrations of dissolved organic carbon that represent the minimum levels required to sustain complete reductive dechlorination.

Pre- and post-treatment concentrations of the targeted contaminants are evaluated to determine the effectiveness of the remedy. For this demonstration, the total molar concentration of VOCs and ethene/ethane were measured to see if enhanced mass transfer of VOCs into the aqueous phase could be achieved. Three statistical comparisons were performed that demonstrated that VOC molar concentrations were increased at the 95% confidence level for two of the three scenarios evaluated. VOC molar concentration increases were statistically significant from 1) 10% whey solution relative to baseline, and 2) from 10% whey solution relative to 1% whey solution. For Cell No. 2, mass transfer was enhanced by a factor of 1.8 to 4.2. In summary, the demonstration was successful in stimulating enhanced mass transfer using injection of a 10% whey solution.

An initial drop in pH due to the whey conditions delayed the onset of methanogenesis and further dechlorination of DCE to VC and ethene. While dechlorination was initially incomplete, this was useful for maintaining a mass balance to evaluate enhanced dissolution.

Monitoring towards the end of the demonstration showed that in seven of eight downgradient wells, mass flux based on total chloroethene concentrations had decreased by a factor of 94 to 99% in May 2006. This indicates that anaerobic degradation of VOCs was stimulated, and was sufficient to degrade a large proportion of VOC mass that was transferred to the aqueous phase.

No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

Secondary water quality parameters that were evaluated for the EGDY site only include pH ferrous iron, and chloride. Other secondary water quality parameters were either not measured or not reported. The following is an evaluation for Test Cell No. 2, where the highest concentrations of VOCs were observed.

Summary of Secondary Water Quality – Test Cell No. 2, EGDY, Fort Lewis, Washington

Parameter	Comparison Criteria	Background (Average Phase 2)	Treatment Zone (1% Whey)	Treatment Zone (10% Whey)	Issues?
pH	<6.5 or >8.5 (b)	6.1 to 6.4	4.6 to 5.6	5.1 to 5.9	Yes – initially inhibited dechlorination if <i>cis</i> -DCE and VC
Total Ferrous Iron (mg/L)	0.3 (b)	<0.5	>3.3	>3.3	Potential – above criteria
Chloride (mg/L)	250 (b)	<0.01	<0.05	<0.05	No

Notes:

Baseline and treatment cells values from wells MW2A1, MW2A2, MW2A4, MW2B4, MW2C4, MW2D1, MW2D2, and MW2D4.

mg/L = milligrams per liter

Criteria based on (a) USEPA MCL; (b) USEPA Secondary Standard; or (c) USEPA Region 9 PRG.

pH. Following the onset of 1% whey injections, pH declined to a range of 4.66 to 5.61. The low pH was maintained for approximately 4 months before it began to rebound between injection events as a result of increased buffering capacity due to bicarbonate production associated with biological activity. The average pH observed during the 10% whey injections was higher (range of 5.1 to 5.9) due to increased buffering capacity. By 1 month post-injection, the pH had rebounded to near the pre-whey values at most locations. The gradual pH increase following 1% w/w whey injections demonstrates the ability of the system to buffer itself naturally over time. This buffering was attribute to carbon dioxide production resulting in more bicarbonate, which increases alkalinity. Significant biological inhibition of dechlorination of *cis*-DCE and VC occurred during the initial periods of low pH.

Ferrous Iron. Ferrous iron concentrations measured prior to whey injections (Phase 2) were generally non-detect or less than 0.5 mg/L in Treatment Cell 2. Ferrous iron concentrations increased following whey injections and were generally greater than 3.0 mg/L during 1% and

10% whey powder injections, indicative of iron reduction (the upper limit of detection was 3.3 mg/L).

Chloride. Baseline concentrations of chloride were typically less than 10 µg/L, and were elevated after injections at concentrations approaching 50 µg/L. However, these concentration are orders o magnitude less than the USEPA Secondary Water Quality Standard of 250 mg/L.

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

Initial tracer tests at the EGDY indicated groundwater velocity was higher than anticipated, with a substantial vertical gradient, and that the injection system that was ineffective at distributing tracer through the high concentration residual contaminant zone due to vertical heterogeneity in permeability and low yields in the extraction wells. Following installation of new injection and extraction wells, a third tracer study demonstrated effective distribution of the tracer throughout the targeted treatment zone. No impacts on hydraulic conductivity were observed following substrate injections.

No. 6: Substrate Persistence and Long-Term Effectiveness

Post injection monitoring was conducted for two months following the last injection. In general, significant rebounds in concentrations of chlorinated ethenes was not observed in the two months after injection was halted. In addition, downgradient mass flux wells were sampled for four months post-injection. The mass flux monitoring results demonstrated that flushing the source area with the 10% whey solution not only increased mass transfer, it also achieved sufficient mass removal to have a beneficial long-term effect on downgradient flux from the source area. Just 2 months after the highest aqueous concentrations of chloroethenes for the entire demonstration were observed at FX3-03, concentrations decreased to just 14% of baseline concentrations in that location. Furthermore, concentrations in FX3-03 in the last three sampling events (April, May, and June 2005) ranged from just 2 to 6% of baseline concentrations. In other words, downgradient mass flux from Cell No. 1 was decreased by 94 to 98% after only 8 months of whey injections. For seven of the eight downgradient wells, downgradient mass flux based on total chloroethenes concentrations had decreased by a factor of 94 to 99% in May 2006.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

The cost associated with poor performance or compliance issues may significantly increase the life-cycle costs of full-scale enhanced *in situ* bioremediation applications. Other than having to re-install the extraction and injection wells, no significant modifications were required, No additional injections or monitoring were conducted.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

There were no apparent limits due to the hydrogeological conditions at the EGDY site. A moderate degree of heterogeneity and low yield from the initial extraction wells did require re-

installation of the extraction and injection wells. In this case, conducting a tracer test prior to substrate injection was highly beneficial in achieving adequate substrate distribution.

COST ASSESSMENT

The following cost assessment is for a theoretical full-scale application for NAPL Area 3 at the Fort Lewis Logistics Center. The cost model assumed a 3-year operations period, with a total cost for cleanup of the 0.5 acre sites estimated to be \$900,000 using the demonstration technology. On a unit basis, this equated to \$56 per cubic yard of aquifer.

Example Cost Estimate for Full-Scale DNAPL Source Area

Cost Element	Data to be Tracked	Project Cost
Start-up Costs (Mobilization) (Total = \$197,100)	• Work Plan • Field Preparation/Procurement (includes drilling and well installation)	• \$55,000 • \$142,100
Preliminary Site Characterization (Total = \$92,600)	• Preliminary Site Characterization (includes tracer tests)	• \$92,600
Capital Costs (Total = \$26,000)	• Construction material cost (extraction well pumps and electrical equipment)	• \$26,000
Operations and Maintenance Cost (Total = \$558,600)	• Capital Equipment Rental (whey injection system) • Equipment Rental (tanks) • Supervision (labor for project management, regulatory interface, oversight, and reporting) • Injection (labor, materials, travel) • Sampling and Analysis (during remediation for labor, analytical, and travel)	• \$23,000 • \$10,000 • \$180,400 • \$180,000 • \$165,200
Long-Term Monitoring	• No cost tracking	• NA
Demobilization (Total = \$26,000)	• Well Abandonment	• \$26,000
Total Application Cost		\$900,300

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** EGDY, Fort Lewis Logistics Center, Washington

NOTE: Unshaded boxes are user input.				
1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	30	1-10,000	feet	Calculations for Test Cell No. 2
Length (Parallel to predominant groundwater flow)	50	1-1,000	feet	
Saturated Thickness	15	1-100	feet	
Treatment Zone Cross Sectional Area	450	--	ft ²	
Treatment Zone Volume	22,500	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	50,504	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	42,086	--	gallons	
Design Period of Performance	0.67	.5 to 5	year	Operated for 8 months (July 2005 to February 2006)
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	Hydraulic data from demonstration plan (see note)
Effective Porosity	25%	.05-50	percent	Estimated value
Average Aquifer Hydraulic Conductivity	54	.01-1000	ft/day	Pumping tests in EGDY ranged from 16 to 114 ft/day
Average Hydraulic Gradient	0.01	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	2.16	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	788.4	--	ft/yr	
Average Groundwater Flux through the Treatment Zone	663,616	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm ³	Assumed value for glacial outwash and drift deposits
Soil Fraction Organic Carbon (foc)	0.10%	0.01-10	percent	Assumed value for glacial outwash and drift deposits
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.2	0.01 to 10	mg/L	Average baseline concentration
Nitrate	1.10	0.1 to 20	mg/L	Average baseline concentration
Sulfate	19	10 to 5,000	mg/L	Average baseline concentration
Carbon Dioxide (estimated as the amount of Methane produced)	6.0	0.1 to 20	mg/L	Methanogenesis occurred at 4 months post-injection
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	1	0.1 to 20	mg/L	Not analyzed (assumed to be 1 mg/L)
Iron (III) (estimated as the amount of Fe (II) produced)	3	0.1 to 20	mg/L	Typically over 3 mg/L post-injection
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.000	--	mg/L	
Trichloroethene (TCE)	35.000	--	mg/L	Maximum baseline concentration
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	13.000	--	mg/L	Maximum baseline concentration
Vinyl Chloride (VC)	0.000	--	mg/L	Not detected during baseline
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	150	-400 to +500	mV	Baseline measured during Phase 2 recirculation
Temperature	12	5.0 to 30	°C	Ranged from 104 to 195 mV during baseline sampling
pH	6.3	4.0 to 10.0	su	Typically ranged from 11 to 13 °C
Alkalinity	72	10 to 1,000	mg/L	Ranged from 6.1 to 6.4 during baseline
Total Dissolved Solids (TDS, or salinity)	NA	10 to 1,000	mg/L	Ranged from 66 to 78 mg/L during baseline
Specific Conductivity	240	100 to 10,000	µs/cm	Not analyzed
Chloride	1	10 to 10,000	mg/L	Ranged from 220 to 260 µs/cm during baseline
Sulfide - Pre injection	NA	0.1 to 100	mg/L	Typically less than 1 mg/L throughout test
Sulfide - Post injection	NA	0.1 to 100	mg/L	Not analyzed
B. Aquifer Matrix				
Total Iron	NA	100 to 10,000	mg/kg	Data not available
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	Not analyzed
Neutralization Potential	NA	1.0 to 100	Percent as CaCO ₃	Not analyzed

NOTES:

Hydraulic data assumes that the net groundwater flux into and out of the treatment cell is zero.

Table S.2 Substrate Calculations in Hydrogen Equivalents**Site Name:** EGDY, Fort Lewis Logistics Center, Washington

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
30	1-10,000	feet
50	1-1,000	feet
15	1-100	feet
450	--	ft ²
22,500	--	ft ³
42,086	--	gallons
0.7	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.3	.05-50	
0.25	.05-50	
54	.01-1000	ft/day
0.01	0.1-0.0001	ft/ft
2.16	--	ft/day
788.4	--	ft/yr
663,616	--	gallons/year
1.7	1.4-2.0	gm/cm ³
0.001	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
1.2	0.42	7.94	0.05	4
1.1	0.39	10.25	0.04	5
19	6.67	11.91	0.56	8
6.0	2.11	1.99	1.06	8
Soluble Competing Electron Acceptor Demand (lb.)			1.71	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
1.0	4.04	27.25	0.15	2
3.0	12.13	55.41	0.22	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			0.37	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.000	0.00	20.57	0.00	8
35.000	12.29	21.73	0.57	6
13.000	4.57	24.05	0.19	4
0.000	0.00	31.00	0.00	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.000	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			0.76	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x C_{gw})
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	0.00	0.00	20.57	0.00	8
107	3.75	8.94	21.73	0.41	6
45	0.59	1.40	24.05	0.06	4
3.0	0.00	0.00	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			0.47		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.2	6.65	7.94	0.84	4
Nitrate (denitrification)	1.1	6.09	10.25	0.59	5
Sulfate	19	105.21	11.91	8.83	8
Carbon Dioxide (estimated as the amount of Methane produced)	6	33.23	1.99	16.70	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				27.0	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	35.000	193.81	21.73	8.92	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	13.000	71.99	24.05	2.99	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				11.91	

Initial Hydrogen Requirement First Year (lb) **42.2****Total Life-Cycle Hydrogen Requirement (lb)** **29.2****5. Design Factors**

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X

Design Factor **1.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)** **29.2****6. Acronyms and Abbreviations**

°C =degrees celsius	meq/100 g = milliequivalents per 100 grams
μs/cm = microsiemens per centimeter	mg/kg = milligrams per kilogram
cm/day = centimeters per day	mg/L = milligrams per liter
cm/sec = centimeters per second	m/m = meters per meters
ft ² = square feet	mV = millivolts
ft/day = feet per day	m/yr = meters per year
ft/ft = foot per foot	su = standard pH units
ft/yr = feet per year	wt/wt H ₂ = concentration molecular hydrogen, weight per weight
gm/cm ³ = grams per cubic centimeter	
kg of CaCO ₃ per mg = kilograms of calcium carbonate per milligram	
lb = pounds	

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

RESET DEFAULT

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 0.66666667

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	653	653	2.96E+08	161
Sodium Lactate Product (60 percent solution)	1.0	653	1,354	2.96E+08	161
Molasses (assuming 60 percent sucrose)	1.0	620	1,034	2.81E+08	153
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	653	816	2.96E+08	161
Ethanol Product (assuming 80% ethanol by weight)	1.0	334	417	1.51E+08	83
Whey (assuming 100% lactose)	1.0	451	644	2.04E+08	111
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	495	495	2.24E+08	98
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	254	254	1.15E+08	63
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	254	423	1.15E+08	63

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents**Site Name:** EGDY, Fort Lewis Logistics Center, Washington**1. Treatment Zone Physical Dimensions**

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	30	feet	9	meters
Length (parallel to groundwater flow)	50	feet	15.2	meters
Saturated Thickness	15	feet	4.6	meters
Design Period of Performance	0.666666667	years	0.666666667	years

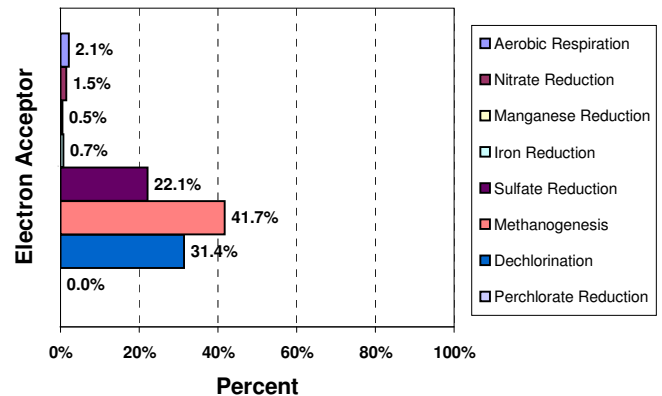
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.25	percent	0.25	percent
Average Aquifer Hydraulic Conductivity	54	ft/day	1.9E-02	cm/sec
Average Hydraulic Gradient	0.01	ft/ft	0.01	m/m
Average Groundwater Seepage Velocity	2.16	ft/day	6.6E+01	cm/day
Average Groundwater Seepage Velocity	788	ft/yr	240.3	m/yr
Total Treatment Zone Pore Volume	42,086	gallons	159,309	liters
Groundwater Flux (per year)	663,616	gallons/year	2,511,990	liters/year
Total Groundwater Volume Treated (over entire design period)	484,497	gallons total	1,833,969	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.1%	0.611
Nitrate Reduction	1.5%	0.434
Sulfate Reduction	22.1%	6.450
Manganese Reduction	0.5%	0.148
Iron Reduction	0.7%	0.219
Methanogenesis	41.7%	12.190
Dechlorination	31.4%	9.167
Perchlorate Reduction	0.0%	0.000
Totals:	100.00%	29.22

Hydrogen demand in pounds/gallon:	6.03E-05
Hydrogen demand in grams per liter:	7.23E-03

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor =****1.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	1,354	123	161	as lactic acid
2. Molasses Product	1,034	86	153	as sucrose
3. Fructose Product	816	73	161	as fructose
4. Ethanol Product	417	60	83	as ethanol
5. Sweet Dry Whey (lactose)	644	sold by pound	111	as lactose
6. HRC®	495	sold by pound	98	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	254	33	63	as soybean oil
8. Emulsified Vegetable Oil	423	54	63	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

SITE SUMMARY

Site 1, Hanscom AFB, Massachusetts

For: Project Files for ESTCP Substrate Loading Study (Project No. 745255)

Revision: 20 July 2009

SITE IDENTIFICATION

Site 1, Hanscom AFB, Massachusetts (ER-9920). Also known as Fire Training Area II.

CONTAMINANT SOURCE

<i>COC</i>	<i>Max. Conc.</i>	<i>DNAPL Present?</i>	<i>Notes</i>
TCE	1,900 µg/L	No	Ref (2)
<i>cis</i> -1,2-DCE	5,300 µg/L	No	Ref (2)
VC	1,300 µg/L	No	Ref (2)
Ethene	67 µg/L	No	Ref (2)

Notes: Max concentrations were obtained from well IRZ-2 for initial sampling event in June 2000.

SUBSTRATE DESIGN/INSTALLATION INFORMATION

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
Project Scale	Pilot		
Substrate Type	Molasses	Yes	
Number of Injection Points (IP)	Single injection well (IRZ-INJ)	No	
IP Spacing Information	NA (single well)	NA	
Injection Date	11 October 2000 (initial) 09 October 2002 (final)		
Injection Interval (depth bgs)	35 to 50 feet bgs	No	
Substrate Loading	An initial loading rate of 40 to 80 pounds of carbohydrate per injection well per week based on previous experience.	Average injection rate of 139 pounds of molasses per week, varying from approx. 60 to 240 lbs/wk with a final injection of approx. 440 pounds.	A total of 1,250 gallons of raw blackstrap molasses, 11,250 gallons of dilution water, 7,575 gallons of push water, and 4,732 grams of potassium bromide were injected.

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
Substrate Loading Rate	A single “batch” consisting of 100 gallons potable water + 10 gallons molasses	A typical “batch” consisted of 180 gallons potable water + 20 gallons molasses + 113 grams potassium bromide	Actual amount of substrate injected was based on field observation of pH (e.g., either a single or double “batch.”
Basis for Loading Rate	Empirical based on previous experience	Based on field observations to limit pH excursion in the injection well but to maximize target concentrations of TOC in downgradient wells.	
Injection Frequency	A total of 32 weekly injections were planned	Yes – went to bi-weekly injections	A total of 47 injections were conducted over a 2-year period.
Injection Rate/Pressure	Approx. 10 gpm at 10 to 15 psi	Yes	Injection pressures increased with biofouling to the point where well seal leaked. Final injections at 1-2 gpm and 2-3 psi to avoid leakage.
Injection Concentration	20 gallons molasses with 180 gallons water	Yes	
Injection amendments	Potassium bromide		
Pre-injection Specified?	No	No	
Post-injection Specified?	No	Yes	Water pushes were initiated approximately 5 months after initial injection
Type of post-injection	Clean Water		
Volume of post-injection	200 gallons		

MONITORING INFORMATION

<i>Sample Collection Date (Reference)</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Reference</i>
June 2000 (baseline)	Yes	Yes	Yes	No	Ref (2)
May 2001 (mid-point)	Yes	Yes	Yes	No	Ref (2)
October 2002 (final)	Yes	Yes	Yes	No	Ref (2)
May 2003 (rebound event)	Yes	Yes	Yes	No	Ref (3)

Note: Nine (9) partial full or abbreviated sampling events, with thirteen (13) additional “Low QA/QC” sampling events were conducted, primarily for geochemical indicators.

REFERENCES

- (1) ARCADIS. 2000. *Technology Demonstration, In-Situ Substrate Addition to Create Reactive Zones for Treatment of Chlorinated Aliphatic Hydrocarbons, Final Demonstration Plan, Hanscom Air Force Base*. Prepared for AFCEE and ESTCP. March 2. (**Work Plan**)
- (2) ARCADIS. 2003. *In-situ Substrate Addition to Create Reactive Zones for Treatment of Chlorinated Aliphatic Hydrocarbons: Hanscom Air Force Base*. Prepared for the Air Force Center of Environmental Excellence (AFCEE) and Environmental Security Technology Certification Program (ESTCP). 04 April. (**Final Report**)
<http://www.estcp.org/Technology/upload/CU-9920-FR-VAFB.pdf>
- (3) ARCADIS. 2007. *Cost and Performance Report: In-situ Substrate Addition to Create Reactive Zones for Treatment of Chlorinated Aliphatic Hydrocarbons*. Prepared for the Environmental Security Technology Certification Program (ESTCP). March. (**Final Cost and Performance Report**)

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates calculated or designed?

The substrate loading rate was based on empirical methods using past experience. The initial dosing was anticipated to be 40 to 80 lbs of carbohydrates per injection well per week. The feed solution was proposed to consist of a 10:1 mixture by volume of potable water to raw blackstrap molasses, where the total consumable carbohydrate concentration in the molasses is approximately 60% by weight.

The dosing objectives were to achieve concentrations of TOC from 500 to 5,000 mg/L in the injection well, and greater than 50 mg/L TOC in the downgradient monitoring wells. It was anticipated that the dosing rate and frequency would be adjusted based on field observations, and determining the optimal strength and frequency of reagent delivery was a primary objective of the demonstration.

2. What modifications to the substrate amendment protocol were required (e.g., concentration and frequency for soluble substrates; and depletion and additional injection of slow-release substrate types such as HRC[®] and EVO).

Substrate (molasses) dosing was variable during the demonstration, as was the use of a water chase to disperse the substrate. For example, a clean water push was initiated with the 7th injection on 20 February 2001. In general, injections were either a “single” batch injection (200 gallons consisting of 20 gallons molasses, 180 gallons potable water, and 113 grams sodium bromide) or a “double” batch injection (400 gallons), with either a “single” water push (200 gallons potable water) or a “half” water push (100 gallons). Overall the average injection rate was approximately 139 pounds of molasses per week, varying from approximately 60 to 240 pounds per week with a final injection of approximately 440 pounds of molasses in October 2002. The substrate loading for each injection event was based field observations to limit pH

excursion in the injection well, while trying to maximize target concentrations of TOC in downgradient wells.

Initial injections proceeded at a rate of approximately 10 gpm at well head pressures of 10 to 15 psig. Due to biological fouling, injection pressures increased to the point that the annular seal of the injection well was breached. Injection pressures had to be reduced, and during the final substrate injections rates were down to 1 to 2 gpm at well head pressures of 2 to 3 psig.

3. Evaluation from Substrate Demand Tool

Site data were input into the substrate requirement tool (attached). The substrate requirement to treat 345,399 gallons (1,307,441 liters) of groundwater over 2 years was 12.17 pounds of molecular hydrogen, or 3.52E-05 pounds per gallon (4.22E-03 grams per liter) of groundwater treated. These calculations assume that the effective treatment zone is 20 feet wide by 200 feet in length by 15 feet in depth.

This hydrogen requirement could be met by 430 pounds of molasses product (approximately 36 gallons), assuming the product is 60 percent sucrose by weight. This results in an effective concentration of 90 mg/L of sucrose if the substrate was uniformly distributed throughout the total volume of groundwater treated. This is reasonably close to the target concentration of 50 mg/L TOC for wells downgradient of the injection well.

The primary electron accepting demand was calculated to be from sulfate reduction (52.5%), followed by iron reduction (26.4%), methanogenesis (11.9%), dechlorination of chlorinated solvents (6.3%), aerobic respiration (1.8%), manganese reduction (1.0%), and nitrate reduction (<0.1%). These calculations assume that all the electron acceptors are completely reduced.

PERFORMANCE OBJECTIVES

No. 1: Ability to Uniformly Distribute Substrate : Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

The target concentrations for distribution of substrate was from 500 to 5,000 mg/L of TOC in the injection well, and greater than 50 mg/L of TOC in the downgradient monitoring wells. Monitoring wells were located at distances of approximately 60 to 100 feet from the injection well. These targets were met for the injection well for a few monitoring wells (IRZ-1 and RAP1-6T), but generally not for downgradient wells IRZ-2 through IRZ-5.

The injection protocol had to be continuously “tuned” (i.e., the injection protocol had to be continuously modified) in an attempt to meet these targets. The ability to inject substrate mixtures of higher concentration to achieve a broader distribution at target concentrations was limited by pH excursion at the injection well. A buffering agent had to be used to achieve target TOC concentrations near the injection well (wells RAP1-6 and IRZ-1). Changes in groundwater flow patterns resulted in other monitoring wells (IRZ2 through IRZ-5) being located in locations that did not adequately define the downgradient extent of substrate. Therefore, conclusions could not be drawn regarding the effective downgradient distribution of substrate.

No. 2: Achieving Optimal Geochemical Conditions

Successful geochemical conditions for stimulating anaerobic degradation of chlorinated solvents is defined as when the groundwater environment is highly anaerobic with DO less than 0.5 mg/L, ORP is less than -200 millivolts (mV), sulfate is reduced by more than 50 percent relative to background conditions, and methane is greater than 1.0 mg/L. These criteria may not apply in all cases. For the Hanscom site, targets for these parameters in downgradient wells included DO less than 1.0 mg/L and ORP less than -200 mV.

Background concentrations of DO were typically less than 1.0 mg/L to start with. ORP was reduced to a range of -150 to -200 mV at wells RAP1-6T and IRZ-1. ORP in other downgradient wells were only moderately reduced, typically from -50 mV to -90 mV for wells IRZ-2 through IRZ-5. Background concentrations of sulfate averaged approximately 26 mg/L, and concentrations were typically reduced to less than 10 mg/L or lower at RAP1-6T and IRZ-1. Sulfate concentrations were not significantly reduced at other locations, corresponding to a lack of DOC. Concentrations of methane did increase at well RAP1-6T and IRZ-1 once the dosing rate could be increased by adding a buffering amendment, with methane at approximately 2 mg/L at well IRZ-1 in October 2002.

Overall, appropriate geochemical conditions were induced only when the target concentrations of TOC were achieved. A lack of appropriate geochemical conditions correlates to substrate distribution, which was not uniform over time as the pattern of groundwater flow varied due to changes in operation of the nearby groundwater extraction system.

No. 3: Remediation Effectiveness: Evaluate efficiency in removal of VOCs based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Determine “threshold” concentrations of dissolved organic carbon that represent the minimum levels required to sustain complete reductive dechlorination.

Performance goals for the Hanscom demonstration were a reduction in total CAHs of 80 percent within 1 year, which is similar to the demonstration study performance objective of a reduction in the total molar concentration of CAHs of greater than 90 percent. It was also anticipated that substrate addition would enhance desorption of CAHs from the aquifer matrix, perhaps initially increasing dissolved concentrations of CAHs. At IRZ-1, TCE was reduced by over 95% in 5 months, post-treatment concentrations of TCE and *cis*-DCE were reduced by over 99%, and VC was reduced by 97% at 7 to 17 months after the last injection.

At RAP1-6T, TCE was reduced by over 80% after 1 year, with post-treatment concentrations of *cis*-DCE and VC reduced by 99% at 13 to 17 months after the last injection. While the specific performance metric was not literally achieved (80% total CAHs at 1 year), the long-term results for these two wells are considered successful within the context of the demonstration. Performance objectives were not achieved at other downgradient wells, likely because they were not located in suitable downgradient locations to monitor the zone of substrate distribution.

No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

Secondary water quality parameters that were evaluated for the Site 1 demonstration include pH, dissolved metals (iron and manganese), total dissolved solids (TDS), biological oxygen demand (BOD), and chemical oxygen demand (COD).

Summary of Secondary Water Quality – Site 1, Hanscom AFB, Massachusetts

Parameter	Comparison Criteria	Baseline	Injection Well	Down-gradient	Issues?
pH	<6.5 or >8.5 (b)	5.8 to 6.3	4.0	6.6 to 7.1	None - adverse conditions did not persist downgradient
Sulfide (mg/L)	--	<0.1	0.3 to 5.0	<1.0	None - adverse conditions did not persist downgradient
Dissolved Iron (mg/L)	0.3 (b)	0.31 to 14	220	13 to 88	Potential – background above criterion
Dissolved Manganese (mg/L)	0.05 (b)	0.1 to 0.3	1.7	0.68 to 1.8	Potential – background above criterion
Total Dissolved Solids (mg/L)	500 (b)	NM	15,000	190 to 360	None - adverse conditions did not persist downgradient
Biological Oxygen Demand (mg/L)	--	ND	14,000	ND to 140	None - adverse conditions did not persist downgradient
Chemical Oxygen Demand (mg/L)	--	23.3 to 120	51,000	ND to 250	None - adverse conditions did not persist downgradient

Notes:

Background data are average concentrations from baseline measurements in Table 4-5 of ARCADIS (2003) for wells IRZ-INJ, IRZ1 through IRZ4, and RAP-6T.

Post injection data are average concentrations from Table 4-7 of ARCADIS (2003) for wells IRZ-INJ (injection well), and IRZ-1 through IRZ-5 and RAP-6T (downgradient wells) sampled October 2002.

mg/L = milligrams per liter; µg/L = micrograms per liter.

Criteria based on (a) USEPA MCL; (b) USEPA Secondary Standard; or (c) USEPA Region 9 PRG.

pH. With the exception of the injection well, pH typically remained above 6.0 downgradient of the injection well and an adverse decrease in pH was not observed.

Sulfide. With the exception of the injection well, sulfide typically remained below 1.0 mg/L downgradient of the injection well and an adverse decrease in pH was not observed.

Dissolved metals. Samples were analyzed for dissolved metals to evaluate impacts on water quality. Dissolved iron increased to as high as 220 mg/L in the injection well at the end of the

injection period in October 2002, and dissolved iron was measured at concentrations of 88 mg/L and 59 mg/L at downgradient wells IRZ-1 and RAP1-6T in October 2002, respectively. Concentrations of dissolved manganese increased to a lesser degree, with dissolved manganese detected in October 2002 at concentrations of 1.7 to 1.8 mg/L in the injection well and downgradient wells IRZ-1 and RAP1-6T. The magnitude of the increase in manganese was much lower compared to iron.

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

No adverse impacts to hydraulic conductivity within the subsurface formation were observed. Biofouling of the injection well was an issue that impacted the amount of labor required for each injection, as flow rates were reduced from approximately 10 gpm down to 1 to 2 gpm.

No. 6: Substrate Persistence and Long-Term Effectiveness

No rebound in concentrations of CAHs was observed as of 17 months after the last injection; rather treatment appeared to continue after injections ceased with reductions in concentrations of *cis*-DCE and VC.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

A total of 32 weekly injections were planned, while a total of 47 injections were conducted over a 2-year period. Injections during the initial period from October 2000 to February 2001 were approximately 80 lbs of molasses per week. Substrate distribution was inadequate after 2 to 3 months of this injection regimen. The injection frequency was increased to roughly a biweekly schedule, and pH had to be controlled by controlling substrate dosing and injection of a clean water “push” beginning in February 2001. The water push followed substrate injection to disperse the substrate away from the injection well. Increasing the injection frequency to bi-weekly (averaging 150 lbs/week of molasses) improved the distribution of substrate to downgradient monitoring wells RAP1-6T and IRZ-1.

Beginning in September 2001, the molasses dosage was doubled for most events, while still keeping a bi-weekly injection frequency and water push, in order to expand the size of the reactive zone and in response to increased groundwater flow. The injection rate during the period from September 2001 through February 2002 was in the range of 150-250 lbs/week. The injection rate was reduced between March and September 2002 in response to diminished pH, although the injection rate during this period was in the range of 100-200 lbs/week.

While the cost of the additional injections was not reported, it could be assumed that the cost of injection increased significantly due to:

- Increasing the injection frequency from weekly to a bi-weekly,

- Increased time for each injection due to rates of injection that were reduced from approximately 10 gpm at well head pressures of 10 to 15 psig to 1 to 2 gpm at well head pressures of 2 to 3 psig due to biofouling and compromise of the injection well seal, and
- The cost of additional substrate and the buffering amendment.

It would not be unreasonable to assume the cost of injection for this site may have doubled due to unanticipated site conditions.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

Unexpected variability in the direction of groundwater flow resulted in non-uniform distribution of organic substrate, and effective treatment was only achieved where substantial concentrations of substrate were observed in downgradient monitoring wells. This was due in large part because the site-wide pump and treat system was operated intermittently.

The biggest factor inhibiting bioremediation performance was an adverse excursion in pH due to the low buffering capacity of the aquifer. The amount of substrate injected had to be limited until a buffering agent was added to the injection solution. This initially resulted in limited distribution of substrate and poor initial results. Once the buffering agent was added, higher strength substrate solutions could be injected and degradation results improved. This site also exhibited a very high electron acceptor demand from ferric iron in the aquifer sediments.

3. COST ASSESSMENT

The cost of the demonstration are tabulated below, with a total demonstration cost of approximately \$433,000. The estimated quantity of aquifer treated was estimated to be 1,200 cubic yards, resulting in an estimated unit cost of \$361 per cubic yard.

Actual demonstration costs were used to extrapolate an estimated cost for a hypothetical full-scale system at Hanscom AFB, with an estimated cost of \$3.6 million. This was compared to an estimated life-cycle cost for the existing pump-and-treat system at Hanscom of \$22.3 million. Although there is considerable uncertainty associated with both estimates, it appears that ERD technology would be much more economical than the pump-and-treat remedy.

Cost Summary, Site 1, Hanscom AFB, Massachusetts

Cost Element	Data to be Tracked	Project Cost
System Design/ Work Plan (Subtotal = \$26,328)	Labor for system design and work plan	\$26,328
Capital Construction/ System Installation (includes baseline characterization) (Subtotal = \$77,369)	- Installation method - Mobilization (includes travel and per diem) - Site Labor - Drilling Subcontractor - Laboratory Subcontractor - Injection equipment) - Equipment Rentals - Expendables, Misc. - Engineering Support - Management Support	- Injection wells \$7,646 \$4,658 \$17,788 \$9,785 \$1,800 \$2,286 \$2,256 \$13,168 \$17,712
Operating and Maintenance Cost (Subtotal = \$161,474)	- Labor - Materials and Consumables - Equipment Cost - Performance Analysis - Other Subs and Expendables	\$113,169 \$7,807 \$7,214 \$25,085 \$8,199
Long-Term Compliance Monitoring (Subtotal = \$167,750)	- Compliance Testing and Analysis - Disposal of Residues	\$166,450 \$1,300
	Total Application Cost Quantity Treated = 1,200 cubic yards Unit Cost = \$361 per cubic yard	\$432,921

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** Site 1, Hanscom AFB, Massachusetts

NOTE: Unshaded boxes are user input.				
1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	20	1-10,000	feet	Assumed treatment zone of approximately 20 by 200 feet
Length (Parallel to predominant groundwater flow)	200	1-1,000	feet	
Saturated Thickness	15	1-100	feet	Depth to GW varies from 2 to 9 feet
Treatment Zone Cross Sectional Area	300	--	ft ²	
Treatment Zone Volume	60,000	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	112,230	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	89,784	--	gallons	
Design Period of Performance	2.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	25%	.05-50	percent	
Effective Porosity	20%	.05-50	percent	
Average Aquifer Hydraulic Conductivity	26	.01-1000	ft/day	Ranges from 3 to 48 ft/day
Average Hydraulic Gradient	0.006	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.78	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	284.7	--	ft/yr	
Average Groundwater Flux through the Treatment Zone	127,808	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm ³	Glacial till overlying granitic bedrock. Silty sand w/ gravel.
Soil Fraction Organic Carbon (foc)	0.05%	0.01-10	percent	
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				See notes
Oxygen	0.6	0.01 to 10	mg/L	Ranged from 0.43 to 1.19 mg/L
Nitrate	0.01	0.1 to 20	mg/L	Ranged from ND to 0.04 mg/L
Sulfate	26	10 to 5,000	mg/L	Ranged from 21.5 to 32.3
Carbon Dioxide (estimated as the amount of Methane produced)	1.0	0.1 to 20	mg/L	Ranged from 0.032 to 2.06 mg/L
B. Solid-Phase Native Electron Acceptors				See notes
Manganese (IV) (estimated as the amount of Mn (II) produced)	1.2	0.1 to 20	mg/L	Total manganese - ranged from 0.73 to 1.8 mg/L
Iron (III) (estimated as the amount of Fe (II) produced)	61.7	0.1 to 20	mg/L	Total iron - ranged from 15 to 220 mg/L
4. Contaminant Electron Acceptors				
				See notes
Tetrachloroethene (PCE)	0.000	--	mg/L	Not detected
Trichloroethene (TCE)	1.195	--	mg/L	Ranged from 560 to 1900 ug/L
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	3.812	--	mg/L	Ranged from 1664 to 5497 ug/L
Vinyl Chloride (VC)	0.897	--	mg/L	Ranged from 360 to 1300 ug/L
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.235	--	mg/L	1,1-DCA ranged from 110 to 350 ug/L
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				See notes
Oxidation-Reduction Potential (ORP)	22	-400 to +500	mV	Ranged from -38 to 200 mV
Temperature	NA	5.0 to 30	°C	Not reported
pH	6.1	4.0 to 10.0	su	Ranged from 5.79 to 6.30
Alkalinity	NA	10 to 1,000	mg/L	Not analyzed during initial sampling event
Total Dissolved Solids (TDS, or salinity)	NA	10 to 1,000	mg/L	Not analyzed
Specific Conductivity	387	100 to 10,000	µs/cm	Ranged from 37 to 512 us/cm
Chloride	20	10 to 10,000	mg/L	Ranged from 14.7 to 23.6 mg/L
Sulfide - Pre injection	0.1	0.1 to 100	mg/L	Ranged from ND to 0.1 mg/L
Sulfide - Post injection		0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	NA	100 to 10,000	mg/kg	Not analyzed
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	Not analyzed
Neutralization Potential	NA	1.0 to 100	Percent as CaCO ₃	Not analyzed

NOTES:

Background data are average concentrations from baseline measurements in Table 4-5 of ARCADIS (2003) for wells IRZ-INJ, IRZ1 through IRZ4, and RAP-6T. Post injection data are average concentrations from Table 4-7 of ARCADIS (2003) for wells IRZ-INJ, IRZ-1 through IRZ-5, and RAP-6T sampled October 2002.

Table S.2 Substrate Calculations in Hydrogen Equivalents**Site Name:** Site 1, Hanscom AFB, Massachusetts

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
20	1-10,000	feet
200	1-1,000	feet
15	1-100	feet
300	--	ft ²
60,000	--	ft ³
89,784	--	gallons
2.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.25	.05-50	
0.2	.05-50	
26	.01-1000	ft/day
0.006	0.1-0.0001	ft/ft
0.78	--	ft/day
284.7	--	ft/yr
127,808	--	gallons/year
1.7	1.4-2.0	gm/cm ³
0.0005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.6	0.46	7.94	0.06	4
0.0	0.01	10.25	0.00	5
26.4	19.78	11.91	1.66	8
1.0	0.75	1.99	0.38	8
Soluble Competing Electron Acceptor Demand (lb.)			2.10	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
1.2	3.46	27.25	0.13	2
61.7	177.83	55.41	3.21	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			3.34	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.000	0.00	20.57	0.00	8
1.195	0.90	21.73	0.04	6
3.812	2.86	24.05	0.12	4
0.897	0.67	31.00	0.02	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.235	0.18	24.55	0.01	4
0.000	0.00	32.00	0.00	2
0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			0.19	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x Cgw)
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	0.00	0.00	20.57	0.00	8
107	0.06	0.41	21.73	0.02	6
45	0.09	0.55	24.05	0.02	4
3.0	0.00	0.01	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.02	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			0.04		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	0.6	0.65	7.94	0.08	4
Nitrate (denitrification)	0.0	0.01	10.25	0.00	5
Sulfate	26.4	28.16	11.91	2.36	8
Carbon Dioxide (estimated as the amount of Methane produced)	1	1.07	1.99	0.54	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				3.0	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	1.195	1.27	21.73	0.06	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	3.812	4.07	24.05	0.17	4
Vinyl Chloride (VC)	0.897	0.96	31.00	0.03	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.235	0.25	24.55	0.01	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				0.27	

Initial Hydrogen Requirement First Year (lb)**8.9****Total Life-Cycle Hydrogen Requirement (lb)****12.2****5. Design Factors**

Microbial Efficiency Uncertainty Factor
 Methane and Solid-Phase Electron Acceptor Uncertainty
 Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)

2X - 4X

2X - 4X

1X - 3X

Design Factor**1.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)****12.2****6. Acronyms and Abbreviations**

°C =degrees celsius

μS/cm = microsiemens per centimeter

cm/day = centimeters per day

cm/sec = centimeters per second

ft² = square feet

ft/day = feet per day

ft/ft = foot per foot

ft/yr = feet per year

gm/cm³ = grams per cubic centimeterkg of CaCO₃ per mg = kilograms of calcium carbonate per milligram

lb = pounds

meq/100 g = milliequivalents per 100 grams

mg/kg = milligrams per kilogram

mg/L = milligrams per liter

m/m = meters per meters

mV = millivolts

m/yr = meters per year

su = standard pH units

wt/wt H₂ = concentration molecular hydrogen, weight per weight

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

RESET DEFAULT

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 2

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	272	272	1.23E+08	94
Sodium Lactate Product (60 percent solution)	1.0	272	564	1.23E+08	94
Molasses (assuming 60 percent sucrose)	1.0	258	430	1.17E+08	90
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	272	340	1.23E+08	94
Ethanol Product (assuming 80% ethanol by weight)	1.0	139	174	6.31E+07	48
Whey (assuming 100% lactose)	1.0	188	268	8.51E+07	65
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	206	206	9.35E+07	57
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	106	106	4.80E+07	37
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	106	176	4.80E+07	37

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: **Site 1, Hanscom AFB, Massachusetts**

1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	20	feet	6	meters
Length (parallel to groundwater flow)	200	feet	61.0	meters
Saturated Thickness	15	feet	4.6	meters
Design Period of Performance	2	years	2	years

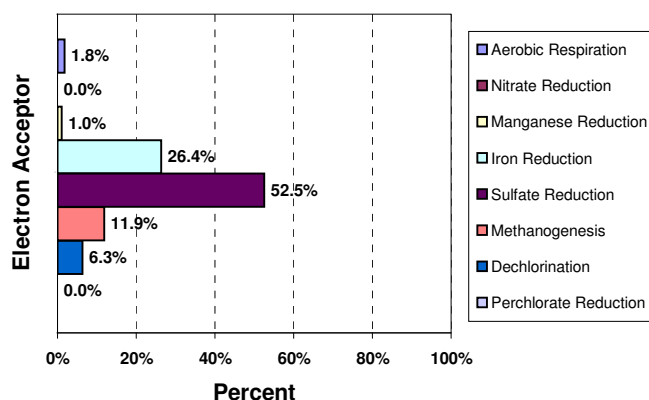
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.25	percent	0.25	percent
Effective Porosity	0.2	percent	0.2	percent
Average Aquifer Hydraulic Conductivity	26	ft/day	9.2E-03	cm/sec
Average Hydraulic Gradient	0.006	ft/ft	0.006	m/m
Average Groundwater Seepage Velocity	0.78	ft/day	2.4E+01	cm/day
Average Groundwater Seepage Velocity	285	ft/yr	86.8	m/yr
Total Treatment Zone Pore Volume	89,784	gallons	339,860	liters
Groundwater Flux (per year)	127,808	gallons/year	483,791	liters/year
Total Groundwater Volume Treated (over entire design period)	345,399	gallons total	1,307,441	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	1.8%	0.221
Nitrate Reduction	0.0%	0.003
Sulfate Reduction	52.5%	6.389
Manganese Reduction	1.0%	0.127
Iron Reduction	26.4%	3.209
Methanogenesis	11.9%	1.448
Dechlorination	6.3%	0.769
Perchlorate Reduction	0.0%	0.000
Totals:	100.00%	12.17

Hydrogen demand in pounds/gallon:	3.52E-05
Hydrogen demand in grams per liter:	4.22E-03

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor =****1.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	564	51	94	as lactic acid
2. Molasses Product	430	36	90	as sucrose
3. Fructose Product	340	30	94	as fructose
4. Ethanol Product	174	25	48	as ethanol
5. Sweet Dry Whey (lactose)	268	sold by pound	65	as lactose
6. HRC®	206	sold by pound	57	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	106	14	37	as soybean oil
8. Emulsified Vegetable Oil	176	23	37	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

SITE SUMMARY**Site 35, Vandenberg AFB, California**

For: Project Files for ESTCP Substrate Loading Study (Project No. 745255)

Revision: 07 August 2009

SITE IDENTIFICATION

Demonstration at Site 35, Vandenberg AFB, California (ER-9920).

CONTAMINANT SOURCE

<i>COC</i>	<i>Max. Conc.</i>	<i>DNAPL Present?</i>	<i>Notes</i>
TCE	1,900 µg/L	No	Ref (3)
<i>cis</i> -1,2-DCE	39 µg/L	No	Ref (3)
VC	ND	No	Ref (3)

Notes: Max concentrations were obtained from well 35-MW12 for baseline sampling in November 2000.

SUBSTRATE DESIGN/INSTALLATION INFORMATION

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
Project Scale	Pilot		
Substrate Type	Molasses	Yes	
Number of Injection Points (IP)	3	Same	
IP Spacing Information	20 feet		
Injection Dates/Duration	27 weekly injections were planned	Same duration	Injections were performed from February 2001 to April 2003 (27 months). Buffering began in October 2002 (20 months after first injection).
Injection Interval (depth bgs)	32 to 42 feet bgs	No change	
Substrate Loading	Empirical – using an initial loading rate of 40 to 80 pounds of carbohydrate per injection well per week based on previous applications	5 to 20 gallons of molasses per point per injection. Average of 48 lbs/week into 3 wells before buffer addition, and average of 123 lbs/wk after	A total of 683 gallons of raw blackstrap molasses, 6,830 gallons of dilution water, 1,500 gallons of push water, 7,718 grams of potassium bromide, and 669 pounds of sodium bicarbonate were injected over a period of 27

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
		buffer additions.	months.
Substrate Loading Rate	A single "batch" consisting of 100 gallons potable water + 10 gallons molasses	Yes	Actual amount of substrate injected was based on field observation of pH (e.g., either a single or double "batch.")
Basis for Loading Rate	Empirical based on site hydrogeology and biogeochemistry		
Injection Frequency	27 weekly injection events were planned	Yes - A total of 31 injections were performed	
Injection Concentration	10 gallons molasses in 100 gallons water		
Injection Rate	Approx. 5 gpm at 18-20 psi.		
Injection amendments	Sodium bromide tracer	Yes - Sodium bicarbonate for buffering	
Pre-injection Specified?	No	No	
Post-injection Specified?	No	Yes	
Type of post-injection	Clean Water	Yes	
Volume of post-injection	100 to 200 gal		

MONITORING INFORMATION

<i>Sample Collection Date</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Reference</i>
Baseline November 2000	Yes	Yes	Yes	No	Ref (3)
Mid-point April 2002	Yes	Yes	Yes	No	Ref (3)
Final May 2003 (1 mo. After last injection)	Yes	Yes	Yes	No	Ref (3)

Note: Thirteen (13) additional "Low QA/QC" sampling events were conducted, primarily for geochemical indicators.

REFERENCES

- (1) ARCADIS. 2000. *Technology Demonstration Plan Vandenberg AFB: Technology demonstration in-situ substrate addition to create reactive zones for treatment of chlorinated aliphatic hydrocarbons*. Prepared for AFCEE and ESTCP. 11 April. (Work Plan)
- (2) ARCADIS. 2003. *Interim Demonstration Scale Test Report, In-situ Substrate Addition to Create Reactive Zones for Treatment of Chlorinated Aliphatic Hydrocarbons*:

Vandenberg Air Force Base. Prepared for AFCEE and ESTCP. October. (**Interim Report**)

- (3) ARCADIS G&M, Inc. 2004. *In-situ Substrate Addition to Create Reactive Zones for Treatment of Chlorinated Aliphatic Hydrocarbons: Vandenberg Air Force Base.* Prepared for the Air Force Center of Environmental Excellence (AFCEE) and Environmental Security Technology Certification Program (ESTCP). 17 December. <http://www.estcp.org/Technology/upload/CU-9920-FR-HAN.pdf> (**Final Report**)
- (4) ARCADIS. 2007. *Cost and Performance Report: In-situ Substrate Addition to Create Reactive Zones for Treatment of Chlorinated Aliphatic Hydrocarbons.* Prepared for the Environmental Security Technology Certification Program (ESTCP). March. (**Final Cost and Performance Report**)

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates calculated or designed?

The substrate loading rate was based on empirical methods using past experience. The initial dosing was anticipated to be 40 to 80 lbs of molasses per each of three injection wells per week. The feed solution was proposed to consist of a 10:1 mixture by volume of potable water to raw blackstrap molasses, where the total consumable carbohydrate concentration in the molasses is approximately 60% by weight.

The dosing objectives were to achieve concentrations of TOC from 500 to 5,000 mg/L in the injection well, and greater than 50 mg/L TOC in the downgradient monitoring wells. It was anticipated that the dosing rate and frequency would be adjusted based on field observations, and determining the optimal strength and frequency of reagent delivery was a primary objective of the demonstration.

During the 27 months of active system operation, a total of 683 gallons of raw blackstrap molasses, 6,830 gallons of dilution water, 1,500 gallons of push water, 7,718 grams of potassium bromide and 669 pounds of sodium bicarbonate (NaHCO_3) were injected. The average molasses injection rate for the three injection wells combined was 48 lbs/week before the addition of a buffer compound, and 123 lbs/week after addition of the buffer. The volume of molasses injected varied for the three injection wells. The total volumes injected were 195 gallons at 35-I-1, 1,333 gallons at 35-I-2 and 140 gallons at 35-I-3.

2. What modifications to the substrate amendment protocol were required (e.g., concentration and frequency for soluble substrates; and depletion and additional injection of slow-release substrate types such as HRC[®] and EVO).

The substrate loading for each injection event was based field observations to limit pH excursion in the injection wells, while trying to maximize target concentrations of TOC in downgradient wells. The site exhibited low buffering capacity, and pH was initially controlled by limiting the substrate dose, reducing the frequency of injection, and injection of an occasional clean water “push” to disperse dissolved substrate away from the immediate vicinity of the injection wells. This revised dosing regime was necessary to avoid further drops in pH, but negatively affected the

consistency of the TOC level in the injection and downgradient monitoring wells and resulted in a limited reaction zone.

Sodium bicarbonate was added to the injection regimen at 20 months after injections started in an attempt to control pH excursion. This allowed for a nearly four-fold increase in the molasses loading rate and helped to expand the reaction zone. Stabilization and mild recovery of pH was observed at most downgradient monitoring wells following the addition of a buffering agent.

3. Evaluation from Substrate Demand Tool

Site data were input into the substrate requirement tool (attached). The substrate requirement to treat 359,360 gallons (1,360,289 liters) of groundwater over 2 years was 78.2 pounds of molecular hydrogen, or 2.18E-04 pounds per gallon (2.61E-02 grams per liter) of groundwater treated. These calculations assume that the effective treatment zone is 60 feet wide by 60 feet in length by 10 feet in depth.

This hydrogen requirement could be met by 2,766 pounds of molasses product (approximately 231 gallons), assuming the product is 60 percent sucrose by weight. This results in an effective time-averaged concentration of 553 mg/L of sucrose if the substrate was uniformly distributed throughout the total volume of groundwater treated. This is in the mid-range of the target concentration of 50 to 5,000 mg/L TOC for wells within the treatment zone. A total of 683 gallons of raw blackstrap molasses injected, which is approximately 3.0 times the estimated stoichiometric demand.

The primary electron accepting demand was calculated to be from sulfate reduction (82.7%), followed by methanogenesis (11.2%), nitrate reduction (3.0%), iron reduction (1.4%), aerobic respiration (1.4%), dechlorination of chlorinated solvents (0.3%), and manganese reduction (0.1%). These calculations assume that all the electron acceptors are completely reduced.

PERFORMANCE OBJECTIVES

No. 1: Ability to Uniformly Distribute Substrate : Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

The target concentrations for distribution of substrate was from 500 to 9,000 mg/L of TOC in the three injection wells, and greater than 50 mg/L of TOC in the downgradient monitoring wells. Only monitoring wells closest to the injection points exhibited elevated concentrations of TOC within the first 2 months of injection. The ability to inject substrate mixtures of higher concentration to achieve a broader distribution of substrate at target concentrations was limited by pH excursion at the injection wells. Substantial differences were also noted in the distribution characteristics of the three injection wells, primarily due to differences in substrate utilization and pH excursion. As of the mid-point monitoring event in April 2002, concentrations of TOC in the downgradient monitoring wells ranged from 4.2 to 2,110 mg/L, with only three of the eight wells sampled exhibiting TOC greater than 50 mg/L.

A buffering agent (sodium bicarbonate) had to be used to achieve higher substrate loading rates (almost four times the mass of molasses per month), and the anaerobic treatment zone continued to expand with improved degradation results. Buffering of the injection mixture was required to

achieve an adequate substrate loading rate, and even then concentrations of TOC greater than 50 mg/L were only consistently observed for the immediate downgradient monitoring wells.

No. 2: Achieving Optimal Geochemical Conditions

Successful geochemical conditions for stimulating anaerobic degradation of chlorinated solvents is defined as when the groundwater environment is highly anaerobic with DO less than 0.5 mg/L, ORP is less than -200 millivolts (mV), sulfate is reduced by more than 50 percent relative to background conditions, and methane is greater than 1.0 mg/L. These criteria may not apply in all cases. For the Vandenberg site, targets for these parameters in downgradient wells included DO less than 1.0 mg/L and ORP less than -200 mV.

Injections of aqueous molasses solution were successful in quickly achieving reducing conditions, as evidenced by depressed DO and ORP measurements in downgradient wells within a few months. Concentrations of TOC in the injection wells were favorable at the initial design loading rates. However, pH levels in injection wells decreased from background levels (pH of 6 to 6.5 su) to near the bottom of the acceptable range for the injection wells (pH of 4 su).

Background concentrations of DO were typically greater than 3 to 4 mg/L to start with, and were typically reduced to less than 0.5 mg/L immediately downgradient of the injection wells and to less than 2.0 mg/L further downgradient. As of the mid-point sampling event in April 2002, ORP was reduced to a range of -203 to +188 mV downgradient of the injection wells. Therefore, the ability to uniformly create optimal geochemical conditions was limited by the amount of substrate that could be injected without adverse pH excursion in the injection wells. Concentrations of methane did increase once the dosing rate could be increased by adding a buffering amendment, with methane at approximately 5.0 to 10.7 mg/L in the downgradient wells in May 2003.

Overall, appropriate geochemical conditions were induced when the target concentrations of TOC were achieved. An initial lack of appropriate geochemical conditions correlates to an inability to substantially increase the substrate loading rate due to pH excursion. This was largely corrected by adding a buffering compound to the injection mixture.

No. 3: Remediation Effectiveness: Evaluate efficiency in removal of VOCs based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Determine “threshold” concentrations of dissolved organic carbon that represent the minimum levels required to sustain complete reductive dechlorination.

The quantitative goal of 80% reduction in total CAHs within 1 year was not attained in all monitoring wells, although reductions in concentrations of TCE were greater than 80% at the most highly treated monitoring wells at 27 months after treatment began.

Reductions in TCE varied downgradient from the injection wells, with little TCE reduction where little or no substrate was delivered, and with 42 to 85 percent reductions where varying levels of substrate distribution were achieved. Concentrations of *cis*-DCE and VC generally increased in the reactive zone, without showing a significant reduction by the end of the initial demonstration. Total molar CAH reductions ranged from 12 to 66 percent.

A lag in time to achieve reduction to *cis*-DCE and VC were attributed to the difficulty in managing pH during the initial 20-month phase of un-buffered injections. During the extended post-treatment monitoring, reductions in concentrations of TCE were greater than 80% at a few specific wells. However, both *cis*-DCE and VC generally increased indicating incomplete treatment. It was concluded that a more intensive substrate delivery regimen would be required to achieve more rapid and complete treatment.

No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

Secondary water quality parameters that were evaluated for Site 35 include pH, dissolved metals (iron and manganese), total dissolved solids (TDS), biological oxygen demand (BOD), and chemical oxygen demand (COD).

Summary of Secondary Water Quality – Site 35, Vandenberg AFB, California

Parameter	Comparison Criteria	Baseline	Injection Wells	Down-gradient	Issues?
pH	<6.5 or >8.5 (b)	6.2 to 6.6	Not Sampled	4.3 to 5.6	Yes - Impacted substrate injections and adverse conditions persisted downgradient
Sulfide (mg/L)	--	<0.1	Not Sampled	ND to 7.0	Potential – elevated concentrations downgradient
Dissolved Iron (mg/L)	0.3 (b)	<0.1	Not Sampled	0.03 to 84	Potential – persisted above criterion but decreased in downgradient direction
Dissolved Manganese (mg/L)	0.05 (b)	<0.05	Not Sampled	0.004 to 0.53	Potential – slightly above criterion
Total Dissolved Solids (mg/L)	500 (b)	NM	Not Sampled	690 to 3,300J	Potential – above criterion but no baseline for comparison
Biological Oxygen Demand (mg/L)	--	<2.0 (ND)	Not Sampled	0.51 to 3,000	None - adverse conditions did not persist downgradient
Chemical Oxygen Demand (mg/L)	--	18.6 to 62.4	Not Sampled	3.1 to 910	None - adverse conditions did not persist downgradient

Notes:

Baseline data are average concentrations from baseline measurements in Table 4-4 of ARCADIS (2004). Post-injection data are concentration ranges from Table 4-6 of ARCADIS (2004) for downgradient wells sampled in May 2003.

mg/L = milligrams per liter; µg/L = micrograms per liter.

Criteria based on (a) USEPA MCL; (b) USEPA Secondary Standard; or (c) USEPA Region 9 PRG.

pH. A significant excursion in pH was observed both near the injection wells and at the downgradient monitoring wells (pH of 4.6 to 5.4 as of May 2003), even after a buffering amendment had been added to the injection regimen.

Sulfide. A few wells exhibited sulfide concentrations greater than 1.0 mg/L during the final full monitoring event, with concentrations as high as 7.0 mg/L. But in general, sulfide concentrations were low (<1.0 mg/L) at the furthest downgradient monitoring locations.

Dissolved metals. Samples were analyzed for dissolved metals to evaluate impacts on water quality. Dissolved iron increased to as high as 84 mg/L at well 35-MW-20 during the final full monitoring event in May 2002. Concentrations decreased in a downgradient direction, with dissolved iron at well 35-MW-13 at only 0.03 mg/L in May 2003. Concentrations of dissolved manganese increased to a much lesser degree, with dissolved manganese detected in May 2003 at concentrations typically below 0.5 mg/L, and further decreasing with distance from the injection zone.

COD and BOD. COD and BOD were elevated immediately downgradient of the injection zone as anticipated. But in general, concentrations of COD and BOD remained low at the furthest downgradient monitoring locations (e.g., well 35-MW-13 remained at baseline levels).

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

No adverse impacts to hydraulic conductivity within the subsurface formation were observed. The arrival times of TOC and bromide at downgradient monitoring wells did suggest the existence of preferential flow paths that were not observable from potentiometric surface data.

No. 6: Substrate Persistence and Long-Term Effectiveness

Elevated TOC levels were sustained through the active phases of the project at downgradient wells 35-MW-20, 35-MW-11, 35-MW-7 and 35-MW-16. TOC remained elevated at these wells for at least 5 months beyond the last injection (through July 2003). At well 35-MW-7, TOC concentrations held constant at a modestly elevated level through February 2004 based on monitoring data from Vandenberg AFB. Post-treatment pH trended upward toward initial levels over a period of several months as substrate was depleted. No rebound in concentrations of CAHs was observed during the 3.5-month post-injection performance monitoring period.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

A total of 27 weekly injections were initially planned, while a total of 31 injections were conducted over a 27-month period. Twenty one (21) injections were conducted from February 2001 to October 2002, and ten (10) injections were performed from October 2002 to April 2003. The injection frequency during the first phase averaged approximately one injection every month, while during the second phase injections were performed on average every two weeks.

While the cost of the additional injections was not reported, it could be assumed that the cost of injection increased significantly due to increasing the total number of injections from 27 to 31 and the need for additional monitoring to determine when and how much to inject.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

The Vandenberg demonstration was initially hampered by the low buffering capacity of the aquifer, which caused pH to be depressed to levels below the desired operating range. However, after a buffer was implemented, more reagent was able to be delivered, and system performance improved.

The biggest factor limiting bioremediation performance was an adverse excursion in pH due to the low buffering capacity of the aquifer. The amount of substrate injected had to be limited until a buffering agent was added to the injection solution after 20 months of injections. This initially resulted in limited distribution of substrate and poor initial results. Once the buffering agent was added, higher strength substrate solutions could be injected and degradation results improved.

3. COST ASSESSMENT

The cost of the demonstration are tabulated below, with a total demonstration cost of \$323,974. The estimated quantity of aquifer treated was estimated to be 237 cubic yards, resulting in an estimated unit cost of \$1,367 per cubic yard of aquifer sediments. Because the demonstration was extensively monitored, actual demonstration costs were used to extrapolate a “real world” pilot test of the same size as the demonstration. The “real world” pilot test cost was estimated to be \$233,624 versus the actual cost of \$323,974. This reduced the cost per cubic yard to \$986.

Cost Summary, Site 35, Vandenberg AFB, California

Cost Element	Data to be Tracked	Project Cost
System Design/ Work Plan (Subtotal = \$26,328)	Labor for system design and work plan	\$26,328
Capital Construction/ System Installation (includes baseline characterization) (Subtotal = \$124,449)	- Installation method - Mobilization (includes travel and per diem) - Site Labor - Drilling Subcontractor - Laboratory Subcontractor - Injection equipment) - Equipment Rentals - Expendables, Misc. - Engineering Support - Management Support	- Injection wells \$17,445 \$20,614 \$23,382 \$11,010 \$1,980 \$5,243 \$9,187 \$13,168 \$22,420
Operating and Maintenance Cost (Subtotal = \$81,876)	- Labor - Materials and Consumables - Equipment Cost - Performance Analysis	\$50,408 \$5,841 \$5,370 \$20,257
Long-Term Compliance Monitoring (Subtotal = \$91,321)	- Compliance Testing and Analysis - Disposal of Residues	\$87,494 \$3,827
	Total Application Cost Quantity Treated = 237 cubic yards Unit Cost = \$1,367 per cubic yard	\$323,974

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** Site 35, Vandenberg AFB, CA

NOTE: Unshaded boxes are user input.				
1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	60	1-10,000	feet	Demonstration was at Site 35
Length (Parallel to predominant groundwater flow)	60	1-1,000	feet	
Saturated Thickness	10	1-100	feet	Injection wells screened from 32 to 42 feet bgs
Treatment Zone Cross Sectional Area	600	--	ft ²	
Treatment Zone Volume	36,000	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	94,273	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	80,806	--	gallons	
Design Period of Performance	2.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	35%	.05-50	percent	
Effective Porosity	30%	.05-50	percent	
Average Aquifer Hydraulic Conductivity	2.50	.01-1000	ft/day	Ranges from 0.9 to 3.8 ft/day by step drawdown test
Average Hydraulic Gradient	0.034	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.28	--	ft/day	Ranged from 0.09 to 0.38 ft/day
Average Groundwater Seepage Velocity through the Treatment Zone	103.4	--	ft/yr	
Average Groundwater Flux through the Treatment Zone	139,277	--	gallons/year	
Soil Bulk Density	1.68	1.4-2.0	gm/cm ³	silty sand
Soil Fraction Organic Carbon (foc)	0.50%	0.01-10	percent	Assumed default value (<2,000 mg/kg from two soil samples)
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				Average of 11 wells during full baseline event
Oxygen	2.9	0.01 to 10	mg/L	Ranged from 1.68 to 4.80 mg/L
Nitrate	7.90	0.1 to 20	mg/L	Ranged from 4.7 to 11.3 mg/L
Sulfate	257	10 to 5,000	mg/L	Ranged from 183 to 306 mg/L
Carbon Dioxide (estimated as the amount of Methane produced)	5.8	0.1 to 20	mg/L	Post injection downgradient wells (up to 10.7 mg/L)
B. Solid-Phase Native Electron Acceptors				Average of 7 downgradient wells post-injection in May 2003
Manganese (IV) (estimated as the amount of Mn (II) produced)	0.5	0.1 to 20	mg/L	Typically less than 0.5 mg/L
Iron (III) (estimated as the amount of Fe (II) produced)	20	0.1 to 20	mg/L	Ranged from less than 0.1 to 84 mg/L
4. Contaminant Electron Acceptors				Average of 11 wells during full baseline event
Tetrachloroethene (PCE)	0.000	--	mg/L	
Trichloroethene (TCE)	0.973	--	mg/L	Ranged from 170 to 1,900 ug/L
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.022	--	mg/L	Only cis-DCE detected (ranged from 6.2J to 39 ug/L)
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				Average of 11 wells during full baseline event
Oxidation-Reduction Potential (ORP)	404	-400 to +500	mV	Ranged from +337 to +443 mV
Temperature	NA	5.0 to 30	°C	Not reported
pH	6.3	4.0 to 10.0	su	Ranged from 6.17 to 6.61
Alkalinity	109	10 to 1,000	mg/L	Ranged from 96 to 143 mg/L
Total Dissolved Solids (TDS, or salinity)	NA	10 to 1,000	mg/L	Not analyzed
Specific Conductivity	1451	100 to 10,000	µs/cm	Ranged from 1,348 to 1,648 µs/cm
Chloride	171	10 to 10,000	mg/L	Ranged from 147 to 192 mg/L
Sulfide - Pre injection	<0.1	0.1 to 100	mg/L	Not detected
Sulfide - Post injection	1.9	0.1 to 100	mg/L	Post-injection in May 2003 (Range from ND to 7.0 mg/L)
B. Aquifer Matrix				
Total Iron	NA	100 to 10,000	mg/kg	Not analyzed
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	Not analyzed
Neutralization Potential	NA	1.0 to 100	Percent as CaCO ₃	Not analyzed

NOTES:

Baseline results from the full baseline monitoring event in November 2000 (Table 4-4 of ARCADIS, 2004).
 Post-injection data from the fullfinal monitoring event in May 2003 (Table 4-6 of ARCADIS, 2004).

Table S.2 Substrate Calculations in Hydrogen Equivalents**Site Name:****Site 35, Vandenberg AFB, CA**

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
60	1-10,000	feet
60	1-1,000	feet
10	1-100	feet
600	--	ft ²
36,000	--	ft ³
80,806	--	gallons
2.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.35	.05-50	
0.3	.05-50	
2.5	.01-1000	ft/day
0.034	0.1-0.0001	ft/ft
0.28	--	ft/day
103.4	--	ft/yr
139,277	--	gallons/year
1.68	1.4-2.0	gm/cm ³
0.005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
2.9	1.96	7.94	0.25	4
7.9	5.33	10.25	0.52	5
257	173.29	11.91	14.55	8
5.8	3.91	1.99	1.97	8
Soluble Competing Electron Acceptor Demand (lb.)			17.28	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.5	1.50	27.25	0.06	2
19.6	58.77	55.41	1.06	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			1.12	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.000	0.00	20.57	0.00	8
0.973	0.66	21.73	0.03	6
0.022	0.01	24.05	0.00	4
0.000	0.00	31.00	0.00	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.000	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			0.03	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x C_{gw})
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	0.00	0.00	20.57	0.00	8
107	0.52	1.97	21.73	0.09	6
45	0.00	0.02	24.05	0.00	4
3.0	0.00	0.00	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			0.09		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	2.9	3.37	7.94	0.42	4
Nitrate (denitrification)	7.9	9.18	10.25	0.90	5
Sulfate	257	298.69	11.91	25.08	8
Carbon Dioxide (estimated as the amount of Methane produced)	5.8	6.74	1.99	3.39	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				29.8	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	0.973	1.13	21.73	0.05	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.022	0.03	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				0.05	

Initial Hydrogen Requirement First Year (lb)**48.4****Total Life-Cycle Hydrogen Requirement (lb)****78.2****5. Design Factors**

Microbial Efficiency Uncertainty Factor
Methane and Solid-Phase Electron Acceptor Uncertainty
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)

2X - 4X

2X - 4X

1X - 3X

Design Factor**1.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)****78.2****6. Acronyms and Abbreviations**

°C =degrees celsius

μS/cm = microsiemens per centimeter

cm/day = centimeters per day

cm/sec = centimeters per second

ft² = square feet

ft/day = feet per day

ft/ft = foot per foot

ft/yr = feet per year

gm/cm³ = grams per cubic centimeterkg of CaCO₃ per mg = kilograms of calcium carbonate per milligram

lb = pounds

meq/100 g = milliequivalents per 100 grams

mg/kg = milligrams per kilogram

mg/L = milligrams per liter

m/m = meters per meters

mV = millivolts

m/yr = meters per year

su = standard pH units

wt/wt H₂ = concentration molecular hydrogen, weight per weight

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

RESET DEFAULT

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 2

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	1,747	1,747	7.92E+08	583
Sodium Lactate Product (60 percent solution)	1.0	1,747	3,625	7.92E+08	583
Molasses (assuming 60 percent sucrose)	1.0	1,660	2,766	7.53E+08	553
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	1,747	2,184	7.93E+08	583
Ethanol Product (assuming 80% ethanol by weight)	1.0	893	1,117	4.05E+08	298
Whey (assuming 100% lactose)	1.0	1,206	1,723	5.47E+08	402
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	1,324	1,324	6.01E+08	353
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	680	680	3.08E+08	227
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	680	1,133	3.08E+08	227

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Site 35, Vandenberg AFB, CA

1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	60	feet	18	meters
Length (parallel to groundwater flow)	60	feet	18.3	meters
Saturated Thickness	10	feet	3.0	meters
Design Period of Performance	2	years	2	years

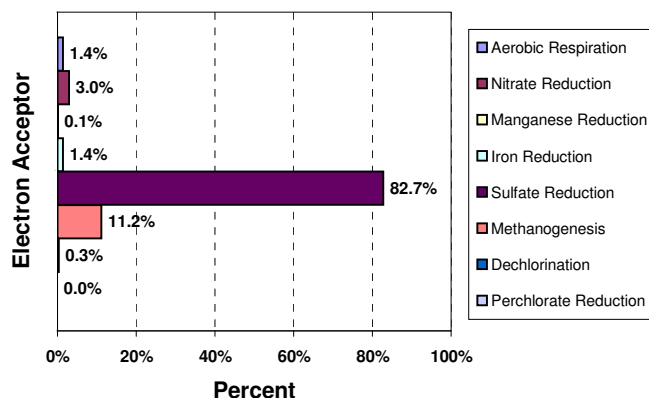
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.35	percent	0.35	percent
Effective Porosity	0.3	percent	0.3	percent
Average Aquifer Hydraulic Conductivity	2.5	ft/day	8.8E-04	cm/sec
Average Hydraulic Gradient	0.034	ft/ft	0.034	m/m
Average Groundwater Seepage Velocity	0.28	ft/day	8.6E+00	cm/day
Average Groundwater Seepage Velocity	103	ft/yr	31.5	m/yr
Total Treatment Zone Pore Volume	80,806	gallons	305,874	liters
Groundwater Flux (per year)	139,277	gallons/year	527,208	liters/year
Total Groundwater Volume Treated (over entire design period)	359,360	gallons total	1,360,289	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	1.4%	1.095
Nitrate Reduction	3.0%	2.311
Sulfate Reduction	82.7%	64.707
Manganese Reduction	0.1%	0.055
Iron Reduction	1.4%	1.061
Methanogenesis	11.2%	8.740
Dechlorination	0.3%	0.228
Perchlorate Reduction	0.0%	0.000
Totals:	100.00%	78.20

Hydrogen demand in pounds/gallon:	2.18E-04
Hydrogen demand in grams per liter:	2.61E-02

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor =**

1.0

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	3,625	330	583	as lactic acid
2. Molasses Product	2,766	231	553	as sucrose
3. Fructose Product	2,184	195	583	as fructose
4. Ethanol Product	1,117	162	298	as ethanol
5. Sweet Dry Whey (lactose)	1,723	sold by pound	402	as lactose
6. HRC®	1,324	sold by pound	353	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	680	87	227	as soybean oil
8. Emulsified Vegetable Oil	1,133	145	227	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

SITE SUMMARY**Area 20, Aerojet Facility, Rancho Cordova, California**

For: Project Files for ESTCP Substrate Loading Study (Job No. 745255)

Review/Update: 15 July 2009

SITE IDENTIFICATION

Area 20, Aerojet Facility, Rancho Cordova, California (SERDP Project CU-1164)

CONTAMINANT SOURCE

<i>COC</i>	<i>Max. Conc.</i>	<i>DNAPL Present?</i>	<i>Notes</i>
Perchlorate	14,000 µg/L	No	Ref (3)
PCE	74 µg/L	No	Ref (3)
TCE	2,600 µg/L	No	Ref (3)
Total DCE	39 µg/L	No	Ref (3)
VC	ND	No	Ref (3)

Notes: Max concentrations were obtained from Well 100B on 19 May 2000.

SUBSTRATE DESIGN/INSTALLATION INFORMATION

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
Project Scale	Expanded Pilot Test	Single-pass active biobarrier	Initial pilot was a closed loop cell using acetate and lactate
Substrate Type	Ethanol	No change	Ethanol was selected to reduce presence of anions or metals in the substrate
Number of Injection Points (IP)	Two extraction wells (plume capture) with one injection well	No change	
IP Spacing Information	Approx. 200 feet between the two extraction wells and the injection well	No change	
Injection Date	20 November 2001 to 25 January 2002		Injected Day 0 through Day 66, final sampling on day 72
Injection Interval (depth bgs)	85 – 100 feet bgs		
Substrate Loading Rate	50 mg/L ethanol	No change	Time weighted average
Basis for Loading Rate	Stoichiometric Calculations	No change	Used a 3-fold design factor to account for uncertainty and biomass production
Injection Rate	Recirculation rate started	Donor added in one-	

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
	at 20 gpm, but fell to 8 gpm by end of test due to biofouling	hour pulses	
Injection amendment?	None		Bromide tracer study conducted prior to substrate injection
Pre-injection Specified?	Tracer Test	No change	
Post-injection Specified?	None	No change	

MONITORING INFORMATION

<i>Sample Collection Date</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Reference</i>
19 May 2000 (baseline)	Yes	Yes	Yes	No	Ref (2,3)
19 November 2001 (pre-injection Day -1)	Yes	Yes	Yes	No	Ref (2,3)
Day 6, 13, 20, 29, 44, 58, 72	Yes	Yes	Yes	Yes – Day 72 only	Ref (2,3)

Notes: Field parameters monitored biweekly.

REFERENCES

- (1) GeoSyntec. 2001. *Pilot Test for In Situ Bioremediation of Perchlorate & Trichloroethene in Groundwater at Area 20*. Prepared for Aerojet, Sacramento, California. Aerojet Document Control No. SR10110767. June. **(Interim Report)**
- (2) GeoSyntec. 2002a. *In Situ Bioremediation of Perchlorate Impacted Groundwater, Final Technical Report*. Prepared for the Strategic Environmental Research & Development Program (CU-1164). June. **(Technical Report)**
- (3) GeoSyntec. 2002b. *Pilot Test for In Situ Bioremediation of Perchlorate & Trichloroethene in Groundwater Using an Active Biobarrier*. Prepared for Aerojet, Rancho Cordova, California. Aerojet Document Control No. SR10112086. Final Report, June. **(Final Report)**
- (4) Cox, E.E., N.D. Durant, M.L. McMaster, D.W. Major, S. Neville, and L. Bonsak. 2004. Rapid and Complete Treatment of Trichloroethene via Bioaugmentation in an Active Biobarrier. In: *Principles and Practices of Enhanced Anaerobic Bioremediation of Chlorinated Solvents* (AFCEE et al., 2004). Appendix E.13.

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates calculated or designed?

The substrate loading rate was based on field observations and calculating the electron acceptor demand. A 3:1 electron donor to electron acceptor ratio was found to be effective for degradation of dissolved oxygen, nitrate, sulfate, perchlorate, and TCE with little donor wasted

on non-required microbial processes. For example, the application of 50 mg/L lactate in a prior pilot test resulted in the generation of nearly 5 mg/L methane, while the application of 50 mg/L of ethanol during the expansion pilot test typically generated less than 0.2 mg/L methane.

The electron acceptor calculations did not account for iron reduction, manganese reduction, or methanogenesis. Furthermore the calculations were based on balanced redox reactions directly with ethanol, versus calculations based on fermentation of ethanol to produce molecular hydrogen. While these conventions may underestimate the substrate requirement, the use of three times the calculated electron acceptor demand resulted in highly efficient transformation of perchlorate and TCE without significant production of methane.

2. What modifications to the substrate amendment protocol were required (e.g., concentration and frequency for soluble substrates; and depletion and additional injection of slow-release substrate types such as HRC[®] and EVO).

No modifications were required, other than injection of a bioaugmentation culture would be needed to achieve the complete dechlorination of TCE. This was anticipated based on the results of the Phase 1 pilot test with lactate and acetate.

3. Evaluation from Substrate Demand Tool

Site data were input into the substrate requirement tool (attached). The substrate requirement to treat 8,349,912 gallons (31,606,972 liters) of groundwater over 1 year was estimated to be 273 pounds of molecular hydrogen, or 3.27E-05 pounds per gallon (3.92E-03 grams per liter) of groundwater treated. These calculations assume that the capture zone is 500 feet wide by 20 feet in depth and that there is no net displacement of groundwater due to recirculation (i.e., the volume of groundwater flowing into the treatment area equals the volume of water leaving the treatment zone).

This hydrogen requirement could be met by 3,896 pounds of ethanol product, assuming the product is 80 percent ethanol by weight. This results in an effective concentration of 45 mg/L of ethanol if the substrate was uniformly distributed throughout the total volume of groundwater treated. This is approximately three times the substrate requirement calculated by GeoSyntec (16.6 mg/L).

As noted above, the electron acceptor calculations did not account for iron reduction, manganese reduction, or methanogenesis and were based on balanced redox reactions directly with ethanol, versus calculations based on fermentation of ethanol to produce molecular hydrogen. Modifying the substrate requirement tool to zero out iron reduction, manganese reduction and methanogenesis, and to set the hydrogen production to be 6 moles of hydrogen per mole of ethanol instead of 2 moles of hydrogen per mole of ethanol, resulted in an effective concentration of 14 mg/L, which is in close agreement with the 16.6 mg/L demand calculated by GeoSyntec.

The primary electron accepting process was nitrate reduction (37.4%), followed by sulfate reduction (27.9%), aerobic respiration (12.9%), perchlorate reduction (14.7%), manganese reduction (1.9%), dechlorination of chlorinated solvents (3.6%), iron reduction (0.5%), and methanogenesis (1.3%). These calculations assume that all the electron acceptors are completely reduced.

PERFORMANCE OBJECTIVES

No. 1: Ability to Uniformly Distribute Substrate : Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

Following electron donor addition, perchlorate concentrations declined rapidly with little to no acclimation period. Perchlorate concentrations at downgradient well 3600 declined from 7.8 mg/L to <0.004 mg/L (the PQL performance objective) within 9 days from the start of ethanol addition, and remained below the PQL (with only one exception) for the duration of the pilot test. At downgradient well 100, perchlorate concentrations declined from 6.3 mg/L to <0.004 mg/L by Day 29 and remained below the PQL. At cross-gradient well 3617, perchlorate concentrations declined from 8.0 mg/L to <0.004 mg/L by Day 20 and remained below the PQL. Perchlorate concentrations at the furthest downgradient well 3618 (100 feet downgradient of the injection well) also declined from 3.9 mg/L to 0.15 mg/L by the end of the pilot test (72 days), with concentrations continuing a decreasing trend through the end of the pilot test.

Coincident with perchlorate reduction, the addition of ethanol promoted rapid dechlorination of TCE (1.7 mg/L) to ethene. At the start of the demonstration, TCE was the dominant VOC in the biobarrier influent and at all downgradient and cross-gradient performance monitoring wells. Dechlorination products present in wells 100 and 3618 were a relic from the previous pilot test in the area. By Day 58, ethene was the dominant product at wells located 35 and 65 feet downgradient, within the portion of the PTA that was previously bioaugmented with KB-1. By Day 72, steady state TCE and 1,2-DCE concentrations were below their respective MCLs at wells 3600 and 100, while VC concentrations had declined to 12 µg/L at well 100, and were continuing to decline. VOC concentrations were also continuing to decline at downgradient well 3618, the furthest downgradient well in the PTA. The calculated half-life for TCE dechlorination to cis-1,2-DCE under steady state conditions ranged between 1.3 to 3.7 days, while the half-life for complete TCE dechlorination to ethene ranged between 4.1 to 11 days.

Cross-gradient well 3617 was located outside of the original area of influence of the bioaugmentation conducted during the initial Aerojet pilot test. As a result, TCE was only dechlorinated to cis-1,2-DCE along the flow path to well 3617 over the 72-day test period. This confirmed that bioaugmentation is required at the Aerojet site to achieve complete TCE reduction to ethene.

No. 2: Achieving Optimal Geochemical Conditions

Successful geochemical conditions for stimulating anaerobic degradation of chlorinated solvents is defined as when the groundwater environment is highly anaerobic with DO less than 0.5 mg/L, ORP is less than -200 millivolts (mV), sulfate is reduced by more than 50 percent relative to background conditions, and methane is greater than 1.0 mg/L. These criteria may not apply in all cases, particularly when geochemical conditions are being carefully controlled with a recirculation system such as applied at the Aerojet site.

Background concentrations of nitrate (average influent of 23 mg/L) and sulfate (average influent of 14 mg/L) at the Area 20 Site were rapidly reduced to less than 1.0 mg/L. Dissolved iron increased to as high as 2.9 mg/L within the reaction zone, but was not detected at distances of 65 to 100 feet downgradient of the reaction zone. Concentrations of manganese increased within the

reaction zone to concentrations as high as 6.7 mg/L, and were typically in the range of 1 to 2 mg/L. Concentrations of methane did increase, but were typically limited to less than 0.2 mg/L. ORP was not reduced to below -200 mV, but were consistently in the manganese to iron reduction range of -50 to -100 mV. Given the high efficiency of removing perchlorate and TCE, these geochemical conditions were optimal for the Area 20 site. In this case, careful control of redox conditions resulted in optimal removal rates with limited impacts on secondary water quality.

No. 3: Remediation Effectiveness: Evaluate efficiency in removal of VOCs based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Determine “threshold” concentrations of dissolved organic carbon that represent the minimum levels required to sustain complete reductive dechlorination.

The success of the application is evaluated by comparing concentrations to site-specific performance criteria, if established. Otherwise, a reduction in contaminant concentration of 99 percent or greater (over two orders of magnitude) is considered successful. For chlorinated aliphatic hydrocarbons (CAHs, or chlorinated solvents) where production of regulated intermediate dechlorination products may occur, a reduction in the total molar concentration of CAHs of greater than 90 percent is considered to be a success.

Perchlorate biodegradation was readily initiated without an acclimation period. Perchlorate concentrations in excess of 8,000 µg/L were consistently reduced to less than the practical quantitation limit (PQL) of 4.0 µg/L within 35 feet of the re-injection well. Perchlorate biodegradation half-lives ranged from 0.5 to 1.8 days. TCE up to 2,000 µg/L in the re-injection wells was also reduced to less than 5.0 µg/L at downgradient wells 3600 and 100 after 44 days of recirculation (a portion of the aquifer that was previously bioaugmented with KB-1[®]). VC did persist in the treatment zone at concentrations above 10 µg/L. The calculated half-life for TCE dechlorination to ethene was 11 days. Carbon tetrachloride and chloroform were also effectively treated, while 1,2-dichloroethane was not.

Ethanol was a highly effective and efficient electron donor for reduction of perchlorate, nitrate and TCE. At a concentration of 50 mg/L (a 3:1 donor to acceptor ratio), the degree of reductions in perchlorate and TCE indicates that little substrate was wasted on non-required microbial processes. Ethanol was rapidly metabolized to acetate and propionate, which were subsequently used as secondary electron donors and depleted within 100 feet of the re-injection well.

No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

Secondary water quality parameters that were evaluated for the Area 20 Site include pH, sulfide, and dissolved metals (iron, manganese, arsenic, and selenium).

Summary of Secondary Water Quality – Area 20, Aerojet Facility, California

Parameter	Comparison Criteria	Background	Treatment Zone	Down-gradient	Issues?
pH	<6.5 or >8.5 (b)	7.0 to 7.8	6.5 to 7.0 after 30 days	6.7 to 7.0 after 30 days	No
Sulfide (mg/L)	NA	<0.50	<0.50 to 2.5	<0.50 to 1.2	No – only a few detections above 0.1 mg/L
Dissolved Iron (mg/L)	0.3 (b)	<0.30	<0.30 to 1.2	<0.30 to 4.6	No – below detection at 100 feet downgradient (well 3618)
Dissolved Manganese (mg/L)	0.05 (b)	<0.005	1.5 to 6.7	0.92 to 1.2	Yes – above criteria
Dissolved Arsenic (mg/L)	0.01 (a)	<0.080	<0.080	<0.080	No – detection limit above criteria but no detections were observed.
Dissolved Selenium (mg/L)	0.05 (a)	<0.10	<0.10	<0.10	No – detection limit above criteria but no detections were observed.

Notes:

Background values from wells 3619 and 3620 (cross-gradient extraction wells), and from 4385 (influent values).

Treatment zone values from wells 3601 and 3600 (post-injection).

Downgradient values from wells 100 and 3618 (post-injection).

mg/L = milligrams per liter; µg/L = micrograms per liter. J-flag indicates concentration is estimated.

Criteria based on (a) USEPA MCL; (b) USEPA Secondary Standard; or (c) USEPA Region 9 PRG.

pH and Sulfide. With few exceptions, pH remained above 6.5 and an adverse decrease in pH was not observed. A few detections of sulfide up to 2.5 mg/L at Day 30 were observed, but subsequently decreased to less than 0.5 mg/L by Day 60.

Dissolved metals. Samples were analyzed for dissolved metals to evaluate impacts on water quality. Dissolved iron increased to as high as 2.9 mg/L within the reaction zone, but was not detected at a distance of 100 feet downgradient of the reaction zone. Concentrations of manganese increased within the reaction zone to concentrations as high as 6.7 mg/L, and were typically in the range of 1 to 2 mg/L. Unlike dissolved iron, concentrations of dissolved manganese remained elevated at the downgradient monitoring locations. Manganese persisted at the site and could be an issue with full-scale applications.

For all samples, concentrations of arsenic and selenium were below detection. Detection limits were slightly higher than USEPA primary drinking water standards. However, a lack of any detections indicates arsenic and selenium are not an issue at the site. The sole groundwater impact appears to be the mobilization and persistence of low levels (about 1 to 2 mg/L) of dissolved manganese.

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

No adverse impacts to hydraulic conductivity within the subsurface formation were observed. Biofouling of the re-injection well was of concern. To mitigate biofouling, ethanol was injected in a pulsed mode, with a one-hour pulse per day. The ethanol was added at a rate to achieve a time-weighted average of 50 mg/L ethanol. In addition, a portable chlorine dioxide gas generator was installed to add chlorine dioxide to inhibit biomass growth.

The chlorine dioxide generator was not installed until after one month of operation had passed. As a result, some biofouling occurred and flow rates had to be reduced on several occasions. At the end of the pilot test, the rate of recirculation had been reduced from an initial rate of 20 gallons per minute (gpm) down to 8 gpm. The study concluded that no recirculation system should operate at the site without a chlorine dioxide gas generator in operation.

No. 6: Substrate Persistence and Long-Term Effectiveness

Because this was a short term pilot test with careful control of the substrate amendment during recirculation, substrate persistence is not an issue that needs to be evaluated. It is likely the system would remain very effective during long-term operation if biofouling could be controlled.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

No modifications were required for the pilot test. However, biofouling of the injection well indicates that biofouling control and well maintenance would be required for long-term operations.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

There were no apparent hydraulic limitations to injection at the Area C Site. However, the rate of injection was limited by biofouling of the injection wells. Modifications to the injection protocol were required to limit the impacts of biofouling. While not a big issue during the pilot test, a long-term application (over a year) would require special consideration to mitigate biofouling.

COST ASSESSMENT

Actual costs for the expanded pilot test were not provided, but estimated costs for a full-scale biobarrier were provided and are summarized in the following cost table. The cost estimate is for a plume with the following characteristics:

- 3000 foot-long plume to a depth of 100 feet.
- Hydraulic conductivity of 30 ft/day and a hydraulic gradient of 0,008.
- Aquifer discharge rate of 224 gallons per minute.
- Four extraction wells, three injection wells, and six monitoring wells.
- Electron donor demand of 50 mg/L ethanol.

The total life-cycle cost assumes a net-present value (NPV) of 6 percent for 30 years.

Cost Summary, Full-Scale Estimate, Aerojet Facility, California

Cost Element	Data to be Tracked	Project Cost
System Design/ Work Plan	Labor for system design and work plan	Included in capitol costs
Capital Construction/ System Installation	- Well permitting, installation, development, and waste handling - Trenching, mechanical, piping, and electrical - KB-1 Culture - Substrate Cost - Electron donor amendment system - Engineering design and startup costs - Contractor profit (15%, equipment only)	\$130,000 \$136,240 \$29,800 - Not specified \$110,297 \$174,800 \$61,000
<i>(Total = \$642,300)</i>		
Annual Operating and Maintenance Cost <i>(Total = \$1,249,000 with net-present worth of 6% for 30 years)</i>	- Annual O&M for first 5 years (quarterly sampling and annual reporting) - Annual O&M for years 6 through 30 (semi-annual sampling and bi-annual reporting)	\$100,000 \$86,700
Total Application Cost (30 years)		\$1,891,000

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** Area 20, Aerojet Facility, California

NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	500	1-10,000	feet	Based on capture zone modeling
Length (Parallel to predominant groundwater flow)	100	1-1,000	feet	
Saturated Thickness	20	1-100	feet	
Treatment Zone Cross Sectional Area	10000	--	ft ²	
Treatment Zone Volume	1,000,000	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	2,244,600	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	1,795,680	--	gallons	
Design Period of Performance	1.0	.5 to 5	year	Not Specified
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	Alluvial sand and gravel
Effective Porosity	24%	.05-50	percent	
Average Aquifer Hydraulic Conductivity	30	.01-1000	ft/day	
Average Hydraulic Gradient	0.008	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	1.00	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	365.0	--	ft/yr	
Average Groundwater Flux through the Treatment Zone	6,554,232	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm ³	Sand
Soil Fraction Organic Carbon (foc)	0.50%	0.01-10	percent	Assumed default value
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	4.0	0.01 to 10	mg/L	Ranged from 1.5 to 5.9 mg/L
Nitrate	15.0	0.1 to 20	mg/L	Ranged from 0.78 to 28 mg/L
Sulfate	13	10 to 5,000	mg/L	Baseline ranged from 10 to 15 mg/L
Carbon Dioxide (estimated as the amount of Methane produced)	0.1	0.1 to 20	mg/L	Methane typically less than 0.1 mg/L
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	2.0	0.1 to 20	mg/L	Manganese Produced - Max. 6.7 mg/L
Iron (III) (estimated as the amount of Fe (II) produced)	1.0	0.1 to 20	mg/L	Ferrous Iron Produced - Max. 1.2 mg/L
4. Contaminant Electron Acceptors				
				Average background concentrations
Tetrachloroethene (PCE)	0.032	--	mg/L	Ranged from 0.024 to 0.036 mg/L
Trichloroethene (TCE)	1.517	--	mg/L	Ranged from 1.4 to 1.6 mg/L
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.104	--	mg/L	Ranged from <0.078 to 0.157 mg/L
Vinyl Chloride (VC)	0.006	--	mg/L	Ranged from <0.005 to 0.027 mg/L
Carbon Tetrachloride (CT)	0.004	--	mg/L	Ranged from <0.005 to 0.006 mg/L
Trichloromethane (or chloroform) (CF)	0.009	--	mg/L	Ranged from 0.006 to 0.010 mg/L
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.002	--	mg/L	Ranged from 0.0016 to 0.0019 mg/L
Dichloroethane (1,1-DCA and 1,2-DCA)	0.008	--	mg/L	Ranged from 0.0092 to 0.010 mg/L
Chloroethane	0.000	--	mg/L	
Perchlorate	7.100	--	mg/L	Ranged from 2.1 to 13 mg/L
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
				Average background concentrations
Oxidation-Reduction Potential (ORP)	102	-400 to +500	mV	Background -52 to +140 mV
Temperature	19	5.0 to 30	°C	Ranged from 18.1 to 19.4 °C
pH	7.1	4.0 to 10.0	su	Ranged from 6.88 to 7.29
Alkalinity	NA	10 to 1,000	mg/L	Not available
Total Dissolved Solids (TDS, or salinity)	NA	10 to 1,000	mg/L	Not available
Specific Conductivity	NA	100 to 10,000	µs/cm	Not available
Chloride	36	10 to 10,000	mg/L	Ranged from 11 to 57 mg/L
Sulfide - Pre injection	NA	0.1 to 100	mg/L	Not available
Sulfide - Post injection	1.2	0.1 to 100	mg/L	Maximum 1.2 mg/L, typically <1.0 mg/L
B. Aquifer Matrix				
Total Iron	NA	100 to 10,000	mg/kg	
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	
Neutralization Potential	NA	1.0 to 100	Percent as CaCO ₃	

NOTES:

Background concentrations based on monitoring data from 19 November 2001 (Table 5 in GeoSyntec, 2002b).
 Post-injection concentrations based wells 3600, 3601, and 4385 after introduction of substrate.

Table S.2 Substrate Calculations in Hydrogen Equivalents
Site Name: **Area 20, Aeroject Facility, California**

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
500	1-10,000	feet
100	1-1,000	feet
20	1-100	feet
10000	--	ft ²
1,000,000	--	ft ³
1,795,680	--	gallons
1.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.3	.05-50	
0.24	.05-50	
30	.01-1000	ft/day
0.008	0.1-0.0001	ft/ft
1.00	--	ft/day
365.0	--	ft/yr
6,554,232	--	gallons/year
1.7	1.4-2.0	gm/cm ³
0.005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
4.0	59.94	7.94	7.55	4
15.0	224.76	10.25	21.93	5
13	194.79	11.91	16.36	8
0.1	1.50	1.99	0.75	8
Soluble Competing Electron Acceptor Demand (lb.)			46.59	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
2.0	139.35	27.25	5.11	2
1.0	69.68	55.41	1.26	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			6.37	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.032	0.47	20.57	0.02	8
1.517	22.73	21.73	1.05	6
0.104	1.56	24.05	0.06	4
0.006	0.09	31.00	0.00	2
0.004	0.06	19.08	0.00	8
0.009	0.13	19.74	0.01	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.002	0.02	22.06	0.00	6
0.008	0.12	24.55	0.00	4
0.000	0.00	32.00	0.00	2
7.100	106.39	12.33	8.63	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			9.78	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x C_{gw})
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	0.04	4.40	20.57	0.21	8
107	0.81	86.15	21.73	3.96	6
45	0.02	2.48	24.05	0.10	4
3.0	0.00	0.01	31.00	0.00	2
224	0.00	0.48	19.08	0.02	8
63	0.00	0.29	19.74	0.01	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.09	22.06	0.00	6
30	0.00	0.13	24.55	0.01	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			4.33		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	4.0	218.77	7.94	27.55	4
Nitrate (denitrification)	15.0	820.38	10.25	80.04	5
Sulfate	13	711.00	11.91	59.70	8
Carbon Dioxide (estimated as the amount of Methane produced)	0.1	5.47	1.99	2.75	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				170.0	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.032	1.72	20.57	0.08	8
Trichloroethene (TCE)	1.517	82.97	21.73	3.82	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.104	5.69	24.05	0.24	4
Vinyl Chloride (VC)	0.006	0.33	31.00	0.01	2
Carbon Tetrachloride (CT)	0.004	0.22	19.08	0.01	8
Trichloromethane (or chloroform) (CF)	0.009	0.48	19.74	0.02	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.002	0.09	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.008	0.44	24.55	0.02	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	7.100	388.31	12.33	31.49	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				35.70	

Initial Hydrogen Requirement First Year (lb) **272.8****Total Life-Cycle Hydrogen Requirement (lb)** **272.8****5. Design Factors**

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X

Design Factor **1.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)** **272.8****6. Acronyms and Abbreviations**

°C =degrees celsius	meq/100 g = milliequivalents per 100 grams
μs/cm = microsiemens per centimeter	mg/kg = milligrams per kilogram
cm/day = centimeters per day	mg/L = milligrams per liter
cm/sec = centimeters per second	m/m = meters per meters
ft ² = square feet	mV = millivolts
ft/day = feet per day	m/yr = meters per year
ft/ft = foot per foot	su = standard pH units
ft/yr = feet per year	wt/wt H ₂ = concentration molecular hydrogen, weight per weight
gm/cm ³ = grams per cubic centimeter	
kg of CaCO ₃ per mg = kilograms of calcium carbonate per milligram	
lb = pounds	

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

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Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 1

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	6,095	6,095	2.76E+09	87
Sodium Lactate Product (60 percent solution)	1.0	6,095	12,645	2.76E+09	87
Molasses (assuming 60 percent sucrose)	1.0	5,790	9,650	2.63E+09	83
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	6,096	7,620	2.77E+09	87
Ethanol Product (assuming 80% ethanol by weight)	1.0	3,117	3,896	1.41E+09	45
Whey (assuming 100% lactose)	1.0	4,207	6,010	1.91E+09	60
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	4,620	4,620	2.10E+09	53
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	2,372	2,372	1.08E+09	34
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	2,372	3,954	1.08E+09	34

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Area 20, Aerojet Facility, California

1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	500	feet	152	meters
Length (parallel to groundwater flow)	100	feet	30.5	meters
Saturated Thickness	20	feet	6.1	meters
Design Period of Performance	1	years	1	years

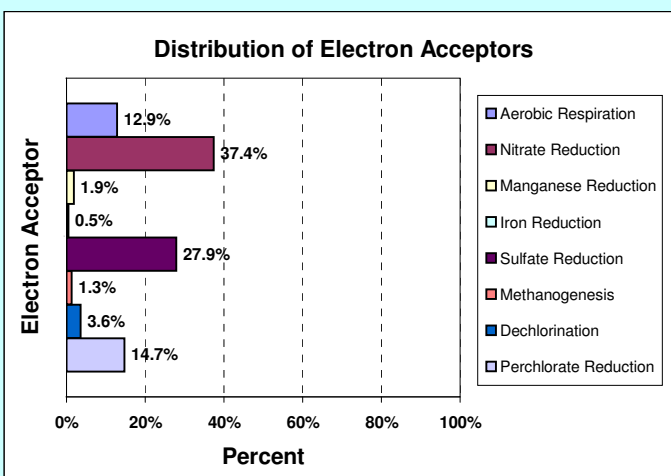
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.24	percent	0.24	percent
Average Aquifer Hydraulic Conductivity	30	ft/day	1.1E-02	cm/sec
Average Hydraulic Gradient	0.008	ft/ft	0.008	m/m
Average Groundwater Seepage Velocity	1.00	ft/day	3.0E+01	cm/day
Average Groundwater Seepage Velocity	365	ft/yr	111.3	m/yr
Total Treatment Zone Pore Volume	1,795,680	gallons	6,797,198	liters
Groundwater Flux (per year)	6,554,232	gallons/year	24,809,774	liters/year
Total Groundwater Volume Treated (over entire design period)	8,349,912	gallons total	31,606,972	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	12.9%	35.101
Nitrate Reduction	37.4%	101.965
Sulfate Reduction	27.9%	76.053
Manganese Reduction	1.9%	5.114
Iron Reduction	0.5%	1.257
Methanogenesis	1.3%	3.501
Dechlorination	3.6%	9.690
Perchlorate Reduction	14.7%	40.122
Totals:	100.00%	272.80

Hydrogen demand in pounds/gallon:	3.27E-05
Hydrogen demand in grams per liter:	3.92E-03

**4. Substrate Equivalents: Design Factor =****1.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	12,645	1,150	87	as lactic acid
2. Molasses Product	9,650	804	83	as sucrose
3. Fructose Product	7,620	680	87	as fructose
4. Ethanol Product	3,896	565	45	as ethanol
5. Sweet Dry Whey (lactose)	6,010	sold by pound	60	as lactose
6. HRC®	4,620	sold by pound	53	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	2,372	304	34	as soybean oil
8. Emulsified Vegetable Oil	3,954	507	34	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

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SITE SUMMARY DATA SHEET

Test Area North (TAN), Operable Unit 1-07B, Idaho National Engineering and Environmental Laboratory (INEEL), Idaho

For: Project Files for ESTCP Substrate Loading Study (Job No. 745255)

Revision: 10 September 2009

SITE IDENTIFICATION

Test Area North (TAN), Operable Unit 1-07B, Idaho National Engineering and Environmental Laboratory (INEEL), Idaho

CONTAMINANT SOURCE

<i>COC</i>	<i>Max. Conc.</i>	<i>DNAPL Present?</i>	<i>Notes</i>
TCE	Up to 100,000 µg/L	Yes	Ref (4)

SUBSTRATE DESIGN/INSTALLATION INFORMATION

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
Project Scale	Pilot	Expanded to Full-Scale Remedy w/ multiple revisions	Optimized injections began in March 2004
Substrate Type	Lactate	Testing	Testing use of Whey Powder in 2005
Number of Injection Points (IP)	One	Two to Three	
IP Spacing Information	NA	50 – 120 feet	
Injection Date	January 1999 to October 2002	March 2004 onward	
Injection Interval (depth bgs)	200 feet thick	100 feet thick	
Substrate Loading	3 to 60% lactate solutions	6% wt/wt lactate and 10% wt/wt whey solutions	
Basis for Loading Rate	Stoichiometry	Stoichiometry	Accounting for biomass growth
Injection Concentration	60% lactate w/w reduced to 3-6% over time	10% Whey w/w	
Injection Amendments	None	None	

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
Injection Volumes	330 gallons increasing to as high as 52,000 gallons	12,000 – 15,000 gallons per event	
Injection Frequency	1-2 times per week increasing to every 8 weeks	Every 2-3 months	
Injection Rate/Pressure	Up to 40 gpm	35-41 gpm	Periodic injections
Pre-injection Specified?	No	No	
Post-injection Specified?	No	No	

MONITORING INFORMATION

<i>Sample Collection Date</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Reference</i>
1999-2003	Yes	Yes	Yes	Yes	Ref (5)
2004-2005	Yes	Yes	Yes	Yes	Ref (7)

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- (7) DOE. 2005. *In Situ Bioremediation Interim Remedial Action Report, Test Area North, Operable Unit 1-07B, Revision 1*. DOE/NE-ID-11221. June. **(Interim Report)**
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INTRODUCTION

Enhanced bioremediation field activities were initiated at Test Area North in 1998 and have been ongoing since that time. Over the years, the remedy has gone through several phases, summarized as follows:

- **Phase I Field Evaluation (November 1998 to October 1999).** Beginning in November 1998, operations consisted of baseline sampling and a conservative tracer test, followed by lactate injection (starting in 1999) in TSF 05 and groundwater monitoring for 9 months. The treatment cells consisted of a 500-ft long aquifer zone, with a single injection well (Well TSF-05) and 14 monitoring wells throughout the treatment cell (including multiple depths in two wells).
- **Pre-Design Phase I (October 1999 to February 2000).** Beginning in October 1999, activities consisted of groundwater monitoring with no lactate injections. The objective of this phase was to determine how the aquifer system would respond to the absence of regular lactate injections, utilizing only the residual electron donor (mainly propionate).
- **Pre-Design Phase II (February 2000 to May 2001).** Beginning in February 2000, the objective of this phase was to maintain favorable conditions for efficient anaerobic reductive dechlorination and to determine the best injection strategy. This phase consisted of the injection of relatively large volumes of sodium lactate less frequently (every 8 weeks).
- **Pre-Design Operations (May 2001 to October 2002).** This phase was initiated in May 2001, with the objectives of continuing to optimize the bioremediation remedy by experimentation with various injection strategies.
- **Interim Operations Phase (November 2002 to October 2003).** The transition from pilot testing to remedy implementation began in November 2002, and included activities designed to evaluate alternate substrates and injection strategies.
- **Initial Operations Phase (October 2003 to 2004).** The goal of this phase was to expand treatment to meet remedial action objectives (RAOs) at downgradient wells TAN-28 and TAN-30 by installing injection well TAN-1859.
- **Optimization Operations Phase (2004 onward).** Beginning in 2004, optimization activities included the use of whey powder. This was proceeded with two lactate injections to establish a lactate “baseline” for comparison. The initial whey injection design called for 12,000 gallons of a 10% by weight whey solution at 40 gpm, followed by a 2,000 gallon water push (Ref [6]). Follow-up whey injections were scheduled for every 8 weeks (2 months).

- **Long-Term Operations Phase (future).** This phase is intended to achieve source zone degradation while maintaining reductions in mass discharge of CAHs in both downgradient and cross gradient directions.

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates were calculated or designed?

Stoichiometric relationships were considered when determining substrate loading rates at the TAN INEEL site. However, the substrate loading rates (volume, concentration, and frequency) were varied widely in an attempt to optimize the system, and substrate loading rates were ultimately determined by experimentation. In addition, relatively high loading rates (e.g., 10% wt/wt whey solutions) were tested to evaluate enhanced dissolution of potential DNAPL.

2. What modifications to the substrate amendment protocol were required (e.g., concentration and frequency of substrate; and depletion and additional injection of substrate).

Several modifications were performed during the course of optimization activities. For example, variations in lactate injection protocols are summarized in the following table.

Summary of Initial Lactate Injections (1999 to 2002)				
Phase	Date	Concentration (wt %)	Volume	Frequency
Field Evaluation	Jan 99 – Sep 99	60% → 3%	330 → 6,600 gal	Once or twice per week
Pre-Design Phase I	Oct 99 – Jan 00	NA	NA	NA
Pre-Design Phase II	Feb 00 – Apr 01	3-6%	13,000 gal	Every 8 weeks
Pre-Design Operations	May 01 – Oct 02		13,000 → 52,000 gal	~ Every 8 weeks

In general, injections went from small volume/high concentration injections to high volume/low concentration injections. The frequency of injections was extended to approximately every 8 weeks as it was found that metabolic acids such as propionate were able to sustain the reaction zone.

The initial whey injection called for 12,000 gallons of a 10% wt/wt solution, which was followed by two additional injections at approximately 8 and 20 weeks following the initial injection.

3. Evaluation from Substrate Estimating Tool

Due to the nature of the formation and hydraulics at the TAN INEEL Site (fractured basalt), an evaluation using the Substrate Estimating Tool was not performed.

PERFORMANCE OBJECTIVES

No. 1: Ability to Uniformly Distribute Substrate: Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

The source zone treatment TAN INEEL covers an area of approximately 200 feet (60 meters) in diameter, initially across an aquifer thickness of 200 feet (60 meters). As contaminants have been removed in the deepest part of the contaminated aquifer, the focus has shifted to the upper 100 feet (30 meters) of the aquifer. The transmissivity of the aquifer is very high, which allows for high injection volumes over a relatively large treatment zone from a single well. An additional injection was added to expand the treatment zone. But in general, appropriate substrate distribution has been readily achieved at this site.

No. 2: Achieving Optimal Geochemical Conditions

Optimal conditions were met throughout the majority of the treatment zone. Complete dechlorination of TCE to ethene was observed with the onset of methanogenesis. Because high concentration solutions of substrate are being used to enhance mass transfer, highly reducing conditions are readily achieved and sustained.

No. 3: Remediation Effectiveness: Evaluate efficiency in removal of VOCs based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Determine “threshold” concentrations of dissolved organic carbon that represent the minimum levels required to sustain complete reductive dechlorination.

The enhanced bioremediation application at the TAN INEEL Site continues to operate effectively, stimulating dechlorination of TCE to ethene throughout the source area. Ethene was present in significant concentrations in all impacted monitoring wells. The results of the optimization efforts indicate that whey powder is a more efficient and cost-effective substrate for both enhanced mass transfer and reductive dechlorination. Further efforts may be needed to reduce the mass discharge of CAHs at certain locations.

No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

Insufficient data are available to evaluate secondary water quality. No adverse conditions have been reported.

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

There are no apparent impacts to hydraulic conductivity at this site. The high secondary permeability of the fractured basalt is beneficial to distribution of the substrates applied.

No. 6: Substrate Persistence and Long-Term Effectiveness

Injection frequencies for whey solutions of every 2 to 3 months appear effective for the TAN INEEL site. Testing at this site indicates that biodegradation rates remain faster than the mass transfer kinetics from injection of high concentration lactate and whey solutions. This has led to an optimization strategy devoted to accelerating mass transfer rates. Ultimate remediation of the source area will require continued injections of high concentration substrate solutions throughout the area impacted by residual source material.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

The additional injections and monitoring at the TAN INEEL site have all been beneficial in optimizing the system for long-term performance and have provided a great deal of beneficial knowledge regarding enhanced mass transfer in DNAPL source zones. This is likely one of the most intensely monitored bioremediation applications. As such, it is difficult to attribute any adverse cost impacts at this site.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

There were no apparent limits due to the hydrogeological conditions at the TAN INEEL site, with secondary permeability in the fractured basalt is very transmissive. A tracer test conducted using tritium as a conservative tracer was beneficial in documenting rates of degradation.

COST ASSESSMENT

Cost data for this site are not available. However, the following site-specific unit costs were provided in Martin and Sorenson (2004) to give an idea of the cost to remediate a deep, fractured rock residual source area, with a treatment volume of about 4 million cubic feet (ft³).

- The average cost to install a monitoring well to 400 ft below ground surface by air rotary drilling at the site is about \$100,000. This cost goes up if drilling is in a zone suspected to have significant radiological contamination. In this case, only one new well was installed during the first four years of operation.
- A heated cargo container plumbed with potable water was installed to serve as an injection trailer at a cost of between \$60,000 and \$100,000.
- The operating costs include lactate injection and sampling and analysis. Lactate is injected approximately once every 2 months. The labor cost per injection is approximately \$1800, and the lactate cost at \$0.75/lb for the 48 drums (about 29,000 lb) of lactate required to treat 4 million ft³ is \$21,800. Assuming eight injections a year for conservatism, and based on the treatment volume and the lactate injection operating costs (one-time capital costs are not included), this yields a cost of \$1.27/yr for the source zone treatment. The fact that the lactate can treat this volume using a single injection well is a significant advantage because of the cost to install new wells. Ultimately a second injection well will be added to increase the treatment zone to about 6 million ft³ to

completely encompass the residual source area. Some economies of scale will be realized as the lactate volume is not expected to increase proportionally to the treatment volume.

- A complete sampling round at 13 monitoring locations with analysis for a full suite of bioremediation parameters costs approximately \$12,000 per round. The analytes include: lactate, volatile fatty acids, chemical oxygen demand, redox-sensitive parameters, tritium, VOCs, dissolved gases, and purge parameters

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SITE SUMMARY DATA SHEET

Building 1419, Indian Head Naval Surface Warfare Center, Maryland

For: Project Files for ESTCP Substrate Loading Study (Job No. 745255)

Revision: 01 September 2009

SITE IDENTIFICATION

Building 1419, Indian Head Division, Naval Surface Warfare Center (IHDIIV), Indian Head, Maryland

CONTAMINANT SOURCE

<i>COC</i>	<i>Max. Conc.</i>	<i>DNAPL Present?</i>	<i>Notes</i>
Perchlorate	430 mg/L	NA	Ref (2) - Geoprobe characterization event. Ranged from 8 to 430 mg/L with average of approximately 170 mg/L.

SUBSTRATE DESIGN/INSTALLATION INFORMATION

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
Project Scale	Pilot		
Substrate Type	Sodium Lactate		
Configuration	Recirculation Plots (Test Plot and Control Plot)		
Number of Injection Wells	Two extraction wells, two injection wells, nine monitoring wells		Per plot, had a second control plot.
IW Spacing Information	12 feet between injection and extraction wells		
Injection Interval (depth bgs)	Approx. 8 – 16 feet bgs injection wells Approx. 6-21 feet bgs extraction wells		
Injection Dates	25 July 2002 to 11 November 2002		111 days of recirculation, final sampling at day 140
Substrate Loading	Approx. 380 mg/L		20,000 gallons recirculated in 15 weeks (111 days)
Basis for Loading Rate	Stoichiometry, Microcosm Studies		Low pH site

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
Injection Concentration	380 mg/L	380 mg/L. An additional dose of lactate (~ 3 gal) was added on Days 19 and 35. The lactate pump was turned off and groundwater was recirculated for 1 week to mix the substrate after each of these additions	
Injection Rate	Approx. 1 gpm per well		Approximately 180 gallons per day through each cell. Groundwater was collected until 40 gallons accumulated, then injected at approx. 2 gpm (cycled injection)
Injection amendments	20% Carbonate and 80% Bicarbonate Mix at 2,500 mg/L	On days 19 and 35 approx. 250 gal of buffer solution was added and the buffer pump turned off for 1 week. After 1 month, 300 gallons of a 30% Carbonate and 87% Bicarbonate Mix at 2,500 mg/L was used, after which the original mixture was used.	pH buffering. Did have to add some additional buffer to maintain pH.
Pre-injection Specified?	Bromide Tracer Test		
Post-injection Specified?	No		

MONITORING INFORMATION

<i>Sample Collection Date</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Reference</i>
Baseline (10 weeks and 1 week prior to recirculation)	Yes	No	Yes	No	Ref (2)
Day 14, 25, 49, 70, 105, 140	Yes	Yes	Yes	No	Ref (2)

REFERENCES

- (1) Envirogen, Inc. 2002. *In Situ Bioremediation of Perchlorate*. Prepared for the Strategic Environmental Research and Development Program (SEDRP Project CU-1163). 21 May. **(Laboratory Studies)**
- (2) Cramer, R. J., C. A. Yates, P. B. Hatzinger, and J. Diebold. 2004. *Field Demonstration of In Situ Perchlorate Bioremediation at Building 1419*. (NOSSA-TR-2004-001). Prepared for the Naval Ordnance Safety and Security Activity, Ordnance Environmental Support Office. 22 January. **(Final Report)**

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates calculated or designed?

Microcosm studies were performed prior to design of the field demonstration. Perchlorate reduction did not occur at an ambient pH of approximately 4.3, but perchlorate was reduced by native microorganisms when pH was raised to 7.0 with a pH modifier (sodium carbonate). Additional microcosms demonstrated that perchlorate reduction could be achieved using sodium lactate as the organic substrate and by raising the pH to 7.0 to 7.3. It was notable that acetate, ethanol, and hydrogen gas did not stimulate perchlorate reduction in the microorganisms. The microcosm study used approximately 250 mg/L of sodium lactate. For the initial design, 380 mg/L of lactate was chosen to provide a reasonable excess of electron donor based on average concentrations of dissolved oxygen, nitrate, and perchlorate. There was no intent to stimulate sulfate reduction or methanogenesis, which were not desired to achieve effective perchlorate reduction.

Titration studies were performed using sediment and groundwater samples from the site and various mixtures of sodium carbonate and sodium bicarbonate. Based on the titration results and consideration of the ability to control the increase in pH, a concentrated stock solution (6.67%) of 80% bicarbonate and 20% carbonate was initially chosen for the concentrated buffer solution.

2. What modifications to the substrate amendment protocol were required (e.g., concentration and frequency for soluble substrates; and depletion and additional injection of slow-release substrate types such as HRC[®] and EVO).

An additional dose of lactate (~ 3 gal of product) was added to the aquifer during the early operation of the system on Days 19 and 35, in conjunction with extra buffer addition. After each of these additions the lactate pump was turned off and the groundwater was recirculated for 1 week to mix the electron donor. A total volume of 91 liters (24 gallons) of the 60% lactate solution was added to the aquifer during the demonstration period (i.e., an average of 0.22 gal/day). A total weight of 58 kilograms of sodium lactate product was added during the 111-day study.

On Days 19 and 35, approximately 250 gallons of buffer solution was injected. After each of these additions, the buffer pump was turned off and groundwater was re-circulated for approximately 1 week to disperse the buffer amendment throughout the formation. During the course of the demonstration, 1,175 gallons of buffer was added to the aquifer. Approximately

875 gallons of this buffer was a 6.67% solution containing 80% bicarbonate and 20% carbonate. The other 300 gallons was a 6.67% solution containing a mixture of 70% bicarbonate and 30% carbonate. The latter solution was added to the aquifer 1 month after the beginning of the demonstration to increase the rate at which the aquifer was buffered. After this addition was complete, the 80% bicarbonate and 20% carbonate mixture was used for the remainder of the demonstration.

3. Evaluation from Substrate Demand Tool

Site data were input into the substrate requirement tool (attached). The substrate requirement to treat 55,690 gallons (210,802 liters) of groundwater over 111 days (0.30 year) was 13.6 pounds of molecular hydrogen, or 2.43E-04 pounds per gallon (2.92E-02 grams per liter) of groundwater treated. These calculations assume that the capture zone is 20 feet wide by 12 feet long by 8 feet in depth, and that there is no net displacement of groundwater due to recirculation (i.e., the volume of groundwater flowing into the treatment area equals the volume of water leaving the treatment zone that would occur under a natural hydraulic gradient).

This hydrogen requirement could be met by 628 pounds (57 gallons) of sodium lactate product, assuming the product is 60 percent sodium lactate by weight. This results in an effective concentration of 652 mg/L of lactic acid if the substrate dissociated to lactic acid and was uniformly distributed throughout the total volume of groundwater treated. This is approximately two times the substrate requirement used (380 mg/L lactate). The electron acceptor calculations did not account for iron reduction, manganese reduction, or methanogenesis. In addition, sulfate reduction was not desired. Modifying the substrate requirement tool to zero out iron reduction, manganese reduction, sulfate reduction, and methanogenesis resulted in an effective concentration of 324 mg/L, which is in close agreement with the 380 mg/L demand used in the demonstration.

Assuming that all electron acceptors are completely reduced, then the primary electron accepting process was sulfate reduction (50.1%), followed by perchlorate (48.4%) with all other processes less than 1%. However, assuming that manganese reduction, iron reduction, sulfate reduction, and methanogenesis are not stimulated, then perchlorate reduction accounts for over 97% of the electron acceptor demand, followed by nitrate reduction (1.5%), and aerobic respiration (1.2%).

PERFORMANCE OBJECTIVES

No. 1: Ability to Uniformly Distribute Substrate : Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

With one exception, substrate was effectively distributed throughout the test plot. A bromide tracer study was conducted prior to injection of substrate and buffer solutions. Bromide was detected in four of nine wells after 1 days, in seven of nine wells after 5 days, and in all wells by 25 days after addition of the bromide tracer. All monitoring wells were in hydraulic communication with the injection wells. The difference in time for appearance of the bromide tracer indicates a moderate degree of heterogeneity.

Lactate was detected in groundwater from seven of nine wells by day 14, and all wells had measurable concentrations of lactate by day 25. Lactate concentrations varied by well and with

time; however, lactate was consistently detected above 10 mg/L in eight of the nine wells during the course of the demonstration, and each of the eight wells had levels exceeding 100 mg/L at one or more sample points.

Test well TPMW-1d generally had the lowest concentration of lactate (< 7 mg/L on five of six samplings), never exceeding 21 mg/L lactate. This was the one well in which perchlorate levels declined only marginally (43%) during the demonstration and in which nitrate never declined below 1 mg/L. The data suggest that either the substrate did not reach the area surrounding this well at high enough concentrations to support complete reduction of perchlorate, or the substrate was rapidly consumed by biological processes other than perchlorate reduction (i.e., denitrification and aerobic respiration). The close proximity of this well to one of the treatment plot injection wells could have impacted groundwater flow to this well, with oxygenated water from outside the treatment preferentially entering the region surrounding the well.

No. 2: Achieving Optimal Geochemical Conditions

Successful geochemical conditions for stimulating anaerobic degradation of perchlorate is a groundwater environment that is anaerobic with DO and nitrate less than 0.5 mg/L, and ORP less than 0.0 millivolts (mV). These criteria may not apply in all cases, particularly when geochemical conditions are being carefully controlled with a recirculation system such as applied at the Building 1419 site.

Concentrations of nitrate (as nitrogen) averaged 2.2 mg/L prior to substrate addition in the test plot. Nitrate was below detection (< 0.2 mg/L nitrate-N) in seven of nine wells by Day 49 after substrate addition. TPMW-1d showed the slowest decline in nitrate concentrations, correlating to a lack of substrate. At Day 140, the average nitrate concentration in the test plot was approximately 0.3 mg/L.

One demonstration objective was to supply adequate substrate to achieve nitrate and perchlorate reduction with limited sulfate reduction. Overall, the degree of sulfate reduction in the test plot was not limited. The average concentration at the start of the demonstration in the nine test plot wells was 174 mg/L, and at the end of the demonstration the average was 240 mg/L. The only well that showed a significant decrease in sulfate concentration was TPMW-2s, but this was based on one sample point collected at day 140.

With the exception of well TPMW-1d, suitable geochemical conditions for perchlorate reduction were achieved. The lack of nitrate and perchlorate reduction observed at well TPMW-1d was primarily due to a lack of substrate and inability to overcome the electron acceptor demand from dissolved oxygen and nitrate.

No. 3: Remediation Effectiveness:

Concentrations of perchlorate throughout the test plot showed an overall decline during the 140 day demonstration. During the two baseline sampling events (69 and 7 days before system startup), perchlorate levels ranged from a low of 72 mg/L in well TPMW-3s to a high of 276 mg/L in TPMW-2d. The average perchlorate concentration was 171 mg/L at 69 days prior to startup and 174 mg/L at 7 days prior to startup. By the end of the 20-week demonstration, perchlorate levels in two test wells (TPMW-1s and TPMW-2s) were below the practical

quantitation limit (PQL) of 5.0 µg/L, one well was less than 20 µg/L (TPMW-5), and two additional wells were less than 1.0 mg/L. The reduction in perchlorate concentration from the start of the demonstration for these four wells was in excess of 99%. Two other wells had perchlorate concentrations of less than 3.7 mg/L (TPMW-3s and TPMW-3d) at the end of the demonstration, and one well (TPMW-4d) was less than 10 mg/L. The percent reduction in perchlorate in each of these wells exceeded 95% from the start to the end of the demonstration.

The only well in which perchlorate levels did not decline precipitously during the demonstration was TPMW-1d. Perchlorate levels fell by only 43% in this well, ending at approximately 90 mg/L after 140 days. This well consistently had the lowest concentration of lactate, and the highest nitrate concentrations during the demonstration. It is possible that the flow pattern in the vicinity of this well continually introduced water from outside of the treatment area.

The concentration of perchlorate at well TPMW-1d did decrease from 200 to 143 mg/L when lactate increased to 21 mg/L, but increased during the following sampling event when lactate decreased to 3.8 mg/L. Other locations exhibited steady decreases in perchlorate with lactate at 11 to 12 mg/L. This suggests that the threshold to achieve effective perchlorate removal is approximately 10 mg/L for this site.

No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

Secondary water quality parameters were either not measured or not reported for the Building 1419 Site.

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

No adverse impacts to hydraulic conductivity within the subsurface formation were observed. In general, injection volumes and rates were maintained over the course of the demonstration. Difficulties were encountered towards the end of the demonstration due to high rates of precipitation and flooding of the test site. Injection was halted just prior to the scheduled end of the demonstration.

No. 6: Substrate Persistence and Long-Term Effectiveness

Because this was a short term pilot test with careful control of the substrate amendment during recirculation, substrate persistence is not an issue that needs to be evaluated. It is likely the system would remain very effective during long-term operation if biofouling could be controlled.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

No modifications were required for the pilot test, although some minor modifications to the injection scenario were incorporated during the test.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

There were no apparent hydraulic limitations to injection at the Building 1419, other than to account for a moderate degree of aquifer heterogeneity.

3. COST ASSESSMENT

Cost data for this demonstration are not available.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** Buidling 1419, Indian Head NSWC, Maryland

NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	20	1-10,000	feet	Assumed 10 foot radius of influence
Length (Parallel to predominant groundwater flow)	12	1-1,000	feet	
Saturated Thickness	8	1-100	feet	Injection from approximately 8 to 16 feet bgs
Treatment Zone Cross Sectional Area	160	--	ft ²	
Treatment Zone Volume	1,920	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	4,310	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	3,591	--	gallons	
Design Period of Performance	0.30	.5 to 5	year	111 days of substrate amendment (recirculation)
Design Factor (times the electron acceptor hydrogen demand)	1.0	2 to 20	unitless	

2. Treatment Zone Hydrogeologic Properties	Values	Range	Units	User Notes
Total Porosity	30%	.05-50	percent	
Effective Porosity	25%	.05-50	percent	
Average Aquifer Hydraulic Conductivity	17.28	.01-1000	ft/day	Average of three slug tests
Average Hydraulic Gradient	0.023	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	1.59	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	580.3	--	ft/yr	
Average Groundwater Flux through the Treatment Zone	173,661	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm ³	Clay and silty sand, sand and gravel at base
Soil Fraction Organic Carbon (foc)	0.50%	0.01-10	percent	Assumed default value

3. Native Electron Acceptors	Values	Range	Units	User Notes
A. Aqueous-Phase Native Electron Acceptors				Average of Test Plot baseline measurements
Oxygen	1.4	0.01 to 10	mg/L	Based on characterization- wells MW-4 to MW-6
Nitrate	2.2	0.1 to 20	mg/L	Ranged from 1.3 to 4.3 mg/L
Sulfate	174	10 to 5,000	mg/L	Ranged from 79 to 320 mg/L
Carbon Dioxide (estimated as the amount of Methane produced)	0.1	0.1 to 20	mg/L	Not measured, assumed to be 0.1 mg/L
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	0.1	0.1 to 20	mg/L	Not measured, assumed to be 0.1 mg/L.
Iron (III) (estimated as the amount of Fe (II) produced)	0.1	0.1 to 20	mg/L	Not measured, assumed to be 0.1 mg/L.

4. Contaminant Electron Acceptors	Values	Range	Units	User Notes
				Average of Test Plot baseline measurements
Tetrachloroethene (PCE)	0.000	--	mg/L	
Trichloroethene (TCE)	0.000	--	mg/L	
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	--	mg/L	
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	174.000	--	mg/L	Average in test plot 7 days prior to injection

5. Aquifer Geochemistry (Optional Screening Parameters)	Values	Range	Units	User Notes
A. Aqueous Geochemistry				Average of Test Plot baseline measurements
Oxidation-Reduction Potential (ORP)	NA	-400 to +500	mV	
Temperature	NA	5.0 to 30	°C	
pH	4.7	4.0 to 10.0	su	Ranged from 3.82 to 5.99
Alkalinity	22	10 to 1,000	mg/L	Ranged from <2.0 to 92 mg/L
Total Dissolved Solids (TDS, or salinity)	NA	10 to 1,000	mg/L	
Specific Conductivity	NA	100 to 10,000	µs/cm	
Chloride	NA	10 to 10,000	mg/L	
Sulfide - Pre injection	NA	0.1 to 100	mg/L	
Sulfide - Post injection	NA	0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	NA	100 to 10,000	mg/kg	
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	
Neutralization Potential	NA	1.0 to 100	Percent as CaCO ₃	

NOTES:

All values are for the lactate test plot, and do not include the control plot.

Table S.2 Substrate Calculations in Hydrogen Equivalents
Site Name: **Buidling 1419, Indian Head NSWC, Maryland**

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
20	1-10,000	feet
12	1-1,000	feet
8	1-100	feet
160	--	ft ²
1,920	--	ft ³
3,591	--	gallons
0.3	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.3	.05-50	
0.25	.05-50	
17.28	.01-1000	ft/day
0.023	0.1-0.0001	ft/ft
1.59	--	ft/day
580.3	--	ft/yr
173,661	--	gallons/year
1.7	1.4-2.0	gm/cm ³
0.005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
1.4	0.04	7.94	0.01	4
2.2	0.07	10.25	0.01	5
174	5.21	11.91	0.44	8
0.1	0.00	1.99	0.00	8
Soluble Competing Electron Acceptor Demand (lb.)			0.45	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.1	0.05	27.25	0.00	2
0.1	0.05	55.41	0.00	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			0.00	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.000	0.00	20.57	0.00	8
0.000	0.00	21.73	0.00	6
0.000	0.00	24.05	0.00	4
0.000	0.00	31.00	0.00	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.000	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
174,000	5.21	12.33	0.42	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			0.42	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x C_{gw})
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	0.00	0.00	20.57	0.00	8
107	0.00	0.00	21.73	0.00	6
45	0.00	0.00	24.05	0.00	4
3.0	0.00	0.00	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			0.00		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	2.03	7.94	0.26	4
Nitrate (denitrification)	2.2	3.19	10.25	0.31	5
Sulfate	174	252.15	11.91	21.17	8
Carbon Dioxide (estimated as the amount of Methane produced)	0.1	0.14	1.99	0.07	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				21.8	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	0.000	0.00	21.73	0.00	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	0.00	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	174.000	252.15	12.33	20.45	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				20.45	

Initial Hydrogen Requirement First Year (lb) **43.1****Total Life-Cycle Hydrogen Requirement (lb)** **13.6****5. Design Factors**

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X

Design Factor **1.0****Total Life-Cycle Hydrogen Requirement with Design Factor (lb)** **13.6****6. Acronyms and Abbreviations**

°C =degrees celsius	meq/100 g = milliequivalents per 100 grams
μs/cm = microsiemens per centimeter	mg/kg = milligrams per kilogram
cm/day = centimeters per day	mg/L = milligrams per liter
cm/sec = centimeters per second	m/m = meters per meters
ft ² = square feet	mV = millivolts
ft/day = feet per day	m/yr = meters per year
ft/ft = foot per foot	su = standard pH units
ft/yr = feet per year	wt/wt H ₂ = concentration molecular hydrogen, weight per weight
gm/cm ³ = grams per cubic centimeter	
kg of CaCO ₃ per mg = kilograms of calcium carbonate per milligram	
lb = pounds	

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

RESET DEFAULT

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 0.3

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	1.0	303	303	1.37E+08	652
Sodium Lactate Product (60 percent solution)	1.0	303	628	1.37E+08	652
Molasses (assuming 60 percent sucrose)	1.0	288	479	1.30E+08	619
HFCS (assuming 40% fructose and 40% glucose by weight)	1.0	303	379	1.37E+08	652
Ethanol Product (assuming 80% ethanol by weight)	1.0	155	194	7.03E+07	333
Whey (assuming 100% lactose)	1.0	209	299	9.48E+07	450
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	1.0	230	230	1.04E+08	395
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	1.0	118	118	5.35E+07	254
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	1.0	118	196	5.35E+07	254

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Buidling 1419, Indian Head NSWC, Maryland

1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	20	feet	6	meters
Length (parallel to groundwater flow)	12	feet	3.7	meters
Saturated Thickness	8	feet	2.4	meters
Design Period of Performance	0.3	years	0.3	years

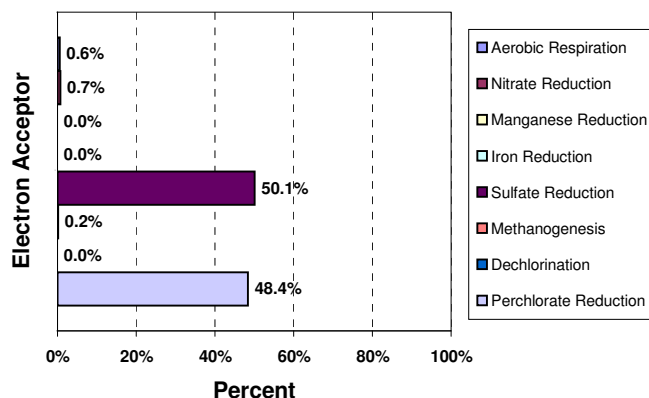
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.25	percent	0.25	percent
Average Aquifer Hydraulic Conductivity	17.28	ft/day	6.1E-03	cm/sec
Average Hydraulic Gradient	0.023	ft/ft	0.023	m/m
Average Groundwater Seepage Velocity	1.59	ft/day	4.8E+01	cm/day
Average Groundwater Seepage Velocity	580	ft/yr	176.9	m/yr
Total Treatment Zone Pore Volume	3,591	gallons	13,594	liters
Groundwater Flux (per year)	173,661	gallons/year	657,360	liters/year
Total Groundwater Volume Treated (over entire design period)	55,690	gallons total	210,802	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	0.6%	0.082
Nitrate Reduction	0.7%	0.100
Sulfate Reduction	50.1%	6.789
Manganese Reduction	0.0%	0.002
Iron Reduction	0.0%	0.001
Methanogenesis	0.2%	0.023
Dechlorination	0.0%	0.000
Perchlorate Reduction	48.4%	6.558
Totals:	100.00%	13.55

Hydrogen demand in pounds/gallon:	2.43E-04
Hydrogen demand in grams per liter:	2.92E-02

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor =****1.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	628	57	652	as lactic acid
2. Molasses Product	479	40	619	as sucrose
3. Fructose Product	379	34	652	as fructose
4. Ethanol Product	194	28	333	as ethanol
5. Sweet Dry Whey (lactose)	299	sold by pound	450	as lactose
6. HRC®	230	sold by pound	395	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	118	15	254	as soybean oil
8. Emulsified Vegetable Oil	196	25	254	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

SITE SUMMARY DATA SHEET**Areas E, F, M, and S, NWIRP McGregor, Texas**

For: Project Files for ESTCP Substrate Loading Study (Job No. 745255)

Review/Update: 10 August 2009

SITE IDENTIFICATION

Areas E, F, M, and S, Naval Weapons Industrial Reserve Plant (NWIRP), McGregor, Texas

CONTAMINANT SOURCES

<i>COC</i>	<i>Max. Conc.</i>	<i>DNAPL Present?</i>	<i>Notes</i>
Perchlorate	Up to 18 mg/L in Trench 2 at Area F on 27 January 2004 (Ref (2))	NA	Concentrations as high as 91 mg/L perchlorate in groundwater and 22 mg/L in seeps have been historically recorded at the facility.
TCE and 1,1-DCE	NA	No	TCE and 1,1-DCE are present at Area E

Notes: Concentrations for the Response Action Effectiveness Report focused on concentrations within the biowalls (Ref 3).

SUBSTRATE DESIGN/INSTALLATION INFORMATION

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
Project Scale	Full-Scale Biowalls and Bioborings		Ref (2,3)
Base Substrate Type	Mushroom Compost, Wood Chips, and Vegetable Oil		
Injected Substrate Type	Emulsified Vegetable Oil (EOS Product)	No change	Used to replenish biowall trenches
Number of Injection Points (IP)	Horizontal Piping (top and bottom of trench) and injection ports		
IP Spacing Information	NA		
Injection Date	August 2006, June 2008		September 2007 injection was pilot test to evaluate injection methods
Injection Interval (depth bgs)	Approx. 3 to 20 feet bgs		

<i>Parameter</i>	<i>Original Design</i>	<i>Revised Design</i>	<i>Notes/Reference</i>
Basis for Loading Rate	<u>Three Methods</u> 1. Manufacturers recommendation based on soil mass 2. EOS Spreadsheet Tool 3. Assumptions from initial installation of biowalls		Used first calculation as most economical application
Substrate Loading Rate	Oil to soil mass ratio of 0.2%		For example, 2,300 pounds EOS for a biowall 380 feet in length, 2.5 feet in width, and with a saturated thickness of 11 feet
Injection amendment?	No		
Pre-injection Specified?	No		
Post-injection Specified?	No		

MONITORING INFORMATION

<i>Sample Collection Date</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Reference</i>
Multiple Events	Yes	Yes	Yes	No	Ref (2,3)

REFERENCES

- (1) EnSafe, Inc. 2005. *Operation and Maintenance Manual for Biowalls, NWIRP McGregor, McGregor, Texas*. Prepared for the Naval Facilities Engineering Command. December 19. **(O&M Plan)**
- (2) EnSafe, Inc. 2008. *Response Action Effectiveness Report*. Prepared for Naval Weapons Industrial Reserve Plant (NWIRP) McGregor, Texas and the Naval Facilities Engineering Command (NAVFAC), Jacksonville, Florida July. **(Operations Effectiveness Report)**

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates calculated or designed?

Three methods were used to determine substrate loading rates for biowall rejuvenation. The first method was based on a recommendation from the emulsified vegetable oil vendor (EOS Remediation) to use a ratio of 0.1 to 0.4% EOS product by weight of the mass of solid media in the biowall. As an example, 2,090 pounds of EOS product was calculated to be required for biowall segment S-1B of 380 feet in length, 2.5 feet in width, a saturated thickness of 10 feet, an assumed “soil” mass of 110 pounds per cubic feet, and a oil to soil mass ratio of 0.2%. This is equivalent to 1,254 pound of soybean oil assuming the EOS product is 60% oil by weight.

The second method used the EOS Remediation design spreadsheet and was based on electron acceptor demand and groundwater specific discharge through the biowall. For the S-1B biowall example above, the design spreadsheet yielded a substrate requirement of approximately 3,780 pounds of EOS product (2,268 pounds of oil) assuming a 2 year design life and an average perchlorate concentration of 1,000 µg/L.

The third method used an assumption initially used when the biowalls were installed. The assumption was that 10 pounds of oil per cubic yard of biowall material was needed for each biowall. For the S-1B biowall, this yielded a requirement of 5,870 pounds of EOS product (3,522 pounds of oil, assuming the product is 60 percent oil by weight).

The first method yielded the lowest of the three calculated substrate requirements, and was selected based on economic considerations.

2. What modifications to the substrate amendment protocol were required (e.g., concentration and frequency for soluble substrates; and depletion and additional injection of slow-release substrate types such as HRC® and EVO).

In August, 2006, after approximately 4 years of passive operation, nearly 8,200 kilograms (22,000 pounds) of emulsified vegetable oil and dilution water were injected into 15 onsite and offsite biowall segments in Area S, where the initial sections of the full-scale system were installed in 2002. The addition of supplemental organic carbon was triggered by routine monitoring results conducted as part of long-term OM&M. Groundwater collected from monitoring ports within several of the Area S biowalls, installed in 2002 and some of the oldest at the site, had TOC and perchlorate concentrations and ORP levels that indicated that the original source of organic substrate was no longer sustaining reducing conditions required to meet perchlorate treatment goals.

The impact of the supplemental substrate injection on long-term biowall effectiveness continued to be evaluated with ongoing long-term groundwater monitoring at the site. Re-injection was expected to occur annually or as needed to maintain reducing conditions. Because the groundwater flow rates are highly sensitive to precipitation at NWIRP McGregor, the re-injection frequency may be variable as the perchlorate mass discharge varies from year to year.

Monitoring through March 2008 was used to evaluate the effectiveness of the biowall systems, and the need to replenish is summarized in the table below. Based on quarterly monitoring, additional injections were conducted in June 2008 for biowalls at Area S, most of which were installed in 2002 and 2003. Biowalls installed in 2005 (Area F and Area M) did not need replenishment.

Table 1. Summary of Biowall Replenishment Based on Monitoring through March 2008

Area	No. Biowalls (full-scale)	Dates of Installation	Biowalls Replenished	Notes
E	1	Not reported	0	Biowall and bioborings to treat perchlorate and chlorinated solvents
F	9	Pilot Biowalls – July 2002 Full-scale Biowalls (9) – July 2005	0	No replenishment required through March 2008
M	7	Full-scale – July 2005	0	No replenishment required through March 2008
S	17	Full-scale - September to December 2002. Trench S-5 installed in Fall 2003. Trench S-3 expanded in Fall 2004. Trench S-8 and S-9 installed in July 2005.	6 of 17 in June 2008 (S-1A, S-2, S-5A, S-6A, S-6B, S-7)	Many biowalls sampling ports were dry in 2007/2008 due to a regional drought. Biowalls replenished in 2008 were mostly first generation (installed 2002-2003).

3. Evaluation from Substrate Requirement Tool

Insufficient data are available to estimate substrate requirements using the substrate requirement tool. Calculations using the EOS Remediation spreadsheet tool were not included in the 2005 O&M Manual.

PERFORMANCE OBJECTIVES

No. 1: Ability to Uniformly Distribute Substrate : Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

An application is considered successful when the targeted concentrations of soluble organic carbon are achieved in all monitoring locations within the intended reaction zone. For the MWIRP McGregor biowalls, quarterly monitoring is conducted to determine the need to replenish substrate for each biowall segment. Approximately 15 biowall segments were replenished in August 2006, and another 6 biowall segments were replenished in June 2008.

Performance verification is monitored post injection by collecting groundwater samples from the biowalls and analyzing for TOC. If concentrations of TOC are significantly greater than pre-injection (greater than 100 mg/L and less than 25% difference between trench ports), then the objectives of substrate replenishment are considered to be met. If these criteria are not met, then re-injection is considered.

No. 2: Achieving Optimal Geochemical Conditions

Successful geochemical conditions for stimulating anaerobic degradation of perchlorate was evaluated by the contractor for the NWIRP McGregor biowalls (EnSafe, 2005). The monitoring protocol developed for perchlorate included perchlorate, DO, nitrate, methane, ORP, pH, TOC, VFAs, humic and fulvic acids, and dissolved hydrogen.

TOC was deemed to be the most useful parameter that indicated effective biodegradation of perchlorate. Depletion of TOC followed a first order rate, and the minimum range at which breakthrough occurred appeared to be between 5 and 10 mg/L. Native microbial populations that utilize perchlorate as an electron acceptor may prefer nitrate for metabolism. Perchlorate degradation was observed to be sensitive to the presence of nitrate (i.e., diminished nitrate reduction due to a lack of organic carbon) at low concentrations of nitrate ranging from 0.1 to 0.5 mg/L.

ORP was also a useful indicator. Increases in ORP to greater than -50 mV were often the first evidence of impending perchlorate breakthrough, although this did not occur at all locations. Another parameter that appeared to be a useful indicator was the concentration of methane. Methane indicates highly reducing conditions, much more reducing than required to sustain perchlorate degradation. However, a decrease in methane to less than 2.0 mg/L appeared to indicate depletion of the biowall substrate and a good correlation was observed between a reduction in methanogenesis and inhibition of perchlorate degradation.

Given these observations, the parameters chosen for quarterly O&M monitoring included perchlorate, VOCs (where present), TOC, ORP, nitrate, methane, DO, and pH. DO and pH were retained primarily as stabilization parameters for well purging. A scoring matrix was established to determine when to replenish the biowalls. The scoring matrix included perchlorate, TOC, ORP, nitrate, and methane. TOC and perchlorate were weighted higher than the other parameters, methane was weighted the least. Other considerations included the number of sample locations indicating replenishment was required. For example, replenishment is initiated when two or more of four total sample locations in a biowall section indicate substrate amendment is needed.

No. 3: Remediation Effectiveness: Evaluate efficiency in removal of VOCs based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Determine “threshold” concentrations of dissolved organic carbon that represent the minimum levels required to sustain complete reductive dechlorination.

The effectiveness of the NWIRP McGregor biowalls was recently reported by EnSafe, Inc. (2008). Each plume management zone (PMZ) has onsite and/or offsite targets for perchlorate or VOCs (Area E). The targets for some PMZs are graduated over time to monitor progress towards achieving cleanup goals. For some PMZs, it is anticipated that up to 30 years may be required to meet cleanup goals. Remediation effectiveness for each of the areas having biowalls (Areas E, F, M, and S) are summarized in the table below.

For Areas E, F, and M, the biowalls are operating as designed, meeting performance expectations, and no replenishment was required as of 2008. The sampling ports for biowalls at Area S were mostly dry in 2008, with perchlorate below detection in the few that were sampled. Several biowalls at Area S were replenished in June 2008. Overall the biowalls are performing to expectation. Some of the early biowalls were not keyed into a confining unit, and a few downgradient monitoring wells suggest some bypass may be occurring. Additional biowalls or bioborings may be considered at future date.

Table 2. Summary of Remediation Effectiveness Based on Monitoring through March 2008

Area	No. Biowalls (full-scale)	Remediation Targets – State of Texas	Remediation Effectiveness (through March 2008)	Notes
E	1	Perchlorate – 17.11 µg/L residential; 51.1 µg/L industrial TCE – 5 µg/L; 1,1-DCE – 7 µg/L; cis-DCE – 70 µg/L	Perchlorate was below detection in the biowall and VOCs were below PCLs	Biowall operating as anticipated and meeting performance objectives
F	9	Perchlorate – Targets for January 2008 range from 17.1 to 150 µg/L	Perchlorate was below detection in all biowall ports except Port F4-Ca at a concentration of 23.6 B µg/L. VOCs within the biowalls were below PCLs	Biowalls operating as anticipated and meeting performance objectives
M	7	Perchlorate – Targets for January 2008 range from 17.1 to 600 µg/L	Perchlorate was below detection in all biowall ports sampled.	Biowalls operating as anticipated and meeting performance objectives
S	17	Perchlorate – Targets for January 2008 range from 17.1 to 200 µg/L	Most biowall ports were dry in 2008, perchlorate was below detection in the few that were sampled	Biowalls operating as designed, with replenishment indicated for several trenches.

Notes: PCL = protective concentration level.

No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

With a few exceptions, secondary water quality parameters are not included in the analytical protocol for the full-scale biowall systems at NWIRP McGregor. pH is measured as part of the well purging protocol. During the biowall optimization study, pH within the biowalls evaluated for optimization ranged from 6.5 to 7.0, while outside of the biowalls pH typically ranged from 6.5 to 7.5 (Tables 2.2 through 2.5 in EnSafe [2005]). An adverse impact on pH was not observed.

Acetone, 2-butanone, and carbon disulfide were included in the VOC analyte suite. Only low concentrations of these fermentation products were observed, typically less than 0.1 mg/L. These compounds were not produced at concentrations that impact water quality downgradient of the biowalls.

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

Data for hydraulic conductivity at the McGregor biowalls is not available. However, the potential for preferential groundwater flow pathways through or around the biowalls is evaluated as part of the O&M monitoring effort. No indication of an adverse loss of hydraulic conductivity was reported.

No. 6: Substrate Persistence and Long-Term Effectiveness

The NWIRP McGregor biowalls have remained effective at reducing concentrations of perchlorate and TCE over periods of 3 to 4 years before replenishment was conducted. The Area S biowalls were mostly installed from 2002 to 2003, with biowalls at Areas F and M installed in 2005. Replenishment was conducted at Area S in 2006 and 2008. Replenishment in 2006 was primarily to test the injection protocol, while replenishment in 2008 was based on monitoring results and the O&M scoring matrix. No loss of effectiveness has been observed.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

It was anticipated that rejuvenation of the biowalls would be required on a periodic basis, and it appears that replenishment will be required every 3 to 4 years to avoid any breakthrough of perchlorate. Costs for replenishment are not available.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

The biowall application at the NWIRP McGregor biowall sites benefited from a weathered bedrock aquifer that does not collapse during trenching operations. Groundwater levels and flow rates are highly dependent on rates of precipitation. The period from 2007 to 2008 was a period of relative drought in Texas, and many biowall sampling ports were dry. It is acknowledged in the reports that periods of high rates of precipitation may increase local rates of groundwater flow, and biowall performance could be impacted during these periods.

3. COST ASSESSMENT

A detailed cost summary for the NWIRP McGregor biowalls is not available.

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SITE SUMMARY**Building 301 Biowall, Offutt AFB, Nebraska**

For: Project Files for ESTCP Substrate Loading Study (Job No. 745255)

Reviewed/Updated: 01 July 2009; BMH

SITE IDENTIFICATION

Building 301 (B301), Offutt AFB, Nebraska

CONTAMINANT SOURCE

<i>COC</i>	<i>Max. Conc.</i>	<i>DNAPL Present?</i>	<i>Notes</i>
TCE	1,300 µg/L	No	Ref (1) - MW33S and MW34S in January 1999
<i>cis</i> -1,2-DCE	270 µg/L	No	Ref (1) - MW31S in January 1999
VC	2.5 µg/L	No	Ref (1) - MW29S in January 1999

Notes: Maximum concentrations were obtained from January 1999 baseline event (Table 2 in GSI, 2001).

SUBSTRATE DESIGN/INSTALLATION INFORMATION

<i>Parameter</i>	<i>Original Design</i>	<i>Modifications?</i>	<i>Notes/Reference</i>
Project Scale	Pilot and Full-Scale		Ref (1,2)
Base Substrate Type	Bark Mulch	No	
Biowall Dimensions – Pilot Biowall	100 feet long by 23 feet deep by 1.0 feet wide	No	
Biowall Dimensions – Full-scale Biowall	500 feet long by 25 feet deep by 1.5 feet wide	No	
Substrate Loading	50% Mulch and 50% Sand mixture	No	Mulch derived from on-Base sources
Basis for Loading Rate	Practical engineering concerns	No	Maximize mulch content while maintaining permeability and limiting compaction
Biowall amendments?	None	After August 2006	Emulsified vegetable oil and a bioaugmentation culture was injected after August 2006

MONITORING INFORMATION

<i>Sample Collection Date</i>	<i>COCs</i>	<i>Carbon Donor</i>	<i>Geochemical Indicators</i>	<i>Microbial Indicators</i>	<i>Reference</i>
January 1999 (baseline) Bi-annual from January 1999 to August 2000	Yes	Yes	Yes	No	Ref (1)
Quarterly from July 2001 to July 2003	Yes	Yes	Yes	No	Ref (2)
AFCEE/EPA (August 2006)	Yes	Yes	Yes	No	Ref (3)

Note: AFCEE/EPA joint study on biowall sustainability study includes sampling biowall material for mineral speciation.

REFERENCES

- (1) Groundwater Services Incorporated (GSI). 2001. *Final Report Mulch Biowall and Surface Amendment Pilot Test, Site Building 301, Offutt AFB, Nebraska*. Prepared for AFCEE. June 18. **(Pilot Report)**
- (2) GSI. 2004. *Final Report for Full-Scale Mulch Wall Treatment of Chlorinated Hydrocarbon-Impacted Groundwater, Offutt Air Force Base, Nebraska, Building 301*. Prepared for AFCEE. **(Final Report)**
- (3) Parsons. 2009. *Demonstration of the Performance and Sustainability of Permeable Mulch Biowalls for Enhanced Bioremediation*. Prepared for AFCEE and the USEPA OSWER. Draft, May. **(Joint AFCEE/EPA Study)**
- (4) AFCEE. 2003. *Cost and Performance Summary Report: Mulch Biowall at Offutt Air Force Base, Nebraska*. June.

SUBSTRATE LOADING EVALUATION

1. How were substrate loading rates calculated or designed?

The biowall mixture used was based on practical engineering considerations for biowall construction. A mix of 50% mulch to 50% sand was used to maximize the organic content of the biowall mixture while reducing the potential for compaction and loss of permeability. No testing of the mulch material was performed.

2. What modifications to the substrate amendment protocol were required (e.g., concentration and frequency for soluble substrates; and depletion and additional injection of slow-release substrate types such as HRC® and EVO).

No modifications to the biowall mixture were required. The full-scale application has an effective life span of at least 5 years based on monitoring in August 2006. Offutt AFB reports

that vegetable oil was injected into the piping at the base of the B301 biowall (after the August 2006 monitoring event) in an effort to treat contaminated groundwater flowing underneath and around the northern end of the biowall (personal communication with Phil Cork). Therefore, the installation of piping was a useful contingency to add during construction.

3. Evaluation from Substrate Demand Tool

Site data were input into the substrate demand tool (attached). The substrate demand to treat 4,196,467 gallons (15,884,911 liters) of groundwater over 5 years was calculated to be 189 pounds of molecular hydrogen, or 4.51E-05 pounds per gallon (5.41E-03 grams per liter) of groundwater treated.

The distribution of primary electron accepting processes was calculated to be methanogenesis (46.4%), followed by sulfate reduction (41.9%), nitrate reduction (4.5%), manganese reduction (3.4%), iron reduction (1.7%), aerobic oxidation (1.2%), and dechlorination of chlorinated solvents (0.9%). Groundwater at the site is naturally mildly anaerobic.

PERFORMANCE OBJECTIVES

No. 1: Ability to Uniformly Distribute Substrate : Evaluate distribution and trends in concentrations of substrate (soluble organic carbon and VFAs) over time.

An application is considered successful when the targeted concentrations of soluble organic carbon are achieved in all monitoring locations within the intended reaction zone. Total organic carbon (TOC) was measured within the biowall at locations BW1, BW6, and BW7 in August 2006 at concentrations less than 5.0 mg/L. Historically, the highest concentration of TOC at the B301 Site was 11.8 mg/L at location MW24S in July 2001. This well is located downgradient of the full-scale biowall. These are relatively low concentrations of TOC for stimulating *in situ* anaerobic bioremediation. Given the evidence for sulfate reduction and methanogenesis within the biowalls, it appears that TOC is not a good indicator of the degree to which the biowalls can stimulate and sustain anaerobic biodegradation processes (Parsons, 2009). Similar to TOC, it appears that VFAs are also not a good indicator of the degree to which the biowalls are stimulating anaerobic biodegradation processes.

No. 2: Achieving Optimal Geochemical Conditions

Successful geochemical conditions for stimulating anaerobic degradation of chlorinated solvents is defined as when the groundwater environment is highly anaerobic with DO less than 0.5 mg/L, ORP is less than -200 mV, sulfate is reduced by more than 50 percent relative to background conditions, and methane is greater than 1.0 mg/L. These criteria may not apply in all cases.

Background concentrations of DO in upgradient wells MW45S and MW46S are typically less than 0.5 mg/L. ORP in August 2006 upgradient of the biowalls was +371 mV at MW45S and +359 mV at MW46S, indicating that although concentrations of DO are low, the groundwater is naturally in an oxidized state. In the full-scale biowall at location BW1, ORP in August 2006 was 16 mV, while ORP at the pilot biowall sampling locations were 113 mV at BW6 and -63 mV at BW7. In general, ORP measurements within and downgradient of the B301 biowalls have been reduced relatively to upgradient conditions, but are only infrequently lower than 0 mV.

Concentrations of sulfate upgradient of the B301 biowalls ranged from 9.6 to 47 mg/L. Concentrations of sulfate within and downgradient of the biowalls after July 2001 ranged from 4.9 to 21 mg/L. In general, sulfate concentrations are reduced by approximately 50 percent, and the biowalls have sustained sulfate reduction for at least 60 months since installation of the full-scale biowall.

Concentrations of dissolved methane in upgradient monitoring locations MW45S and MW46S have been consistently measured at less than 0.010 mg/L. Within the full-scale biowall at location MW45S, concentrations of methane are elevated relative to background, with methane at 5.2 mg/L in August 2006. For locations within the pilot biowall, the concentrations of methane were 0.25 mg/L for BW6 and 3.6 mg/L for BW7 in August 2006. The B301 biowalls have stimulated and sustained methanogenesis for at least 5 years, although the data for location BW6 in August 2006 indicates that methanogenesis may start to diminish after a period of approximately 7 years post-installation.

The primary TEAPs within the biowalls at the B301 Site are sulfate reduction and methanogenesis, with manganese reduction and iron reduction occurring to a lesser extent. Negative redox potentials have rarely been measured during the B301 biowall application, although dechlorination of TCE and *cis*-DCE was observed. The higher than expected redox potentials may be the result of mixing of groundwater from different redox zones during sampling, or measurement inaccuracies in the redox probe (GSI, 2004).

Concentrations of dissolved hydrogen measured in August 2006 ranged from 1.1 to 13 nanomoles per liter (nmol/L) (Parsons, 2009). Taken in the context of depleted sulfate levels in groundwater, these concentrations of dissolved hydrogen suggest that sulfate reduction is the predominant redox reaction occurring within the biowall. Concentrations over 2 nmol/L were observed at pilot biowall locations BW6 and BW7, suggesting that the pilot biowalls have sustained sufficient levels of organic substrate to provide optimal levels of dissolved hydrogen for anaerobic reductive dechlorination of TCE and *cis*-DCE. In this case, dissolved hydrogen is a better indication than TOC or VFAs of the degree to which biowalls can stimulate and sustain anaerobic biodegradation processes.

No. 3: Remediation Effectiveness: Evaluate efficiency in removal of VOCs based on trend analysis and geochemical conditions such as redox levels and alternate electron acceptors. Determine “threshold” concentrations of dissolved organic carbon that represent the minimum levels required to sustain complete reductive dechlorination.

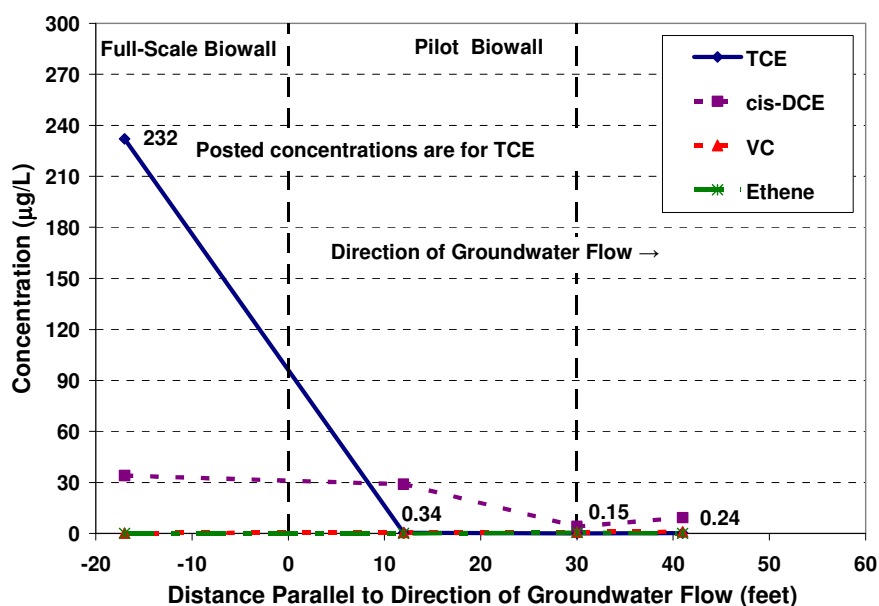
Over the first 31 months of operation, the pilot biowall was found to remove 75 percent of TCE in groundwater and 64 percent of the total chlorinated ethenes passing through the pilot biowall (GSI, 2001). Biotic reductive dechlorination was responsible for some of the removal as evidenced by the production of dechlorination products (e.g., *cis*-DCE) shortly after installation, but molar conservation of TCE to DCE to VC was not observed. Therefore, other degradation processes are thought to account for the extent of TCE removal (Parsons, 2009).

Greater reductions in concentrations of TCE have been observed in the full-scale biowall system. In the north section of the full-scale biowall, removal of up to 95 percent of TCE and 80 percent of total CAHs was observed through 2003 (GSI, 2004).

The B301 biowalls remain very effective at reducing concentrations of TCE and *cis*-DCE in August 2006, five years after installation of the full-scale biowall. Concentrations of TCE continue to be reduced by over 99 percent within the full-scale and pilot biowalls, to concentrations below 1.0 µg/L in the downgradient pilot biowall. Reductions in the concentration of *cis*-DCE are less pronounced in the full-scale biowall, but a reduction in *cis*-DCE is observed in the pilot biowall without an accumulation of VC (see figure below). Concentrations of *trans*-DCE have increased over time within the biowalls, and this may indicate that the biowalls are losing their effectiveness to completely transform TCE to innocuous end products.

Short-circuiting around the northernmost portion of the biowall may be occurring, suggesting that system performance may be compromised by local variations in groundwater hydraulics. But overall, the biowall system is performing to expectations and meeting all performance objectives within the downgradient pilot biowall monitoring wells.

**Concentration of Chlorinated Ethenes over Distance along Southern
Transect – August 2006**



No. 4: Impacts to Secondary Water Quality: Evaluate changes in secondary water quality parameters as a function of substrate type, concentration, and availability.

Secondary water quality parameters that were evaluated for the B301 biowall include pH, sulfide, total dissolved solids, and dissolved inorganics (ferrous iron, manganese, arsenic, and selenium).

Summary of Secondary Water Quality – B301 Biowall, Offutt AFB, Nebraska

Parameter	Comparison Criteria	Background	Treatment Zone	Down-gradient	Issues?
pH	<6.5 or >8.5 (b)	5.82 to 6.89	5.10 to 6.76	6.10 to 6.59	No
Sulfide (mg/L) (August 2006 data only)	NA	0.07 to 0.08	<0.01 to 0.74	<0.10 to 0.05	No – only one detection above 0.1 mg/L
Total Dissolved Solids (mg/L)	500 (b)	390	420 to 480	460 to 480	No – August 2006 data only
Total Manganese (mg/L) (August 2006 data only)	0.05 (b)	0.2 to 1.3	0.7 to 3.9	0.7 to 5.1	Potential – background above criteria.
Total Ferrous Iron (mg/L)	0.3 (b)	0.05 to 0.39	0.13 to 3.9	<0.02 to 5.0	Potential – background above criteria
Dissolved Manganese (mg/L) (August 2006 data only)	0.05 (b)	0.010F (MW45S)	1.1 to 2.3 (BW1 and BW6)	0.66 (MW33S)	Potential – above criteria within and downgradient of biowall.
Dissolved Arsenic (mg/L) (August 2006 data only)	0.01 (a)	0.008F (MW45S)	0.003F to 0.007F (BW1 and BW6)	<0.010 (MW33S)	No
Dissolved Selenium (mg/L) (August 2006 data only)	0.05 (a)	0.008F (MW45S)	0.009F to 0.012F (BW1 and BW6)	0.016F (MW33S)	No

Notes:

Background values from wells MW45S and MW46S (upgradient).

Treatment zone values from wells BW1, BW6, and BW7.

Downgradient values from wells MW33S and MW31S (post-installation).

mg/L = milligrams per liter; µg/L = micrograms per liter. F-flag indicates the concentration is estimated.

Criteria based on (a) USEPA MCL; (b) USEPA Secondary Standard; or (c) USEPA Region 9 PRG.

pH and Sulfide. With few exceptions, pH remained in a range from approximately 5.1 to 6.8 within the biowalls and an adverse decrease in pH was not observed. Only a few low level detections of sulfide were observed.

Dissolved and Total Metals. Filtered samples (dissolved metals) for arsenic, selenium, and manganese were analyzed in samples collected from wells along the axis of the northern flow path through the biowalls in August 2006. Unfiltered samples (total metals) for manganese and ferrous iron were measured in the field.

With a single exception, concentrations of dissolved arsenic were below the reporting limit of 0.010 mg/L for all samples within and downgradient of the reaction zone in August 2006. Arsenic was measured at a concentration of 0.11 mg/L in a sample from well MW24S, located between the two biowalls. Concentrations of selenium were less than a reporting limit of 0.020 mg/L, with low estimated concentrations from 0.008F to 0.016F mg/L. Based on the criteria listed in the table above, solubilization of arsenic and selenium is not of concern at the B301 Biowall Site.

Concentrations of dissolved manganese in August 2006 were low, ranging from 0.010F mg/L upgradient to 4.8 mg/L in well MW24S, located between the two biowalls. Dissolved manganese was 0.66 mg/L in downgradient well MW33S. Concentration of total manganese (unfiltered samples analyzed in the field) within and downgradient of the biowalls similarly ranged from 0.7 to 5.1 mg/L. Concentrations of ferrous iron in upgradient wells MW45S and MW46S ranged from 0.01 mg/L to 0.39 mg/L. Within and downgradient of the biowalls, concentrations of ferrous iron were only slightly elevated in a few locations, ranging from below detection up to 3.9 mg/L at location BW7 (within the pilot biowall). Similar to manganese, these data indicate that there is some bioavailable ferric iron at the B301 Site, which may be reduced to ferrous iron under anaerobic conditions stimulated by the biowalls.

In summary, there is a potential for manganese and iron production to be an issue at the B301 biowall site, but it appears the impact dissipates with distance downgradient of the biowall and this issue has not been a concern regarding biowall performance.

No. 5: Impacts to Hydraulic Conductivity: Evaluate hydraulic data, including potentiometric surface and hydraulic conductivity, before and after injection to determine adverse impacts to groundwater flow.

The biowall systems were installed approximately 1,400 feet downgradient of Building 301. Shallow sediments in this area consist of approximately 1 to 3 feet of fill, overlying either a stiff, low plastic, silty clay (topsoil) or a stiff, light to reddish brown, low plastic, silty clay. The depth to groundwater in the biowall area is approximately 6 to 9 feet bgs.

The hydraulic conductivity was previously measured by aquifer testing in the alluvial silt and clay near the biowall, and averaged 3.5 ft/day (1.2E-03 cm/sec) (GSI, 2001). Hydraulic gradient was also measured to be approximately 0.01 ft/ft. Using an assumed effective porosity of 0.15, the estimated groundwater seepage velocity was calculated to be approximately 0.23 ft/day, or 85 ft/yr.

Slug tests are conducted in five wells within the biowalls in 2001, 2002, and 2003 (GSI, 2004). The reduction in hydraulic conductivity from 2001 to 2003 ranged from 18 to 31 percent. This indicates compaction and degradation of the mulch in the biowall has lowered the hydraulic conductivity of the biowall mixture, although it is less than a 50% reduction.

Slug tests were conducted at selected wells in August 2006, ranging from 3.6 ft/day (1.3E-03 cm/sec) to 20 ft/day (7.1E-03 cm/sec) in wells outside of the biowalls, and from 2.3 ft/day (8.1E-04 cm/sec) to 12.3 ft/day (4.3E-03 cm/sec) for wells within the biowalls (Parsons, 2009). It appears that the hydraulic conductivity of the biowall is slightly less than that of the surrounding

formation. This may be a potential cause for some bypass of contaminated groundwater around or underneath the biowalls.

No. 6: Substrate Persistence and Long-Term Effectiveness

The B301 biowalls remain very effective at reducing concentrations of TCE and *cis*-DCE in August 2006, five years after installation of the full-scale biowall. Concentrations of TCE continue to be reduced by over 99 percent within the full-scale and pilot biowalls, to concentrations below 1.0 µg/L in the pilot biowall. Reductions in the concentration of *cis*-DCE are less pronounced in the full-scale biowall, but a reduction in *cis*-DCE is observed in the pilot biowall without an accumulation of VC. Concentrations of *trans*-DCE have increased over time within the biowalls, and this may indicate that the biowalls are losing their effectiveness to completely transform TCE to innocuous end products.

No. 7: Need for and Cost of Additional Injections or Monitoring: Evaluate the impact on life-cycle cost to implement modifications to injection protocols.

No modifications were performed for the B301 biowalls through 5 years following full-scale installation. Offutt AFB reports that vegetable oil was injected into the piping at the base of the B301 biowall (after the August 2006 monitoring event) in an effort to treat contaminated groundwater flowing underneath and around the northern end of the biowall (personal communication with Phil Cork). A bioaugmentation culture was also added, but monitoring data through August 2006 does not indicate this was necessary to achieve performance objectives.

No. 8: Application in Difficult Hydrogeological Conditions: Note what geochemical or hydrogeological conditions enhance or inhibit bioremediation performance.

The application at the B301 Biowall Site did not encounter any difficult hydrogeological conditions. The application benefited from:

- Silty clay that did not collapse or flow during trenching operations.
- Average groundwater flow velocity of 85 ft/year, which is suitable for a biowall application of limited thickness.

3. COST ASSESSMENT

A detailed cost summary for the B301 Biowall at Offutt AFB, Nebraska is not available. The reported cost to install the pilot-scale biowall was \$360 per linear foot (Ref[4]), or approximately \$36,000 for trenching and materials.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents**Site Name:** B301 Biowall, Offutt AFB, Nebraska

NOTE: Unshaded boxes are user input.				
1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	500	1-10,000	feet	
Length (Parallel to predominant groundwater flow)	1.5	1-1,000	feet	
Saturated Thickness	17.5	1-100	feet	
Treatment Zone Cross Sectional Area	8,750	--	ft ²	
Treatment Zone Volume	13,125	--	ft ³	
Treatment Zone Total Pore Volume (total volume x total porosity)	19,640	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	14,730	--	gallons	
Design Period of Performance	5.0	.5 to 5	year	Not Specified - Monitored for 5 years
Design Factor (times the electron acceptor hydrogen demand)	5.0	2 to 20	unitless	
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	20%	.05-50	percent	Silty sand and silty clay
Effective Porosity	15%	.05-50	percent	Estimated
Average Aquifer Hydraulic Conductivity	3.5	.01-1000	ft/day	
Average Hydraulic Gradient	0.01	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.23	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	85.2	--	ft/yr	
Average Groundwater Flux through the Treatment Zone	836,347	--	gallons/year	
Soil Bulk Density	1.65	1.4-2.0	gm/cm ³	Sand
Soil Fraction Organic Carbon (foc)	0.50%	0.01-10	percent	Assumed default value of formation
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				*Average of upgradient wells MW45S and MW46S
Oxygen	0.50	0.01 to 10	mg/L	Ranged from <0.14 to 1.3 mg/L
Nitrate	2.50	0.1 to 20	mg/L	Ranged from 1.3 to 4.3 mg/L
Sulfate	27	10 to 5,000	mg/L	Ranged from 9.6 to 47 mg/L
Carbon Dioxide (estimated as the amount of Methane produced)	5.0	0.1 to 20	mg/L	Methane Produced - Max. 6.4 mg/L
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	5.0	0.1 to 20	mg/L	Manganese Produced - Max. 5.1 mg/L
Iron (III) (estimated as the amount of Fe (II) produced)	5.0	0.1 to 20	mg/L	Ferrous Iron Produced - Max 5.0 mg/L
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.000	--	mg/L	Maximum concentrations:
Trichloroethene (TCE)	1.000	--	mg/L	MW34S on 7/30/03
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.051	--	mg/L	MW46S on 9/28/05
Vinyl Chloride (VC)	0.001	--	mg/L	MW46S on 9/28/05
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				*Average of upgradient wells MW45S and MW46S
Oxidation-Reduction Potential (ORP)	202	-400 to +500	mV	Background ranged from 11 to 371 mV
Temperature	15	5.0 to 30	°C	Background ranged from 13.9 to 15.6 °C
pH	6.3	4.0 to 10.0	su	Background ranged from 5.52 to 6.89
Alkalinity	438	10 to 1,000	mg/L	Background ranged from 318 to 592 mg/L
Total Dissolved Solids (TDS, or salinity)	390	10 to 1,000	mg/L	Average of upgradient wells MW45S and MW46S
Specific Conductivity	588	100 to 10,000	µs/cm	Background ranged from 564 to 666 µs/cm
Chloride	11	10 to 10,000	mg/L	Ranged from 5.9 to 17 mg/L
Sulfide - Pre injection	0.08	0.1 to 100	mg/L	Ranged from 0.07 to 0.08 mg/L
Sulfide - Post injection	0.28	0.1 to 100	mg/L	Maximum 0.74 mg/L
B. Aquifer Matrix				
Total Iron	5,630	100 to 10,000	mg/kg	Average of soil two samples for bioavailable Fe ³⁺
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	
Neutralization Potential	NA	1.0 to 100	Percent as CaCO ₃	

NOTES:

Background data based on sampling from July 2001 to August 2006 at locations MW45S and MW46S.
 Values for methane, manganese, and ferrous iron are post biowall installation.

Table S.2 Substrate Calculations in Hydrogen Equivalents**Site Name:** B301 Biowall, Offutt AFB, Nebraska

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

Width (Perpendicular to predominant groundwater flow direction)
 Length (Parallel to predominant groundwater flow)
 Saturated Thickness
 Treatment Zone Cross Sectional Area
 Treatment Zone Volume
 Treatment Zone Total Pore Volume (total volume x total porosity)
 Design Period of Performance

Values	Range	Units
500	1-10,000	feet
1.5	1-1,000	feet
17.5	1-100	feet
8750	--	ft ²
13,125	--	ft ³
14,730	--	gallons
5.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity
 Effective Porosity
 Average Aquifer Hydraulic Conductivity
 Average Hydraulic Gradient
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Seepage Velocity through the Treatment Zone
 Average Groundwater Flux through the Treatment Zone
 Soil Bulk Density
 Soil Fraction Organic Carbon (foc)

0.2	.05-50	
0.15	.05-50	
3.5	.01-1000	ft/day
0.01	0.1-0.0001	ft/ft
0.23	--	ft/day
85.2	--	ft/yr
836,347	--	gallons/year
1.65	1.4-2.0	gm/cm ³
0.005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)**A. Aqueous-Phase Native Electron Acceptors**

Oxygen
 Nitrate (denitrification)
 Sulfate
 Carbon Dioxide (estimated as the amount of methane produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.5	0.06	7.94	0.01	4
2.5	0.31	10.25	0.03	5
27	3.32	11.91	0.28	8
5.0	0.61	1.99	0.31	8
Soluble Competing Electron Acceptor Demand (lb.)			0.63	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)
 Manganese (IV) (estimated as the amount of Mn (II) produced)
 Iron (III) (estimated as the amount of Fe (II) produced)

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
5.0	175.09	27.25	6.43	2
5.0	175.09	55.41	3.16	1
Solid-Phase Competing Electron Acceptor Demand (lb.)			9.59	

C. Soluble Contaminant Electron Acceptors

Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
0.000	0.00	20.57	0.00	8
1.000	0.12	21.73	0.01	6
0.051	0.01	24.05	0.00	4
0.001	0.00	31.00	0.00	2
0.000	0.00	19.08	0.00	8
0.000	0.00	19.74	0.00	6
0.000	0.00	21.06	0.00	4
0.000	0.00	25.04	0.00	2
0.000	0.00	20.82	0.00	8
0.000	0.00	22.06	0.00	6
0.000	0.00	24.55	0.00	4
0.000	0.00	32.00	0.00	2
0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)			0.01	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x C_{gw})
 Tetrachloroethene (PCE)
 Trichloroethene (TCE)
 Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)
 Vinyl Chloride (VC)
 Carbon Tetrachloride (CT)
 Trichloromethane (or chloroform) (CF)
 Dichloromethane (or methylene chloride) (MC)
 Chloromethane
 Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)
 Trichloroethane (1,1,1-TCA and 1,1,2-TCA)
 Dichloroethane (1,1-DCA and 1,2-DCA)
 Chloroethane
 Perchlorate

Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
263	0.00	0.00	20.57	0.00	8
107	0.54	0.72	21.73	0.03	6
45	0.01	0.02	24.05	0.00	4
3.0	0.00	0.00	31.00	0.00	2
224	0.00	0.00	19.08	0.00	8
63	0.00	0.00	19.74	0.00	6
28	0.00	0.00	21.06	0.00	4
25	0.00	0.00	25.04	0.00	2
117	0.00	0.00	20.82	0.00	8
105	0.00	0.00	22.06	0.00	6
30	0.00	0.00	24.55	0.00	4
3	0.00	0.00	32.00	0.00	2
0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)			0.03		

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents**4. Treatment Cell Electron-Acceptor Flux (per year)****A. Soluble Native Electron Acceptors**

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	0.5	3.49	7.94	0.44	4
Nitrate (denitrification)	2.5	17.45	10.25	1.70	5
Sulfate	27	188.43	11.91	15.82	8
Carbon Dioxide (estimated as the amount of Methane produced)	5	34.89	1.99	17.54	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				35.5	

B. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt H ₂)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	1.000	6.98	21.73	0.32	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.051	0.35	24.05	0.01	4
Vinyl Chloride (VC)	0.001	0.01	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				0.34	

Initial Hydrogen Requirement First Year (lb) **46.1**

Total Life-Cycle Hydrogen Requirement (lb) **189.4**

5. Design Factors

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X

Design Factor **5.0**

Total Life-Cycle Hydrogen Requirement with Design Factor (lb) **947.1**

6. Acronyms and Abbreviations

°C =degrees celsius	meq/100 g = milliequivalents per 100 grams
μs/cm = microsiemens per centimeter	mg/kg = milligrams per kilogram
cm/day = centimeters per day	mg/L = milligrams per liter
cm/sec = centimeters per second	m/m = meters per meters
ft ² = square feet	mV = millivolts
ft/day = feet per day	m/yr = meters per year
ft/ft = foot per foot	su = standard pH units
ft/yr = feet per year	wt/wt H ₂ = concentration molecular hydrogen, weight per weight
gm/cm ³ = grams per cubic centimeter	
kg of CaCO ₃ per mg = kilograms of calcium carbonate per milligram	
lb = pounds	

Table S.3
Hydrogen Produced by Fermentation Reactions of Common Substrates

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H ₂ /Mole Substrate
Lactic Acid	C ₃ H ₆ O ₃	90.1	2	0.0448	2 to 3
Molasses (assuming 100% sucrose)	C ₁₂ H ₂₂ O ₁₁	342	8	0.0471	8 to 11
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	C ₆ H ₁₂ O ₆	180	4	0.0448	4 to 6
Ethanol	C ₂ H ₆ O	46.1	2	0.0875	2 to 6
Whey (assuming 100% lactose)	C ₁₂ H ₂₂ O ₁₁	342	11	0.0648	11
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	C ₃₉ H ₅₆ O ₃₉	956	28	0.0590	28
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	C ₁₈ H ₃₂ O ₂	281	16	0.1150	16

RESET DEFAULT

Table S.4
Estimated Substrate Requirements for
Hydrogen Demand in Table S.3

Design Life (years): 5

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	5.0	21,159	21,159	9.60E+09	604
Sodium Lactate Product (60 percent solution)	5.0	21,159	43,899	9.60E+09	604
Molasses (assuming 60 percent sucrose)	5.0	20,101	33,502	9.12E+09	574
HFCS (assuming 40% fructose and 40% glucose by weight)	5.0	21,164	26,455	9.60E+09	604
Ethanol Product (assuming 80% ethanol by weight)	5.0	10,822	13,527	4.91E+09	309
Whey (assuming 100% lactose)	5.0	14,606	20,866	6.63E+09	417
HRC [®] (assumes 40% lactic acid and 40% glycerol by weight)	5.0	16,040	16,040	7.28E+09	366
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	5.0	8,236	8,236	3.74E+09	235
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	5.0	8,236	13,727	3.74E+09	235

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH₃-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid (C₃H₆O₃) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H₂O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC[®] weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: B301 Biowall, Offutt AFB, Nebraska

1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	500	feet	152	meters
Length (parallel to groundwater flow)	1.5	feet	0.5	meters
Saturated Thickness	17.5	feet	5.3	meters
Design Period of Performance	5	years	5	years

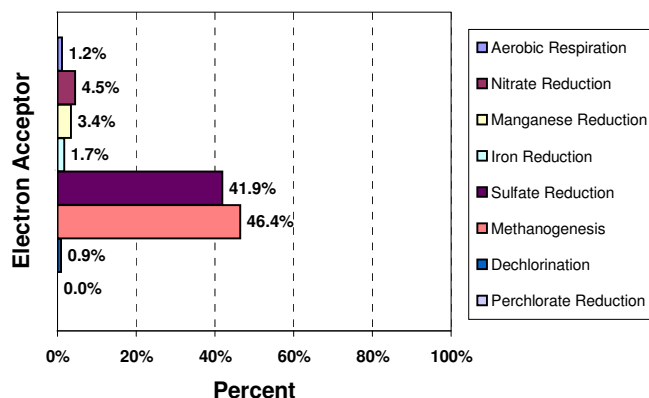
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.2	percent	0.2	percent
Effective Porosity	0.15	percent	0.15	percent
Average Aquifer Hydraulic Conductivity	3.5	ft/day	1.2E-03	cm/sec
Average Hydraulic Gradient	0.01	ft/ft	0.01	m/m
Average Groundwater Seepage Velocity	0.23	ft/day	7.1E+00	cm/day
Average Groundwater Seepage Velocity	85	ft/yr	26.0	m/yr
Total Treatment Zone Pore Volume	14,730	gallons	55,758	liters
Groundwater Flux (per year)	836,347	gallons/year	3,165,831	liters/year
Total Groundwater Volume Treated (over entire design period)	4,196,467	gallons total	15,884,911	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	1.2%	2.205
Nitrate Reduction	4.5%	8.541
Sulfate Reduction	41.9%	79.385
Manganese Reduction	3.4%	6.425
Iron Reduction	1.7%	3.160
Methanogenesis	46.4%	87.984
Dechlorination	0.9%	1.721
Perchlorate Reduction	0.0%	0.000
Totals:	100.00%	189.42

Hydrogen demand in pounds/gallon:	4.51E-05
Hydrogen demand in grams per liter:	5.41E-03

Distribution of Electron Acceptors**4. Substrate Equivalents: Design Factor =****5.0**

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	43,899	3,991	604	as lactic acid
2. Molasses Product	33,502	2,792	574	as sucrose
3. Fructose Product	26,455	2,362	604	as fructose
4. Ethanol Product	13,527	1,960	309	as ethanol
5. Sweet Dry Whey (lactose)	20,866	sold by pound	417	as lactose
6. HRC®	16,040	sold by pound	366	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	8,236	1,056	235	as soybean oil
8. Emulsified Vegetable Oil	13,727	1,760	235	as soybean oil

Notes:

- Quantity assumes product is 60% sodium lactate by weight.
- Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
- Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
- Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
- Quantity assumes product is 70% lactose by weight.
- Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
- Quantity of neat soybean oil, corn oil, or canola oil.
- Quantity assumes commercial product is 60% soybean oil by weight.

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APPENDIX D

**TECHNICAL MEMORANDUM FOR THE DP98 SITE,
ELMENDORF AFB, ALASKA**

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FINAL TECHNICAL MEMORANDUM

13 January 2009

To: Donna Baumler and Gary Fink, 3 CES/CEANR, Elmendorf AFB, Alaska

Cc: Dr. Andrea Leeson, ESTCP, Arlington, Virginia and Erica Becvar, AFCEE-TDE, Brooks City-Base, Texas

From: Bruce Henry, Parsons, Denver, Colorado

Subject: Long-Term Monitoring Results for an Enhanced Monitored Natural Attenuation Treatability Study at the DP98 Site, Elmendorf AFB, Alaska

This technical memorandum provides a summary of a monitoring event for an enhanced *in situ* bioremediation application for remediation of chlorinated solvents in groundwater at the DP98 Site, Elmendorf Air Force Base (AFB), Alaska. A treatability study for enhanced natural attenuation was conducted by the United States Air Force (USAF) from June 2005 to September 2006, with approximately 14 months of post-injection monitoring (USAF, 2007). The site was sampled in June 2008 as part of a bioremediation study being funded by the Environmental Security Technology Certification Program (ESTCP, Project No. ER-0627) entitled *Loading Rates and Impacts of Substrate Delivery for Enhanced Anaerobic Bioremediation* (Parsons, 2008). The following sections describe the purpose and results of the June 2008 sampling event.

PURPOSE AND OBJECTIVES

The ESTCP has initiated a program to determine the effectiveness of enhanced *in situ* bioremediation to remediate chlorinated solvents, perchlorate, and explosives in groundwater. While a number of demonstration projects have been implemented for enhanced *in situ* bioremediation, there is still a lack of definitive guidance for determining appropriate substrate loading rates and delivery methods based on site-specific conditions. This study is intended to supplement guidance developed to date by ESTCP for enhanced *in situ* bioremediation. The final product of this demonstration will be a technical report describing the results of multiple case study evaluations. In addition, a guidance addendum will be prepared to the *Principles and Practices of Enhanced Anaerobic Bioremediation of Chlorinated Solvents* (AFCEE *et al.*, 2004) and a cost and performance report will be prepared in accordance with ESTCP guidance.

The objectives of the ESTCP demonstration are to:

- 1) Better understand the effects that substrate amendment loading rates (i.e., the volume, concentration, and frequency of injection) have on substrate persistence (maintenance of the reaction zone) and distribution (mixing and radius of influence);

PARSONS

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- 2) Determine how control of substrate loading rates affects amendment reactivity and development of optimal geochemical and redox conditions for anaerobic biodegradation;
- 3) Identify substrate loading rates that have adverse impacts on secondary water quality;
- 4) Evaluate the effect that differing substrate types or loading rates may have on hydraulic conductivity based on physical/chemical or biological (biomass) effects of the substrate amendment; and
- 5) Use this information to develop practical guidelines for designing and optimizing substrate loading rates and injection scenarios for differing substrate types and for differing geochemical and hydrogeologic conditions.

To achieve these objectives the ESTCP demonstration evaluates approximately 18 case studies that represent a variety of site conditions and a variety of substrate types. The DP98 site at Elmendorf AFB was selected as a case study site, and a field monitoring event was proposed to evaluate long-term performance and the impacts of injection of a mixed substrate of emulsified vegetable oil and sodium lactate to treat chlorinated solvents in groundwater.

SAMPLING AT THE DP98 SITE

Sampling activities for the DP98 at Elmendorf AFB, Alaska are listed in Table 1 (attached), and sample locations are shown on Figure 1 (attached). Screening for *Dehalococcoides* species and reductase genes was also conducted at the Kenney Avenue Plume (four samples), where an extensive biogeochemical sample protocol has been recently implemented by the Air Force. Only groundwater samples were collected at Elmendorf AFB, Alaska. The Alaska Department of Environmental Conservation (ADEC) requires that the collection, interpretation, reporting of data, and the required sampling and analysis be conducted or supervised by an ADEC "Qualified Person." Parsons provided the required personnel to meet this requirement per State of Alaska Administrative Code 18 AAC 75.990(100). This technical memorandum contains laboratory analytical data (Attachment A), including a Laboratory Data Review Checklist (ADEC, 2008) completed by an ADEC Qualified Person.

DP98 SAMPLING RESULTS

The shallow aquifer at the DP98 site contains elevated levels of chlorinated aliphatic hydrocarbons (CAHs, commonly referred to as chlorinated solvents), primarily trichloroethene (TCE) and *cis*-1,2-dichloroethene (*cis*-DCE). Prior to substrate injection, the distribution of TCE and *cis*-DCE in groundwater indicated that limited reductive dechlorination of chloroethenes was occurring at the site. However, geochemical data indicated that the process was electron donor (substrate) limited.

An “initial condition” groundwater sampling event was conducted immediately prior to injection in July 2005. Emulsified vegetable oil and sodium lactate was injected into three wells in late July 2005. Performance monitoring events were conducted in September 2005 (2 months after injection), May/June 2006 (10 months), and September 2006 (14 months). Results of the treatability study are contained in *Treatability Study for Enhanced Monitored Natural Attenuation at DP98, Elmendorf AFB, Alaska* (USAF, 2007). The following sections summarize the historical treatability study data with an update using the June 2008 results.

Hydrogeology

The site layout is shown on Figure 1, and well construction data are summarized in Table 2. Fill material (silty sand and gravel) was encountered from depths of 5 to 10 feet below ground surface (bgs). Silty sand and silty clay was encountered from depths of approximately 10 to 25 feet bgs. At a depth of approximately 26 to 31 feet, layers of relatively higher permeability silty sand and gravel were observed in each boring, with the exception of the boring for DP98MW-04. The variation in lithology from clay to silty sand and gravel indicates that a moderate degree of heterogeneity exists within the shallow saturated zone at the DP98 test site.

The depth to groundwater measurements were collected during each monitoring event (Table 3). Groundwater was encountered at depths of 10 to 15 feet bgs. Groundwater elevations fluctuated by approximately 3 to 4 feet between summer and fall monitoring events. The potentiometric surface for June 2008 is shown on Figure 1, which shows groundwater flow is towards the northwest. The direction of groundwater flow for other monitoring events was similar. The hydraulic gradient measured between upgradient well DP98MW-04 and downgradient well DP98MW-06 for July 2005 was approximately 0.030 foot per foot (ft/ft). Groundwater elevations were approximately 1.5 to 2.0 feet higher in June 2008, when the hydraulic gradient measured between well DP98MW-04 and DP98MW-06 was 0.048 ft/ft.

Slug test were conducted to estimate the average hydraulic conductivity at the DP98 site (Table 4). Pre-injection estimates of hydraulic conductivity ranged from 0.09 feet per day (ft/day) at well DP98MW-04 to 1.7 ft/day at well DP98INJ-02.

An effective porosity of 22 percent has been assumed for the DP98 site, consistent with the value used in the DP98 Treatability Study (USAF, 2007). This value for effective porosity was based in part on values of specific yield (another term for effective porosity) listed in Spitz and Moreno (1996), where values for fine gravel and coarse sand range from 13 to 43 percent. A fair amount of silt and clay was observed in sediments from the DP98 well borings, and values of hydraulic conductivity calculated from slug tests are less than 2 ft/day, which are at the lower end of a range that might be expected for sand and gravel. Therefore, it was thought that effective porosity at the DP98 site averaged around 20 to 25 percent, and an intermediate value of 22 percent was arbitrarily selected. A review of other DP98 reports shows that a range of values have been used, including 13 percent for the 2001 Engineering Evaluation/Corrective Action Report (USAF, 2001), 25 percent for the 2003 DP98 Remedial Investigation/Feasibility

Study (USAF, 2003), and 30 percent for a 2008 modeling effort (USAF, 2008). A value of 22 percent is within the mid-range of these values.

Assuming an effective porosity of 22 percent and a hydraulic gradient of 0.030 ft/ft, the range of advective groundwater flow for July 2005 ranged from 4.5 to 86 feet per year (ft/yr). For June 2008, when the hydraulic gradient was calculated to be 0.048 ft/ft, the groundwater advective flow velocity is estimated to range from 38 to 120 ft/yr. Hydraulic conductivity and groundwater flow rate for well DP98MW-04 is approximately an order of magnitude lower than estimates for the other three well locations. This discrepancy is likely due the absence of a coarse grained sand interval at the base of the screened interval for DP98MW-04, which was observed at other well locations downgradient of well DP98MW-04. It is not unusual for hydraulic conductivity to range over an order of magnitude or more based on aquifer heterogeneity.

Hydraulic conductivity for well DP98MW-04 increased over time, from 0.09 ft/day to approximately 0.45 to 0.58 ft/day in June and October 2006. This may be due to repeated purging of the well over time and removal of fines from the well screen. This well was noted to repeatedly go dry during development, limiting the ability to adequately develop the well. Conversely, the hydraulic conductivity measured for well DP98INJ-02 decreased slightly over time from July 2005 to October 2006. One possible explanation is biofouling of the aquifer or well screen due to the high levels of organic carbon at this injection location. However, the hydraulic conductivity at DP98INJ-02 increased in June 2008, indicating any effects from the injection were not long-term. Hydraulic conductivity at downgradient well locations DP98MW-05 and DP98MW-06 remained relatively stable over time.

Substrate Distribution

In July 2005, approximately 2,244 gallons of an oil-in-water emulsion (containing vegetable oil and sodium lactate) and a water push of 1,060 gallons (containing sodium lactate) were injected into the shallow aquifer at the DP98 Site through injection wells DP98INJ-01, DP98INJ-02, and DP98INJ-03 (Figure 1). Make-up water, sodium lactate, and the pre-mixed emulsion were metered into the injection system to produce the mixtures specified in Table 5. Out of approximately 3,100 gallons of make-up water, approximately 1,900 gallons were native groundwater and 1,200 gallons were from a potable water supply. Based on the quantities of each substrate and the total volume injected, the average concentration of the overall substrate mixture was 19.3 grams per liter (g/L) lactic acid and 18.5 g/L vegetable oil. The effective oil saturation of the injected fluid was 2.0 percent. The amount of substrate applied was intended to sustain highly reducing conditions for approximately 18 months based on site-specific stoichiometry and a conservative estimate of non-specific substrate demand (Appendix D of USAF, 2005).

The radius of influence of the injected substrate at each injection point can be estimated given 1) the amount of substrate injected, 2) the length of the injection screen, 3) an assumed effective porosity of the aquifer matrix of 22 percent, and 4) an assumed uniform horizontal and radial distribution of substrate away from the injection well screen. Based on the measured volumes of

emulsion/water mixture injected into the formation, this provides a column of substrate approximately 9.2 to 9.4 feet in diameter (a radius of 4.6 to 4.7 feet) around each injection well. The estimated radius of influence is slightly less than a targeted radius of influence of 5.0 feet (USAF, 2005).

Distribution of substrate can be observed either in the form of physical oil or emulsion, or measured by analysis of total organic carbon (TOC) in groundwater. TOC data (Table 6) collected during performance monitoring indicate that substrate was distributed around the injection wells and to downgradient monitoring well locations DP98MW-05 and DP98MW-06. Concentrations of TOC in September 2006 for these locations ranged from 130 to 460 milligrams per liter (mg/L), with the highest concentration at well location DP98MW-05.

The distribution of substrate, indicated by measurement of TOC, suggests that a relatively large proportion of the vegetable oil droplets may have migrated on the order of 10 to 15 feet before adsorbing to the aquifer matrix in the vicinity of well DP98MW-05. Lactic acid (from sodium lactate) also migrated through the reaction zone, presumably the source of elevated levels of TOC at well location DP98MW-06. It was also noted that an elevated level of TOC (50 mg/L) was measured at cross-gradient well location 41755-WL04 in September 2005, but not in May/June 2006. This suggests that the distribution of lactic acid (from dissolution of the sodium lactate) during injection and due to advection and dispersion with groundwater flow impacted a much larger area than anticipated.

For June 2008, concentrations of TOC at the injection well locations ranged from 100 to 290 mg/L, with the highest concentration being measured at the center injection well location DP98INJ-02. At the downgradient locations (DP98MW-05 and DP98MW-06), levels of TOC decreased from over 90 mg/L in September 2006 to less than 20 mg/L in June 2008. While it appears elevated levels of organic carbon have been sustained through June 2008 (35 months post-injection) within the immediate injection zone, substrate levels are depleted within 15 to 30 feet downgradient of the injection wells. This duration of sustained, elevated levels of substrate within the immediate injection zone (close to 3 years) is double the duration that was intended during design of the treatability study. This suggests that the design estimates of non-specific substrate demand were high. Alternatively, the substrate may have persisted due to slow rates of biodegradation in a cold weather environment. Groundwater temperatures at the DP98 site are less than 10 degrees Celsius.

Chlorinated Aliphatic Hydrocarbons in Groundwater

CAHs detected in groundwater for each monitoring event are summarized in Table 7, and chlorinated ethenes (TCE, *cis*-DCE, and VC) over time are posted on Figure 2. Changes in concentration and molar fractions of chloroethenes over time for each monitoring well are included in Attachment B. The maximum initial concentration of TCE was detected at injection well DP98INJ-01 at 8,180 micrograms per liter ($\mu\text{g/L}$). The maximum initial concentration of *cis*-DCE was 6,340 $\mu\text{g/L}$ at injection well location DP98INJ-02. Vinyl chloride (VC) was not

detected in any well during the pre-injection sampling event. Low estimated levels (less than 110 µg/L) of 1,1-DCE and methylene chloride (MC) were also detected.

Within the injection zone (DP98INJ-01 through DP98INJ-03), concentrations of TCE decreased slightly in September 2005, but decreased dramatically to levels below detection in May/June 2006. Downgradient of the immediate injection location, concentrations of TCE from September 2005 to May/June 2006 were reduced from 1,220 to 294 at location DP98MW-05; and from 92F µg/L (estimated concentration) to less than 5.4 µg/L (detection limit) at location DP98MW-06. From July 2005 to September 2005, concentrations of *cis*-DCE in the injection well locations similarly decreased. However, from September 2005 to May/June 2006 concentrations of *cis*-DCE increased to over 10,000 µg/L at each of the injection well locations.

The initial decrease in both TCE and *cis*-DCE shortly after injection is interpreted to be a result of partitioning of chloroethenes into the vegetable oil substrate. It is difficult to attribute the decrease in both TCE and *cis*-DCE to reductive dechlorination. However, from September 2005 to May/June 2006, a dramatic decrease in TCE and a corresponding increase in *cis*-DCE indicates dechlorination of TCE to *cis*-DCE. VC was detected at an estimated concentration of 74F µg/L at location DP98INJ-02. This indicates that dechlorination of *cis*-DCE to VC was occurring, but only to a limited extent.

Total molar concentrations of chloroethenes (TCE+DCE+VC) increased at most locations from September 2005 to May/June 2006 (Attachment B). This is interpreted to be due, in part, to enhanced desorption of TCE and transformation of TCE to *cis*-DCE. *cis*-DCE has less affinity for sorption to the aquifer matrix and for partitioning into the vegetable oil substrate. As a result, a greater molar concentration of *cis*-DCE should be expected in the dissolved phase.

In September 2006, concentrations of TCE within the treatment zone remained less than detection limits, and concentrations of *cis*-DCE decreased by approximately 10 to 30 percent (with the exception of downgradient well DP98-MW06). This was suspected to be a result of depletion of TCE within the treatment zone, where the rate at which *cis*-DCE is degraded is greater than the rate at which it is produced by dechlorination of TCE (or lack of production from TCE).

Concentrations of TCE in June 2008 (35 months after injection) ranged from less than 1.0 µg/L up to 15 µg/L for the injection wells. TCE was detected at 120 µg/L in downgradient well DP98MW-05 and 32 µg/L in downgradient well DP98MW-06. Concentrations of TCE in the downgradient wells appear to be rebounding as concentrations of TOC have decreased, but the concentrations remain low compared to initial concentrations before injection.

Concentrations of *cis*-DCE in June 2008 remain elevated, while concentrations of VC have uniformly increased across the treatability study monitoring network. The highest concentration of VC was 200 µg/L at injection well DP98INJ-02, decreasing to 75 µg/L at downgradient well DP98MW-05 and to 45 µg/L at downgradient well DP98MW-06. Note that VC has not been produced in injection well DP98INJ-01, and concentrations of ethene and ethane remain low

(Table 6). It is apparent that the native microbial population has acclimated over time and is capable of limited reduction of *cis*-DCE to VC, but not of VC to ethene and ethane.

Total molar concentrations remain fairly stable for most wells (Attachment B), with a substantial increase at well DP98MW-05 (Figure B.5B). This suggests that a source of CAHs persists at the site. Changes in total molar concentration may be related to changes in the water table. Figure 5 plots changes in total molar concentration of chlorinated ethenes and water table elevation over time for wells DP98INJ-02 and DP98MW-05. It appears that there is an inverse relationship between total molar concentration and water table elevation; as the water table goes up, total molar concentrations go down. It should be noted that the DP98 wells are screened below the water table. In this case, there may be a higher rate of dilution of an upgradient source when groundwater levels are high. There does not appear to be any particular impact on degradation of TCE, as it primarily is degraded to *cis*-DCE for all events (see molar fraction plots in Appendix B).

Toxicity Reduction

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA) remediation evaluation processes require that each candidate technology be evaluated against nine criteria, including long-term effectiveness and the reduction of contaminant toxicity, mobility, and mass over time. A common concern of reductive dechlorination technologies is the generation of toxic dechlorination products, specifically VC. These dechlorination products have the potential to pose an equal or greater risk to human health and the environment than the parent compound of concern. VC is a known human carcinogen and has been assigned a federal maximum contaminant level (MCL) of 2.0 µg/L. The physiochemical properties of VC also make it more mobile in soil gas and groundwater than TCE.

Although decreases in TCE concentrations in groundwater at the DP98 Site have been accompanied by increases in intermediate dechlorination products (*cis*-DCE and VC), calculated toxicity equivalents provide quantitative evidence that the overall toxicity of the chloroethene compounds in groundwater has been substantially reduced. For this calculation, wells DP98INJ-01, DP98INJ-02, DP98INJ-03, DP98MW-05, and DP98MW-06 were used as they are located within the treatability study treatment zone.

Toxicity equivalents are calculated by dividing each compound's concentration by its MCL (Downey *et al.*, 2006). The overall plume toxicity equivalent is the sum of the individual compound's toxicity equivalents. In this way, a given concentration of a relatively toxic compound such as VC that has a relatively low MCL will yield a higher toxicity equivalent than the same concentration of a less toxic compound such as *cis*-DCE. This approach allows the degree to which the toxicity of site contaminants has changed over time to be quantified.

Based on a comparison of the July 2005 (baseline) chlorinated ethene concentrations, the overall toxicity reduction achieved in groundwater at the DP98 site was 35 percent in September

2005, 85 percent in September 2006, and 76 percent in June 2008 (Figure 3). Therefore, while reductive dechlorination of TCE is incomplete within the treatability study treatment zone, an overall net reduction in groundwater toxicity has been achieved. Furthermore, as of 2007 VC has not been detected in groundwater monitoring wells downgradient of the treatment zone (USAF, 2008), indicating that VC attenuates before reaching potential points of exposure in the downgradient wetlands. VC may degrade by a number of degradation processes, including aerobic and anaerobic oxidation. The creation of VC plumes that exceed the initial footprint of the parent CAHs (i.e., TCE and *cis*-DCE) is rarely observed in practice (AFCEE *et al.*, 2004).

Fuel Hydrocarbons in Groundwater

Fuel hydrocarbons detected in groundwater for each monitoring event are summarized in Table 8. Fuel releases also occurred at the DP98 site, which have induced reducing groundwater conditions. The occurrence of elevated levels of *cis*-DCE throughout much of the CAH plume at the DP98 site is attributed to these conditions. With the exception of well DP98MW-06, concentrations of benzene, toluene, ethylbenzene and xylenes (BTEX) are low within the pilot test area, typically less than 15 µg/L. Concentrations of ethylbenzene and m&p xylenes are higher at well DP98MW-06 (58 µg/L and 16 µg/L in June 2008, respectively), as is naphthalene (300 µg/L in June 2008). The presence of these fuel constituents may have induced reducing conditions, which may be one reason the initial concentration of TCE in July 2005 (140F µg/L) was lower at DP98MW-06 than any other location within the treatability study well network.

Groundwater Geochemistry

Biodegradation of an organic substrate depletes the aquifer of dissolved oxygen (DO) and lowers the oxidation-reduction potential (ORP), thereby stimulating conditions conducive to anaerobic biodegradation processes. After the DO is consumed, anaerobic microorganisms typically use native electron acceptors (as available) in the following order of preference: nitrate, manganese and ferric iron hydroxides or oxyhydroxides, sulfate, and finally carbon dioxide (methanogenesis). Evaluation of the distribution of these electron acceptors can provide evidence of where and how biodegradation of CAHs may occur. The following summarizes geochemical conditions within the pilot test area in June 2008, approximately 35 months after substrate injection (Table 6).

- ORP remained consistently at or below -25 millivolts (mV), measured relative to a silver/silver chloride (Ag/AgCl) reference electrode.
- Concentrations of DO generally remained less than 0.5 mg/L.
- Soluble manganese remained elevated at concentrations ranging from 31 to 66 mg/L.
- Concentrations of soluble ferrous iron in September 2006 ranged from 26 to 45 mg/L, but decreased to a range of 1.3 to 12 mg/L in June 2008.

- Concentrations of sulfate in upgradient well DP98MW-04 have ranged from 8.1 to 13 mg/L, and were less than 1.0 mg/L in all the treatment zone wells in September 2006. Concentrations of sulfate in June 2008 remained depleted relative to the upgradient location, but did increase to a range of 3.3 to 4.2 mg/L.
- Methane remained elevated in June 2008 at concentrations up to 16 mg/L.

The primary terminal electron accepting processes (TEAPs) occurring at the site are manganese reduction, iron reduction, and methanogenesis. Natural levels of sulfate at the site are low, less than 15 mg/L. ORP measurements are consistently in the manganese and iron reduction range. Measurement of ORP depends on the coupled oxidation-reduction reactions that are occurring in the aquifer, and likely reflect a mixture of the TEAPs that are occurring. The occurrence of methanogenesis indicates the reaction zone is sufficiently reducing for fermentation reactions to occur. This includes the generation of molecular hydrogen - the primary electron donor for reductive dechlorination of CAHs. This suggests that measurements of ORP at this site may not be a good indication of the potential for reductive dechlorination of CAHs to occur. Rather, levels of TOC, methane, and dissolved hydrogen may be better indicators that conditions are conducive to reductive dechlorination.

Impacts on Secondary Water Quality

Select dissolved metals (filtered samples for arsenic, selenium, and manganese) were analyzed in samples collected from wells along the axis of the treatment zone to determine the potential for degradation of secondary water quality (Table 9). Baseline levels of arsenic ranged from less than a detection limit of 0.010 mg/L up to 0.016 mg/L at well location DP98MW-06. After injection, concentrations of arsenic within the treatment zone ranged from 0.012 to 0.037 mg/L with the highest concentrations being measured in June 2008. This indicates that arsenic is only slightly elevated under the highly anaerobic conditions stimulated by substrate addition.

Baseline concentrations of dissolved manganese ranged from 8.0 mg/L up to 41M mg/L in the duplicate samples for location DP98MW-06. After injection, concentrations of manganese within the treatment zone ranged from 13M to 44M mg/L. Concentrations of manganese in June 2008 ranged from 21M to 25M mg/L. Overall, concentrations of manganese did not increase substantially above levels found at locations impacted by fuel hydrocarbons.

Baseline concentrations of selenium ranged from 0.0098F mg/L to 0.014F mg/L (estimated concentrations). Concentrations of selenium within the treatment zone after substrate injection ranged from 0.018F mg/L to 0.035 mg/L (duplicate sample for well DP98MW-06). Similar to arsenic, it appears that selenium was only slightly elevated following substrate injection.

For all samples, concentrations of selenium were below USEPA primary drinking water standards. Baseline levels of arsenic were less than or close to the USEPA primary drinking water standard, with a higher concentration above the MCL at location DP98MW-06. Concentrations of arsenic were only slightly higher than the standard within the treatment zone.

after substrate injection. Background and treatment zone concentrations of manganese are elevated above USEPA recommended secondary drinking water quality standard. The shallow groundwater at the DP98 is not a drinking water source, and the magnitude of the increase in concentrations of arsenic and selenium is likely to be limited to the anaerobic reactive zone. The effects of anaerobic groundwater conditions on secondary water quality should dissipate as the substrate is depleted over time and groundwater geochemistry returns to background conditions.

Microbial Evaluation

Because it was not known whether the microbial population at the DP98 site was capable of completely dechlorinating TCE to ethene, select groundwater samples were submitted for quantification of *Dehalococcoides* species and select reductase enzymes via the Bio-Dechlor Census analysis provided by Microbial Insights, Inc. Results of Bio-Dechlor Census targeted gene detection for both the DP98 and Kenney Plume sites are listed on Table 10.

It is clear from the distribution of chlorinated ethenes at the DP98 site that microorganisms capable of the sequential dechlorination of TCE to DCE, and of DCE to VC, exist at the site. However, levels of ethene and ethane have remained low and there is no indication that the microbial populations is capable of further dechlorination of VC. The Bio-Dechlor sample results indicate that *Dehalococcoides* species exist at only very low concentrations in groundwater. Only the sample collected from location DP98MW-05 had a detectable concentration of *Dehalococcoides* at a low estimated (J-flag) concentration of 1.73E-01 cells per milliliter. All other results for *Dehalococcoides* and the functional genes for TCE reductase, BAV1 VC reductase, and VC reductase enzymes were below method detection limits.

Results for the Kenney Plume were similarly non-detect. Microcosm studies using soil and groundwater from the Kenney Plume suggest that native dechlorinating populations are present at very low densities, and grow at a very slow rate in the cold water environment at Elmendorf AFB (GeoSyntec, 2007). The conversion of TCE to *cis*-DCE at both sites occurs with the onset of methanogenesis, and it is possible that the dechlorination of TCE to *cis*-DCE is carried out by non-*Dehalococcoides* species. Dechlorination of *cis*-DCE to VC has been observed only at the DP98 site, and the limited production of VC may reflect a low population density and rate of growth of *Dehalococcoides* species.

Substrate Depletion

Table 11 lists data for total biomass by phospholipid fatty acid (PLFA) analysis, TOC, and volatile fatty acids (VFAs). After injection, biomass generally increased by an order of magnitude within the DP98 treatment zone. Concentrations of TOC were the highest right after injection, with a maximum of 460 mg/L at location DP98MW-05 in September 2005. Concentrations of TOC remain elevated in the injection wells in June 2008, ranging from 100 to 290 mg/L. Concentrations of TOC were depleted close to initial concentrations in the downgradient wells, ranging from 10 mg/L at well DP98MW-05 to 18 mg/L at DP98MW-06.

The most prevalent VFAs measured in groundwater were propionic, acetic, and butyric acid (Table 11). The concentration of total VFAs was as high as 1,072 mg/L at well DP98MW-05 at two months after injection, presumably due to the migration and degradation of the sodium lactate included in the injection mixture. Lactate may be fermented to propionate and butyrate, or directly to acetate. Propionate and butyrate may then be further fermented to acetate. The eventual breakdown of propionate and butyrate to acetate is evident as the concentration of acetic acid relative to the other VFAs increases over time. These fermentation reactions produce molecular hydrogen, which is used as a primary electron donor during reductive dechlorination of CAHs.

Figure 4 plots the change in average TOC and total VFA concentrations for the three injection wells and the two downgradient monitoring wells. The average injection well concentration of TOC and total VFAs increased from September 2006 to June 2008, so it is not possible to extrapolate the depletion of organic substrate in the injection wells. Concentrations of TOC in the injection wells continues to be 100 mg/L or higher. TOC has decreased to initial concentrations in the two downgradient monitoring wells, and VFAs were below detection in June 2008. Therefore, the size of the reaction zone appears to have decreased to the immediate area of the injection wells.

SUMMARY

The treatability study at the DP98 site stimulated widespread dechlorination of TCE to *cis*-DCE over the 14 months of monitoring following injection, with only infrequent dechlorination of *cis*-DCE to VC. The amount of substrate applied was intended to stimulate highly reducing conditions for a period of approximately 18 months (USAF, 2005). After the treatability study was completed (USAF, 2007), it was not known how long the substrate injection would sustain anaerobic conditions suitable for anaerobic reductive dechlorination, or whether a native microbial population capable of further reduction of VC to ethene was present.

In June 2008, approximately 35 months after injection, concentrations of TCE within the immediate reaction zone continued to be reduced to concentrations less than or equal to 15 µg/L, a reduction of over 99 percent relative to initial concentrations. Concentrations of TCE at downgradient wells DP98MW-05 and DP98MW-06 rebounded to 120 µg/L and 32 µg/L, respectively. This is a moderate rebound compared to initial concentrations of 2,000 µg/L and 140F µg/L at wells DP98MW-05 and DP98MW-06, respectively.

Concentrations of *cis*-DCE remain elevated in June 2008, with the highest concentration of *cis*-DCE being 18,000 µg/L at location DP98MW-05. VC was detected at all but one well (DP98INJ-01) within the treatment zone, at concentrations up to 200 µg/L at DP98MW-05. This indicates that the native microbial population is capable of dechlorinating *cis*-DCE to VC, but only to a limited extent. This may be related to slow reaction kinetics for transformation of *cis*-DCE to VC. Further dechlorination of VC to ethene was not evident. Targeted gene detection using the Bio-Dechlor Census analysis indicates that only very low concentrations of *Dehalococcoides* are present in groundwater at the site.

Based on a comparison with the July 2005 (baseline) chlorinated ethene concentrations, the overall toxicity reduction achieved in groundwater at the DP98 site was 35 percent in September 2005, 85 percent in September 2006, and 76 percent in June 2008. Therefore, while sequential reductive dechlorination of TCE, *cis*-DCE, and VC is incomplete within the treatability study treatment zone, an overall net reduction in groundwater toxicity has been achieved and sustained.

The primary TEAPs occurring at the site are manganese reduction, iron reduction, and methanogenesis. Natural levels of sulfate at the site are low, less than 15 mg/L. ORP measurements are consistently in the manganese and iron reduction range, although methane concentrations in June 2008 remained as high as 16 mg/L. This indicates that anaerobic conditions suitable for reductive dechlorination of CAHs to occur has been sustained.

Concentrations of TOC remain elevated in the injection wells in June 2008, ranging from 100 to 290 mg/L. Concentrations of TOC were depleted close to initial concentrations in the downgradient wells. The average concentration of TOC and total VFAs in the injection wells increased from September 2006 to June 2008, so it is not possible to extrapolate when depletion of organic substrate will occur within the area of the injection wells. Based on decreasing concentrations of TOC and a moderate rebound in concentrations of TCE at downgradient wells DP98MW-05 and DP98-MW-6, the size of the effective reactive zone appears to have decreased to immediate area of the injection wells.

ENHANCED IN SITU BIOREMEDIATION AT ELMENDORF AFB, ALASKA

It appears that biotic reductive dechlorination (halorespiration) of TCE in the cold water environment at Elmendorf AFB is limited by low populations and slow growth rates of *Dehalococcoides* species. The toxicity of the groundwater plume may be reduced by dechlorination of TCE to *cis*-DCE or VC, but further dechlorination of *cis*-DCE and VC to ethene may not occur. Alternative treatment technologies such as *in situ* biogeochemical transformation, *in situ* chemical reduction (ISCR), aerobic co-metabolism, or *in situ* chemical oxidation (ISCO) could be considered as alternative technologies that reduce the potential for production of *cis*-DCE and VC.

AFCEE is currently demonstrating engineered biogeochemical transformation by addition of iron, sulfate, and organic substrates to create reactive iron sulfide minerals. Emulsified zero valent iron and other commercial products with fine iron particles (e.g., EHC[®]) also may stimulate chemical reduction of TCE. Aerobic cometabolism of TCE in the presence of dissolved oxygen and a co-substrate such as methane, propane, ammonia, or toluene is another potential treatment technology. It is unknown whether these processes can be successfully stimulated at Elmendorf AFB, but they may warrant consideration as alternate technologies that limit the production of intermediate dechlorination products.

Biogeochemical transformation and aerobic co-metabolism are dependent to a large degree on microbial processes, and rates of degradation may be slower in a low temperature environment such as at Elmendorf AFB. Biogeochemical transformation is dependent on iron and sulfate

reducing bacteria, which are likely to be more robust than microbes that directly facilitate reductive dechlorination of chlorinated solvents. Chemical reactions also may be temperature dependent, so technologies that use direct chemical reduction may occur at slower rates. Slower reaction rates may be mitigated in some cases by increasing the size of the reaction zone and the effective residence time of contaminants, although field pilot tests are recommended to evaluate field-scale reaction rates and the extent of degradation that can be achieved before implementing any new *in situ* technology at Elmendorf AFB..

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TABLES

TABLE 1
GROUNDWATER SAMPLING PROTOCOL AT THE DP98 SITE
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Location Identifier	Location Description	Aquifer Test Analysis	Water Level Measurement	Groundwater Analyses								
				VOCs ^{a/} (SW8260B)	Methane, Ethane, Ethene (AM20GAX)	Chloride, Sulfate (SW9056)	Total Organic Carbon (SW9060M)	Volatile Fatty Acids (AM21)	Molecular Screening (Microbial Insights)	Dissolved Metals (SW6010B) ^{b/}	Well Head Analyses ^{c/}	Mobile Lab Analyses ^{d/}
Injection Wells												
DP98INJ-01	Reaction Zone		1	1	1	1	1	1			1	1
DP98INJ-02	Reaction Zone	1	1	1	1	1	1	1	1	1	1	1
DP98INJ-03	Reaction Zone		1	1	1	1	1	1			1	1
Groundwater Monitoring Wells												
DP98MW-04	Upgradient	1	1	1	1	1	1	1	1	1	1	1
DP98MW-05	Downgradient	1	1	1	1	1	1	1	1		1	1
DP98MW-06	Downgradient		1	1	1	1	1	1		1	1	1
41755-WL04	Crossgradient		1	1	1	1	1				1	1
SUBTOTALS		3	7	7	7	7	7	6	3	3	7	7
QA/QC												
Duplicates				1	1	1	1	1	1	1	1	1
MS				1								
MSD				1								
Trip Blanks				1								
TASK TOTAL				11	8	8	8	7	4	4	8	8

^{a/} Volatile organic compounds (VOCs) include aromatic and chlorinated aliphatic hydrocarbons.

^{b/} Dissolved metals analyses include manganese, arsenic, and selenium.

^{c/} Well head analyses include dissolved oxygen, oxidation-reduction potential, pH, temperature, and conductivity.

^{d/} Mobile lab analyses include carbon dioxide, alkalinity, ferrous iron, hydrogen sulfide, and manganese.

TABLE 2
SUMMARY OF MONITORING WELL CONSTRUCTION
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Well/Borehole Identification	Monitoring Location	Completion Date	Well Diameter (inches)	Screened Interval (feet bgs) ^{a/}	Ground Elevation (feet amsl) ^{b/}	Elevation Top of Casing ^{c/} (feet amsl)	Survey Northing ^{d/} (feet)	Survey Easting ^{d/} (feet)	Survey Northing ^{e/} (meters)	Survey Easting ^{e/} (meters)
Injection Wells										
DP98INJ-01	Injection	19-Jul-05	2.0	21.5 - 31.5	195.9	198.54	2654492.74	1667584.43	6795683.77	347410.52
DP98INJ-02	Injection	21-Jul-05	2.0	21.0 - 31.0	196.1	199.03	2654499.24	1667593.72	6795685.62	347413.44
DP98INJ-03	Injection	21-Jul-05	2.0	21.0 - 31.0	196.1	199.02	2654504.47	1667601.67	6795687.10	347415.94
Monitoring Wells										
DP98-MW-04	20' Upgradient	21-Jul-05	2.0	20.5 - 30.5	196.5	199.28	2654480.95	1667604.04	6795679.91	347416.33
DP98MW-05	15' Downgradient	20-Jul-05	2.0	21.0 - 31.0	195.5	197.95	2654511.21	1667585.63	6795689.38	347411.15
DP98MW-06	30' Downgradient	20-Jul-05	2.0	21.0 - 31.0	194.7	197.32	2654523.99	1667577.96	6795693.38	347408.99
Existing Wells										
41755-WL04	Crossgradient	NA ^{f/}	2.0	20.1 - 30.1	195.2	198.07	2654548.03	1667630.68	6795699.96	347425.38
41755-WL05	Crossgradient	NA	2.0	13.3 - 23.3	193.6	196.79	2654488.55	1667509.86	6795683.54	347387.76

^{a/} feet bgs indicates depth in feet below ground surface.

^{b/} feet amsl indicates elevation in feet above mean sea level.

^{c/} Vertical coordinates in feet relative to North American Vertical Datum of 1988 (NAVD88).

^{d/} Horizontal coordinates in feet relative to Alaskan State Plane, North American Datum of 1983, Zone 4 (ASP-NAD83-Zone 4).

^{e/} Horizontal coordinates in meters relative to World Geodetic System of 1984, Universal Transverse Mercator Zone 6N (WGS84-UTM-6N).

^{f/} NA indicates data not available.

TABLE 3
SUMMARY OF GROUNDWATER ELEVATIONS
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Well/Borehole Identification	Date	Screened Interval (feet bgs) ^{a/}	Ground Surface (feet amsl) ^{b/}	Elevation Datum (feet amsl)	Depth to Water (feet btoc) ^{c/}	Groundwater Elevation (feet amsl)
Injection Wells						
DP98INJ-01	25-Jul-05	21.5 - 31.5	195.9	198.54	17.86	180.68
	30-Jul-05				17.29	181.25
	19-Sep-05				14.51	184.03
	30-May-06				17.10	181.44
	21-Sep-06				12.68	185.86
	19-Jun-08				15.78	182.76
DP98INJ-02	25-Jul-05	21.0 - 31.0	196.1	199.03	18.44	180.59
	30-Jul-05				17.94	181.09
	19-Sep-05				15.12	183.91
	30-May-06				17.60	181.43
	21-Sep-06				13.40	185.63
	19-Jun-08				16.27	182.76
DP98INJ-03	25-Jul-05	21.0 - 31.0	196.1	199.02	18.62	180.40
	30-Jul-05				18.03	180.99
	19-Sep-05				15.27	183.75
	30-May-06				17.65	181.37
	21-Sep-06				13.38	185.64
	19-Jun-08				16.62	182.40
Monitoring Wells						
DP98MW-04	25-Jul-05	20.5 - 30.5	196.5	199.28	18.48	180.80
	30-Jul-05				18.02	181.26
	19-Sep-05				14.80	184.48
	30-May-06				17.60	181.68
	21-Sep-06				13.10	186.18
	19-Jun-08				16.11	183.17
DP98MW-05	25-Jul-05	21.0 - 31.0	195.5	197.95	18.02	179.93
	30-Jul-05				17.46	180.49
	19-Sep-05				15.22	182.73
	30-May-06				17.49	180.46
	21-Sep-06				13.20	184.75
	19-Jun-08				16.53	181.42

TABLE 3 (Continued)
SUMMARY OF GROUNDWATER ELEVATIONS
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Well/Borehole Identification	Date	Screened Interval (feet bgs) ^{a/}	Ground Surface (feet amsl) ^{b/}	Elevation Datum (feet amsl)	Depth to Water (feet btoc) ^{c/}	Groundwater Elevation (feet amsl)
DP98MW-06	25-Jul-05	21.0 - 31.0	194.7	197.32	18.01	179.31
	30-Jul-05				17.56	179.76
	19-Sep-05				15.58	181.74
	30-May-06				17.50	179.82
	22-Sep-06				NM ^{d/}	NM
	19-Jun-08				16.56	180.76
41755-WL04	25-Jul-05	20.1 - 30.1	195.2	198.07	19.40	178.67
	30-Jul-05				19.27	178.80
	19-Sep-05				17.52	180.55
	30-May-06				18.80	179.27
	22-Sep-06				NM	NM
	19-Jun-08				17.82	180.25
41755-WL05	25-Jul-05	13.3 - 23.3	193.6	196.79	17.23	179.56
	30-Jul-05				17.30	179.49
	19-Sep-05				14.75	182.04
	30-May-06				16.70	180.09
	22-Sep-06				NM	NM
	19-Jun-08				NM	NM

^{a/} feet bgs indicates feet below ground surface.

^{b/} feet amsl indicates elevation in feet above mean sea level.

^{c/} feet btoc indicates depth in feet below top of casing.

^{d/} NM indicates datum not measured.

TABLE 4
HYDRAULIC CONDUCTIVITIES AND AVERAGE GROUNDWATER VELOCITIES
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Monitoring Well	Date	Rising or Falling Test	Screened Interval (ft bgs) ^{a/}	Casing Inside Diameter (inches)	Borehole Diameter (inches)	Casing Stickup (feet ags) ^{b/}	Filter Pack Porosity (percent)	Static Water Level (feet btoc) ^{c/}	Base Permeable Barrier (ft bgs)	Hydraulic Conductivity			Estimated Effective Porosity	Hydraulic Gradient (ft/ft) ^{e/}	Average Groundwater Velocity (ft/day)	Average Groundwater Velocity (ft/yr) ^{h/}	
										(K)							
										(ft/day) ^{d/}	(cm/sec) ^{e/}	(gpd/ft ²) ^{f/}					
DP98-INJ02																	
DP98INJ-02	30-Jul-05	Rising	21 - 31	2.0	8.25	2.5	0.35	18.44	35.0	1.69	5.97E-04	12.641	0.22	0.030	0.23	84	
DP98INJ-02	30-Jul-05	Falling	21 - 31	2.0	8.25	2.5	0.35	18.44	35.0	1.75	6.18E-04	13.090	0.22	0.030	0.24	87	
Average Baseline - 30 July 2005										1.72	6.07E-04	12.866	0.22	0.030	0.23	86	
DP98INJ-02	19-Sep-05	Rising	21 - 31	2.0	8.25	2.5	0.35	15.12	35.0	1.37	4.84E-04	10.248	0.22	0.054	0.34	123	
DP98INJ-02	19-Sep-05	Falling	21 - 31	2.0	8.25	2.5	0.35	15.12	35.0	1.50	5.30E-04	11.220	0.22	0.054	0.37	134	
Average - 19 September 2005										1.44	5.07E-04	10.734	0.22	0.054	0.35	129	
DP98INJ-02	1-Jun-06	Rising	21 - 31	2.0	8.25	2.5	0.35	17.60	35.0	1.04	3.67E-04	7.779	0.22	0.037	0.17	64	
DP98INJ-02	1-Jun-06	Rising	21 - 31	2.0	8.25	2.5	0.35	17.60	35.0	1.20	4.24E-04	8.976	0.22	0.037	0.20	74	
Average- 01 June 2006										1.12	3.95E-04	8.378	0.22	0.037	0.19	69	
DP98INJ-02	3-Oct-06	Rising	21 - 31	2.0	8.25	2.5	0.35	13.40	35.0	0.98	3.46E-04	7.330	0.22	0.041	0.18	67	
DP98INJ-02	3-Oct-06	Rising	21 - 31	2.0	8.25	2.5	0.35	13.40	35.0	1.01	3.57E-04	7.555	0.22	0.041	0.19	69	
Average - 03 October 2006										1.00	3.51E-04	7.443	0.22	0.041	0.19	68	
DP98INJ-02	20-Jun-08	Rising	21 - 31	2.0	8.25	2.5	0.35	13.40	35.0	1.47	5.19E-04	10.996	0.22	0.048	0.32	117	
DP98INJ-02	20-Jun-08	Rising	21 - 31	2.0	8.25	2.5	0.35	13.40	35.0	1.58	5.58E-04	11.818	0.22	0.048	0.34	126	
Average - 20 June 2008										1.53	5.38E-04	11.407	0.22	0.048	0.33	121	
DP98-MW04																	
DP98MW-04	30-Jul-05	Rising	20.5 - 30.5	2.0	8.25	2.5	0.35	18.48	35.0	0.07	2.47E-05	0.524	0.22	0.030	0.01	3.5	
	30-Jul-05	Falling	20.5 - 30.5	2.0	8.25	2.5	0.35	18.48	35.0	0.11	3.88E-05	0.823	0.22	0.030	0.02	5.5	
Average Baseline - 30 July 2005										0.09	3.18E-05	0.673	0.22	0.030	0.01	4.5	
DP98MW-04	19-Sep-05	Rising	20.5 - 30.5	2.0	8.25	2.5	0.35	14.80	35.0	0.23	8.12E-05	1.720	0.22	0.054	0.06	21	
	19-Sep-05	Falling	20.5 - 30.5	2.0	8.25	2.5	0.35	14.80	35.0	0.32	1.13E-04	2.394	0.22	0.054	0.08	29	
Average - 19 September 2005										0.28	9.71E-05	2.057	0.22	0.054	0.07	25	
DP98MW-04	1-Jun-06	Rising	20.5 - 30.5	2.0	8.25	2.5	0.35	17.60	35.0	0.58	2.05E-04	4.338	0.22	0.037	0.10	36	
Average- 01 June 2006										0.58	2.05E-04	4.338	0.22	0.037	0.10	36	
DP98MW-04	3-Oct-06	Rising	20.5 - 30.5	2.0	8.25	2.5	0.35	13.10	35.0	0.42	1.48E-04	3.142	0.22	0.041	0.08	29	
	3-Oct-06	Rising	20.5 - 30.5	2.0	8.25	2.5	0.35	13.10	35.0	0.47	1.66E-04	3.516	0.22	0.041	0.09	32	
Average - 03 October 2006										0.45	1.57E-04	3.329	0.22	0.041	0.08	30	
DP98MW-04	20-Jun-08	Rising	20.5 - 30.5	2.0	8.25	2.5	0.35	13.10	35.0	0.44	1.55E-04	3.291	0.22	0.048	0.10	35	
	20-Jun-08	Rising	20.5 - 30.5	2.0	8.25	2.5	0.35	13.10	35.0	0.49	1.73E-04	3.665	0.22	0.048	0.11	39	
Average - 20 June 2008										0.47	1.64E-04	3.478	0.22	0.048	0.10	37	

TABLE 4 (Continued)
HYDRAULIC CONDUCTIVITIES AND AVERAGE GROUNDWATER VELOCITIES
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Monitoring Well	Date	Rising or Falling Test	Screened Interval (ft bgs) ^{a/}	Casing Inside Diameter (inches)	Borehole Diameter (inches)	Casing Stickup (feet ags) ^{b/}	Filter Pack Porosity (percent)	Static Water Level (feet btoc) ^{c/}	Base Permeable Barrier (ft bgs)	Hydraulic Conductivity			Estimated Effective Porosity	Hydraulic Gradient (ft/ft) ^{e/}	Average Groundwater Velocity (ft/day)	Average Groundwater Velocity (ft/yr) ^{h/}	
										(K)							
										(ft/day) ^{d/}	(cm/sec) ^{e/}	(gpd/ft ²) ^{f/}					
DP98-MW05																	
DP98MW-05	30-Jul-05	Rising	21 - 31	2.0	8.25	2.5	0.35	18.02	35.0	0.65	2.29E-04	4.862	0.22	0.030	0.09	32	
	30-Jul-05	Falling	21 - 31	2.0	8.25	2.5	0.35	18.02	35.0	0.70	2.47E-04	5.236	0.22	0.030	0.10	35	
Average Baseline - 30 July 2005										0.68	2.38E-04	5.049	0.22	0.030	0.09	34	
DP98MW-05	19-Sep-05	Rising	21 - 31	2.0	8.25	2.5	0.35	15.22	35.0	0.78	2.75E-04	5.834	0.22	0.054	0.19	70	
	19-Sep-05	Falling	21 - 31	2.0	8.25	2.5	0.35	15.22	35.0	0.76	2.68E-04	5.685	0.22	0.054	0.19	68	
Average - 19 September 2005										0.77	2.72E-04	5.760	0.22	0.054	0.19	69	
DP98MW-05	1-Jun-06	Rising	21 - 31	2.0	8.25	2.5	0.35	17.49	35.0	0.64	2.26E-04	4.787	0.22	0.037	0.11	39	
	1-Jun-06	Rising	21 - 31	2.0	8.25	2.5	0.35	17.49	35.0	0.68	2.40E-04	5.086	0.22	0.037	0.11	42	
Average- 01 June 2006										0.66	2.33E-04	4.937	0.22	0.037	0.11	41	
DP98MW-05	3-Oct-06	Rising	21 - 31	2.0	8.25	2.5	0.35	13.20	35.0	0.62	2.19E-04	4.638	0.22	0.041	0.12	42	
	3-Oct-06	Rising	21 - 31	2.0	8.25	2.5	0.35	13.20	35.0	0.70	2.47E-04	5.236	0.22	0.041	0.13	48	
Average - 03 October 2006										0.66	2.33E-04	4.937	0.22	0.041	0.12	45	
DP98MW-05	20-Jun-08	Rising	21 - 31	2.0	8.25	2.5	0.35	13.20	35.0	0.47	1.66E-04	3.516	0.22	0.048	0.10	37	
	20-Jun-08	Rising	21 - 31	2.0	8.25	2.5	0.35	13.20	35.0	0.48	1.69E-04	3.590	0.22	0.048	0.10	38	
Average - 20 June 2008										0.48	1.68E-04	3.553	0.22	0.048	0.10	38	
DP98MW-06																	
DP98MW-06	30-Jul-05	Rising	21 - 31	2.0	8.25	2.5	0.35	18.01	35.0	1.21	4.27E-04	9.051	0.22	0.030	0.17	60	
	30-Jul-05	Falling	21 - 31	2.0	8.25	2.5	0.35	18.01	35.0	1.13	3.99E-04	8.452	0.22	0.030	0.15	56	
Average Baseline - 30 July 2005										1.17	4.13E-04	8.752	0.22	0.030	0.16	58	
DP98MW-06	19-Sep-05	Rising	21 - 31	2.0	8.25	2.5	0.35	15.58	35.0	1.55	5.47E-04	11.594	0.22	0.054	0.38	139	
	19-Sep-05	Falling	21 - 31	2.0	8.25	2.5	0.35	15.58	35.0	1.24	4.38E-04	9.275	0.22	0.054	0.30	111	
Average - 19 September 2005										1.40	4.92E-04	10.435	0.22	0.054	0.34	125	
DP98MW-06	1-Jun-06	Rising	21 - 31	2.0	8.25	2.5	0.35	17.50	35.0	1.67	5.90E-04	12.492	0.22	0.037	0.28	103	
	1-Jun-06	Rising	21 - 31	2.0	8.25	2.5	0.35	17.50	35.0	1.68	5.93E-04	12.566	0.22	0.037	0.28	103	
Average- 01 June 2006										1.68	5.91E-04	12.529	0.22	0.037	0.28	103	
DP98MW-06	3-Oct-06	Rising	21 - 31	2.0	8.25	2.5	0.35	NM	35.0	1.55	5.47E-04	11.594	0.22	0.041	0.29	105	
	3-Oct-06	Rising	21 - 31	2.0	8.25	2.5	0.35	NM	35.0	1.44	5.08E-04	10.771	0.22	0.041	0.27	98	
Average - 03 October 2006										1.50	5.28E-04	11.183	0.22	0.041	0.28	102	

^{a/} ft bgs = feet below ground surface.

^{b/} ft ags = feet above ground surface.

^{c/} ft btoc = feet below top of casing.

^{d/} ft/day = feet per day.

^{e/} cm/sec = centimeters per second.

^{f/} gpd/ft² = gallons per day per square feet.

^{g/} ft/ft = foot per foot.

^{h/} ft/yr = foot per year.

TABLE 5
SUBSTRATE INJECTION SCENARIO
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Well ID	Injection Points		Emulsion Injection Mixture						Post-Emulsion Push			Total Volume		Injection Interval (feet)	Estimated Effective Porosity (percent)	Radius of Influence (feet)
	Injection Interval (feet)	Injection Spacing (feet)	Product Volume (gallons)	Soybean Oil Component (gallons) (pounds)		WillClear		Makeup Water (gallons)	WillClear		Makeup Water (gallons)	Substrate (pounds)	Water/ Substrate (gallons)			
						Volume (gallons)	Lactic Acid (pounds)		Volume (gallons)	Lactic Acid (pounds)						
DP98INJ-01	20-30	10	36	21	166	20.0	106	675	10.0	53	340	326	1,081	10	22%	4.6
DP98INJ-02	20-30	10	38	22	175	20.4	108	707	10.0	53	350	336	1,125	10	22%	4.7
DP98INJ-03	20-30	10	36	21	167	29.6	157	682	10.0	53	340	378	1,098	10	22%	4.6
TOTAL:			110	65	509	70	372	2,064	30	159	1,030	1,040	3,304			
SUBSTRATE CONCENTRATIONS																
Final Percent Substrate by Weight:			4.0%		Final Lactic Acid Concentration:			19.3	grams/liter			Percent Oil by Volume in Emulsion:			2.9%	
Final Percent Water by Weight:			96.0%		Final Oil Concentration:			18.5	grams/liter			Final Residual Percent Oil by Volume:			2.0%	
NOTES: Sodium Lactate Product																
1. Assumes WillClear sodium lactate product is 60 percent sodium lactate by weight.																
2. Molecular weight of sodium lactate (CH ₃ -CHOH-COONa) = 112.06.																
3. Molecular weight of lactic acid (C ₆ H ₆ O ₃) = 90.08.																
4. Specific gravity of WillClear Product = 1.323 @ 20 degrees Celsius.																
5. Weight of WillClear Product = 11.0 pounds per gallon.																
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H ₂ O x 0.60 x (90.08/112.06) = 5.31 lb/gal.																
NOTES: Vegetable Oil Emulsion Product																
1. Assumes emulsion product is 60 percent soybean oil by weight.																
2. Soybean oil is 7.8 pounds per gallon.																

TABLE 6
GROUNDWATER GEOCHEMICAL DATA
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Sample Location	Sample Date	Temp (°C) ^{a/}	pH (su) ^{b/}	Conductivity (µS/cm) ^{c/}	Dissolved Oxygen (mg/L) ^{d/}	Redox Potential (mV) ^{e/}	Total Organic Carbon (mg/L)	Total VFAs (mg/L)	Nitrate-Nitrite (as N) (mg/L)	Manganese (mg/L)	Ferrous Iron (mg/L)	Sulfate (mg/L)	Hydrogen Sulfide (mg/L)	Chloride (mg/L)	Bromide (mg/L)	Carbon Dioxide (mg/L)	Alkalinity (mg/L)	Dissolved Hydrogen (nM) ^{f/}	Methane (µg/L) ^{g/}	Ethene (µg/L)	Ethane (µg/L)
Upgradient Location																					
DP98MW-04	26-Jul-05	10.9	6.86	1,015	0.80	-288	11	ND ^{h/}	0.06	8.0	0.3	12	<0.1	83	1.0 F ^{i/}	>200	357	NA ^{j/}	130	27	17
	20-Sep-05	9.8	6.66	605	2.11	-65	8.9	ND	<0.05	8.8	3.5	12	0.11	65	1.0 F	262	292	NA	280	10	6.3
	2-Jun-06	8.2	6.68	420	0.30	-89	8.6	ND	<0.05	8.1	3.0	8.2	0.11	36	1.0 F	320	364	1.50	220	2.1	1.0
	21-Sep-06	7.6	6.76	571	0.16	-136	6.4	0.5	0.08	4.7	7.5	13	0.04	38	1.1	320	345	NA	190	1.9	1.1
	19-Jun-08	8.5	6.80	439	0.24	-85	1.9 F	ND	NA	10.5	3.0	8.1	0.03	26	NA	174	514	NA	150 M ^{k/}	0.42	0.21
Injection Locations																					
DP98INJ-01	25-Jul-05	7.4	6.59	1,039	0.90	-84	8.9	ND	<0.05	8.6	0.8	7.1	<0.10	97	1.0 F	260	357	NA	240	1.2	0.94
	19-Sep-05	8.6	6.78	1,690	0.59	-108	270	617	<0.05	16	4.0	3.0	0.06	82	13	344	620	NA	440	1.4	1.1
	1-Jun-06	7.5	6.75	2,100	0.24	-103	110	166	0.02 F	20	19	1.6	0.02	66	4.6	502	470	NA	8,400	3.2	5.5
	21-Sep-06	7.4	6.86	1,020	0.09	-69	110	179	0.03 F	19	29	<1.0	0.03	62	2.8	460	620	NA	10,000	1.6	0.84
	19-Jun-08	7.0	6.70	1,220	0.76	-69	130	279	NA	41	1.8	4.2	0.12	49	NA	468	912	NA	16,000 M	1.2	0.39
DP98INJ-02	26-Jul-05	8.0	6.49	992	1.06	-26	10	ND	0.03 F	9.3	2.0	4.6	0.2	84	NA	425	374	NA	650	0.48	0.19
	19-Sep-05	8.7	6.74	1,550	0.92	-80	240	740	<0.050	13	4.4	3.2	0.10	78	12	562	608	NA	630	0.73	0.43
	2-Jun-06	7.8	6.48	1,139	0.40	-61	260	369	<0.05	16	24	2.4	0.02	53	6.6	510	856	3.80	6,500	1.00	0.20
	21-Sep-06	7.6	6.60	1,027	0.13	-14	170	321	0.04 F	22	29	0.74 F	0.03	65	4.5	600	680	NA	9,900	1.3	0.42
	19-Jun-08	7.6	6.52	1,098	0.20	-25	290	354	NA	66	7.2	3.5	0.07	47	NA	508	780	NA	15,000 M	1.2	0.18
DP98INJ-03	26-Jul-05	7.2	6.51	980	0.80	14	10	ND	0.06	7.9	0.5	6.1	<0.1	83	1.1	>200	340	NA	820	0.15	0.090
	19-Sep-05	8.3	6.84	843	0.61	-86	130	317	<0.05	8.5	3.2	3.0	0.09	77	7.3	396	596	NA	790	0.91	0.58
	31-May-06	7.0	6.85	359	0.28	-83	110	163	0.02 F	19	13	1.7	0.01	67	5.3	640	612	NA	12,000	2.0	0.20
	21-Sep-06	7.4	6.86	1,095	0.16	-43	120	173	0.03 F	20	26	0.94 F	<0.01	78	3.7	560	720	NA	13,000	1.3	0.53
	19-Jun-08	7.2	6.71	1,118	0.27	-70	100	214	NA	31	1.3	3.3	0.12	71	NA	620	760	NA	16,000 M	0.96	0.16
Downgradient Locations																					
DP98MW-05	25-Jul-05	7.2	6.51	959	0.66	-61	12	ND	<0.05	13	3.5	4.7	<0.1	73	1.0 F	300	374	NA	590	0.43	0.37
	20-Sep-05	7.3	6.54	2,140	0.74	-70	460	1,072	<0.05	46	18	3.1	1.00	83	31	482	754	NA	600	0.67	0.32
	2-Jun-06	6.9	6.57	949	0.45	-92	320	659	<0.05	41	30	1.7	0.01	81	12	432	1,094	3.30	1,900	1.5	0.24
	21-Sep-06	7.1	6.75	1,287	0.18	-55	96	272	0.04 F	31	32	0.74 F	0.06	65	6.9	740	860	NA	7,400	2.6	0.68
	19-Jun-08	8.4	6.91	942	0.26	-59	10	1.2	NA	45	5.9	3.9	<0.01	48	NA	716	500	NA	8,600 M	0.95	0.25
DP98MW-06	25-Jul-05	7.1	6.18	921	0.24	-98	19	ND	<0.05	21	3.9	3.1	0.1	47	NA	>250	391	NA	3,200	2.3	1.2
	20-Sep-05	7.0	6.48	1,720	0.68	-80	300	687	<0.05	25	38	3.0	0.05	65	20	458	634	NA	3,400	2.6	1.4
	1-Jun-06	6.8	6.55	2,800	0.20	-81	100	145	<0.05	39	32	1.6	0.01	66	6.5	642	780	NA	920	0.17	0.015
	22-Sep-06	6.6	6.72	1,075	0.17	-64	91	130	0.03 F	38	45	<1.0	<0.01	55	5.6	740	790	NA	10,000	1.6	0.36
	19-Jun-08	6.6	6.64	725	0.27	-54	18	ND	NA	35	12	3.4	0.02	24	NA	436	604	NA	12,000 M	0.82	0.13

TABLE 6 (Continued)
GROUNDWATER GEOCHEMICAL DATA
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Sample Location	Sample Date	Temp (°C) ^{a/}	pH (su) ^{b/}	Conductivity (µS/cm) ^{c/}	Dissolved Oxygen (mg/L) ^{d/}	Redox Potential (mV) ^{e/}	Total Organic Carbon (mg/L)	Total VFAs (mg/L)	Nitrate-Nitrite (as N) (mg/L)	Manganese (mg/L)	Ferrous Iron (mg/L)	Sulfate (mg/L)	Hydrogen Sulfide (mg/L)	Chloride (mg/L)	Bromide (mg/L)	Carbon Dioxide (mg/L)	Alkalinity (mg/L)	Dissolved Hydrogen (nM) ^{f/}	Methane (µg/L) ^{g/}	Ethene (µg/L)	Ethane (µg/L)
Crossgradient Location																					
41755-WL04	26-Jul-05	6.3	6.44	1,020	0.15	11	6.9	NA	<0.05	NA	2.0	5.4	<0.1	110	NA	400	340	NA	1,100	0.073	0.028
	19-Sep-05	7.2	6.98	1,180	0.88	-90	50	NA	<0.05	8.7	3.0	3.1	0.01	100	3.9	220	510	NA	1,300	0.23	0.083
	31-May-06	6.2	7.00	644	0.49	-123	7.3	NA	NA	14.0	3.2	2.1	<0.01	120	3.9	372	600	NA	3,800	0.34	0.076
	22-Sep-06	6.6	6.88	836	0.15	-34	3.6 F	NA	0.03 F	12.3	8.7	0.68 F	<0.01	57	5.6	310	555	NA	3,800	0.38	0.12
	19-Jun-08	6.8	6.90	737	0.24	-59	2.5 F	NA	NA	18.1	1.6	3.7	0.02	97	NA	276	470	NA	5,800 M	0.37	0.076
Quality Assurance/Quality Control Samples																					
DP98INJ-13 (dup)	26-Jul-05	--	--	--	--	--	11	--	<0.05	--	0.5	5.6	<0.1	89	NA	>200	340	NA	870	0.13	0.076
DP98MW-15 (dup)	20-Sep-05	--	--	--	--	--	480	--	<0.05	18	45	<1.0	1.00	83	29	496	750	NA	550	0.92	0.43
DP98MW-02 (dup)	2-Jun-06	--	--	--	--	--	240	--	<0.05	17	23	2.3	0.01	58	5.8	496	840	3.00	4,900	0.77	0.17
DP98MW-11 (dup)	21-Sep-06	--	--	--	--	--	110	--	0.04 F	--	--	0.73 F	--	62	2.7	--	--	NA	9,800	1.5	0.75
DP98MW-04 (dup)	19-Jun-08	--	--	--	--	--	--	--	--	10.0	2.7	--	0.03	--	--	170	502	--	--	--	--
DP98INJ-12 (dup)	19-Jun-08	--	--	--	--	--	290	--	--	--	--	3.5	--	47	--	--	--	--	14,000 M	1.2	0.17

^{a/} °C = degrees Centigrade.

^{b/} su = standard pH units.

^{c/} µS/cm = microsiemens per centimeter.

^{d/} mg/L = milligrams per liter.

^{e/} mV = millivolts.

^{f/} nM = nanomoles.

^{g/} µg/L = micrograms per liter.

^{h/} ND = not detected.

^{i/} F-flag indicates the concentration is below the laboratory reporting limit but above the method detection limit, and the concentration is estimated.

^{k/} M-flag indicates recovery/RPD poor for MS/MSD or sample/duplicate.

TABLE 7
SUMMARY OF CHLORINATED ALIPHATIC HYDROCARBONS DETECTED IN GROUNDWATER
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Sample Identification	Sampling Location	Sample Date	Months	Dilution Factor	PCE ^{a/}	TCE ^{a/}	cis -1,2-DCE ^{a/}	trans -1,2-DCE	1,1-DCE	VC ^{a/}	1,1-DCA ^{a/}	Chloroform	Methylene Chloride	Chloro-methane	Acetone	2-Butanone
			from Injection		(µg/L) ^{b/}	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)
Upgradient Location																
DP98MW-04	20' Upgradient	26-Jul-05	0	200	<9.20 ^{c/}	2,040	2,880	<7.80	<4.40	<6.20	<4.4	<4.6	108 F ^{d/}	<6.8	<46.0	<140
		19-Sep-05	2	200	<9.20	5,680	2,430	<7.80	<4.40	<6.20	<4.40	<4.60	<17.8	<6.80	342 F	<136
		2-Jun-06	10	200	<6.00	4,370	4,330	<5.40	<9.20	<7.60	<6.60	<5.80	32.0 F	<25.2	<165	<130
		21-Sep-06	14	200	<6.00	4,340	2,840	<5.40	<9.20	<7.60	<6.60	<5.80	<6.80	<25.2	<165	<130
		19-Jun-08	35	1	<1.0	3200 B (50X)	3,300 B (50X)	5.0	16	1.2	<1.0	<1.0	<1.0	1.2	<10	<5.0
Injection Wells																
DP98INJ-01	Injection	25-Jul-05	0	200	<9.20	8,180	4,470	<7.80	<4.40	<6.20	<4.40	<4.60	60.0 F	<6.80	<46.0	<140
		19-Sep-05	2	200	<9.20	5,150	3,740	<7.80	<4.40	<6.20	<4.40	<4.60	<17.8	<6.80	342 F	<136
		1-Jun-06	10	200	<6.00	<5.4	10,100	<5.40	36.0 F	<7.60	<6.60	<5.80	44.0 F	<25.2	<165	<130
		21-Sep-06	14	500	<15.0	<13.5	9,080	<13.5	<23.0	<19.0	<16.5	<14.5	<17.0	<63.0	<412	<324
		19-Jun-08	35	1	<1.0	6.4	8,700 B (50X)	25	42	<1.0	<1.0	<1.0	<1.0	26	11	<5.0
DP98INJ-02	Injection	26-Jul-05	0	200	<9.20	4,920	6,340	<7.80	22.0 F	<6.20	<4.4	<4.60	84.0 F	<6.80	<46.0	<140
		19-Sep-05	2	200	<9.20	1,980	4,690	<7.80	<4.40	<6.20	<4.40	<4.60	<17.8	<6.80	346 F	<136
		2-Jun-06	10	200	<6.00	<5.40	11,100	<5.40	44.0F	74.0 F	<6.60	<5.80	32.0 F	<25.2	<165	<130
		21-Sep-06	14	500	<15.0	<13.5	7,820	<13.5	<23.0	<19.0	<16.5	<14.5	<17.0	<63.0	<412	<324
		19-Jun-08	35	1	<1.0	15	11,000 B (50X)	24	44	200 (50X)	1.2	<1.0	<1.0	9.0	2.7 F	<5.0
DP98INJ-03	Injection	26-Jul-05	0	200	<9.20	2,810	5,540	<7.80	22.0 F	<6.20	<4.40	<4.60	72.0 F	<6.80	<46.0	<140
		19-Sep-05	2	200	<9.20	2,730	3,980	<7.80	<4.40	<6.20	<4.40	<4.60	<17.8	<6.80	278 F	<136
		31-May-06	10	500	<15.0	<13.5	10,100	<13.5	<23.0	<19.0	<16.5	<14.5	60.0 F	<63.0	<412	<324
		21-Sep-06	14	500	<15.0	<13.5	6,320	<13.5	<23.0	<19.0	<16.5	<14.5	<17.0	<63.0	<412	<324
		19-Jun-08	35	1	<1.0	<1.0	5,500 B (50X)	13	24	120	<1.0	<1.0	<1.0	4.0	6.6 F	<5.0
Downgradient Wells																
DP98MW-05	10' Downgradient	25-Jul-05	0	200	<9.20	2,000	5,730	<7.80	24.0 F	<6.20	<4.4	<4.6	64.0 F	<6.8	<46.0	<140
		20-Sep-05	2	200	<9.20	1,220	6,630	<7.80	22.0 F	<6.20	<4.40	<4.60	<17.8	<6.80	236 F	<136
		2-Jun-06	10	200	<6.00	294	12,400	<5.40	40.0 F	<7.60	<6.60	<5.80	32.0 F	<25.2	<165	<130
		21-Sep-06	14	500	<15.0	<13.5	9,750	<13.5	<23.0	<19.0	<16.5	<14.5	<17.0	<63.0	<412	<324
		19-Jun-08	35	1	<1.0	120	18,000 (200X)	43	83	75	1.2	<1.0	<1.0	1.5	6.8 F	<5.0
DP98MW-06	20' Downgradient	25-Jul-05	0	200	<9.20	140 F	4,440	<7.80	<4.40	<6.20	<4.4	<4.6	98.0 F	<6.8	<46.0	<140
		20-Sep-05	2	200	<9.20	92.0 F	5,430	<7.80	<4.40	<6.20	<4.40	<4.60	<17.8	<6.80	296 F	<136
		1-Jun-06	10	200	<6.00	<5.40	6,850	20.0 F	<9.20	<7.60	<6.60	<5.80	26.0 F	<25.2	<165	<130
		22-Sep-06	14	200	<6.00	20.0 F	7,120	<5.40	<9.20	<7.60	<6.60	<5.80	32.0 F	<25.2	<165	<130
		19-Jun-08	35	1	<1.0	32	5,900 B (50X)	21	29	45	<1.0	<1.0	<1.0	1.6	3.6 F	<5.0

TABLE 7 (Continued)
SUMMARY OF CHLORINATED ALIPHATIC HYDROCARBONS DETECTED IN GROUNDWATER
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Sample Identification	Sampling Location	Sample Date	Months	Dilution Factor	PCE ^{a/}	TCE ^{a/}	cis -1,2-DCE ^{a/}	trans -1,2-DCE	1,1-DCE	VC ^{a/}	1,1-DCA ^{a/}	Chloroform	Methylene Chloride	Chloro-methane	Acetone	2-Butanone
			from Injection		(µg/L) ^{b/}	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	
Crossgradient Wells																
41755-WL04	Crossgradient	26-Jul-05	0	200	<9.20	2,680	3,850	<7.80	<4.40	<6.20	<4.4	<4.6	94.0 F	<6.8	<46.0	<140
		20-Sep-05	2	200	<9.20	2,140	3,740	<7.80	<4.40	<6.20	<4.40	<4.60	<17.8	<6.80	276 F	<136
		31-May-06	10	200	<6.00	386	6,950	<5.40	<26.0	<7.60	<6.60	<5.80	22.0 F	<25.2	<165	<130
		22-Sep-06	14	200	<6.00	688	4,670	<5.40	<26.0	<7.60	<6.60	<5.80	<6.80	<25.2	<165	<130
		19-Jun-08	35	1	<1.0	360 B (50X)	5,700 B (50X)	9.3	30	15	<1.0	<1.0	<1.0	2.2	<10	<5.0
Injection Makeup Tank Water																
Tank Water	--	26-Jul-05	0	200	<9.20	2,280	4,830	<7.80	<4.40	<6.20	<4.4	<4.6	56.0 F	<6.8	<46.0	<140
Quality Assurance/Quality Control Samples																
DP98INJ-04	Dup of INJ-01	25-Jul-05	0	200	<9.20	8,140	4,360	<7.80	<4.40	<6.20	<4.4	<4.6	102 F	<6.8	<46.0	<140
DP98MW-16	Dup of MW-06	22-Sep-05	2	200	<9.20	80.0 F	5,330	<7.80	<4.40	<6.20	<4.40	<4.60	<17.8	<6.80	324 F	<136
DP98MW-02	Dup of INJ-02	2-Jun-06	10	200	<6.00	<5.40	10,800	<5.40	38.0 F	54.0 F	<6.60	<5.80	32.0 F	<25.2	<165	<130
DP98INJ-11	Dup of INJ-01	21-Sep-06	14	500	<15.0	<13.5	9,340	<13.5	<23.0	<19.0	<16.5	<14.5	50.0 F	<63.0	<412	<324
DP98INJ-12	Dup of INJ-02	19-Jun-08	35	1	<1.0	4.4	12,000 (100X)	23	44	200 (50X)	1.2	<1.0	<1.0	4.7	<10	<5.0
TB-1	--	25-Jul-05	0	1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<2.0	<1.0	<10	<10
TB-2	--	20-Sep-05	2	1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<2.0	<1.0	1.25 F	<10
TB-3	--	2-Jun-06	10	1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<2.0	<1.0	<10	<10
TB-4	--	21-Sep-06	14	1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<2.0	<1.0	<10	<10
TB-2-06-2008	--	19-Jun-08	35	1	<1.0	<1.0	1.8 B	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<10	<5.0

^{a/} PCE = tetrachloroethene, TCE = trichloroethene, DCE = dichloroethene, VC = vinyl chloride, DCA = dichloroethane.

^{b/} µg/L = micrograms per liter.

^{c/} less than (<) indicates the concentration is below the indicated laboratory reporting limit.

^{d/} F-flag indicates the concentration is below the laboratory reporting limit but above the method detection limit, and the concentration is estimated.

^{d/} B-flag indicates the analyte was detected in the method blank. "(X50)" indicates this analyte was re-run at a higher dilution to bring the analyte within the method calibration range.

TABLE 8
SUMMARY OF FUEL HYDROCARBONS DETECTED IN GROUNDWATER
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Sample Identification	Sampling Location	Sample Date	Months from Injection	Dilution Factor	Benzene (µg/L) ^{a/}	Toluene (µg/L)	Ethyl-benzene (µg/L)	o-Xylene (µg/L)	m&p-Xylene (µg/L)	Napthalene (µg/L)	1,2,4-Trimethylbenzene (µg/L)	Isopropylbenzene (µg/L)	n-Propylbenzene (µg/L)
Upgradient Location													
DP98MW-04	20' Upgradient	26-Jul-05	0	200	<3.40	<3.20	<5.00	<7.00	<8.20	40.0 F ^{b/}	<4.80	<3.00	<2.40
		19-Sep-05	2	200	<3.40	<3.20	<5.00	<7.00	<8.20	<25.4	<4.80	<3.00	<2.40
		2-Jun-06	10	200	<2.00	<3.60	<4.80	<2.80	<5.60	<4.80	<2.40	<4.20	<1.80
		21-Sep-06	14	200	<2.00	<3.60	<4.80	<2.80	<5.60	<4.80	<2.40	<4.20	<1.80
		19-Jun-08	35	1	<1.0	<1.0	<1.0	<1.0	<2.0	20	<1.0	1.4	<1.0
Injection Wells													
DP98INJ-01	Injection	25-Jul-05	0	200	<3.40	<3.20	<5.00	<7.00	<8.20	<25.0	<4.80	<3.00	<2.40
		19-Sep-05	2	200	<3.40	<3.20	<5.00	<7.00	<8.20	<25.4	<4.80	<3.00	<2.40
		1-Jun-06	10	200	<2.00	<3.60	<4.80	<2.80	<5.60	58.0 F	<2.40	<4.20	<1.80
		21-Sep-06	14	500	<5.00	<9.00	<12.0	<7.00	<14.0	<12.0	<6.00	<10.5	<4.50
		19-Jun-08	35	1	1.6	<1.0	2.4	<1.0	<2.0	36	1.5	7.9	5.0
DP98INJ-02	Injection	26-Jul-05	0	200	<3.40	<3.20	<5.00	<7.00	<8.20	40.0 F	<4.80	<3.00	<2.40
		19-Sep-05	2	200	<3.40	<3.20	<5.00	<7.00	<8.20	<25.4	<4.80	<3.00	<2.40
		2-Jun-06	10	200	<2.00	<3.60	<4.80	<2.80	<5.60	24.0 F	<2.40	<4.20	<1.80
		21-Sep-06	14	500	<5.00	<9.00	<12.0	<7.00	<14.0	<12.0	<6.00	<10.5	<4.50
		19-Jun-08	35	1	1.7	<1.0	1.9	<1.0	<2.0	31	<1.0	6.0	3.7
DP98INJ-03	Injection	26-Jul-05	0	200	<3.40	<3.20	<5.00	<7.00	<8.20	<25.0	<4.80	<3.00	<2.40
		19-Sep-05	2	200	<3.40	<3.20	<5.00	<7.00	<8.20	<25.4	<4.80	<3.00	<2.40
		31-May-06	10	500	<5.00	<9.00	<12.0	<7.00	<14.0	<12.0	<6.00	<10.5	<4.50
		21-Sep-06	14	500	<5.00	<9.00	<12.0	<7.00	<14.0	<12.0	<6.00	<10.5	<4.50
		19-Jun-08	35	1	<1.0	<1.0	<1.0	<1.0	<2.0	13	1.0 F	3.1	2.0
Downgradient Wells													
DP98MW-05	10' Downgradient	25-Jul-05	0	200	<3.40	<3.20	<5.00	<7.00	<8.20	<25.0	<4.80	<3.00	<2.40
		20-Sep-05	2	200	<3.40	<3.20	<5.00	<7.00	<8.20	<25.4	<4.80	<3.00	<2.40
		2-Jun-06	10	200	<2.00	<3.60	<4.80	<2.80	<5.60	24.0F	<2.40	<4.20	<1.80
		21-Sep-06	14	500	<5.00	<9.00	<12.0	<7.00	<14.0	<12.0	<6.00	<10.5	<4.50
		19-Jun-08	35	1	3.6	<1.0	15	<1.0	1.3 F	16	<1.0	24	20
DP98-MW06	20' Downgradient	25-Jul-05	0	200	<3.40	<3.20	<5.00	<7.00	<8.20	360	28 F	24 F	32 F
		20-Sep-05	2	200	<3.40	<3.20	66.0 F	<7.00	<8.20	492	30.0 F	28.0 F	34.0 F
		1-Jun-06	10	200	<2.00	<3.60	62.0 F	<2.80	<5.60	450	<2.40	<4.20	<1.80
		22-Sep-06	14	200	<2.00	<3.60	46.0 F	<2.80	<5.60	330	42.0 F	<4.20	30.0 F
		19-Jun-08	35	1	2.0	<1.0	58	<1.0	16	300	50	46	44

TABLE 8 (Continued)
SUMMARY OF FUEL HYDROCARBONS DETECTED IN GROUNDWATER
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Sample Identification	Sampling Location	Sample Date	Months from Injection	Dilution Factor	Benzene (µg/L) ^{a/}	Toluene (µg/L)	Ethylbenzene (µg/L)	o-Xylene (µg/L)	m&p-Xylene (µg/L)	Napthalene (µg/L)	1,2,4-Trimethylbenzene (µg/L)	Isopropylbenzene (µg/L)	n-Propylbenzene (µg/L)
Crossgradient Wells													
41755-WL04	Crossgradient	26-Jul-05	0	200	<3.40	<3.20	<5.00	<7.00	<8.20	<25.0	<4.80	<3.00	<2.40
		20-Sep-05	2	200	<3.40	<3.20	<5.00	<7.00	<8.20	<25.4	<4.80	<3.00	<2.40
		31-May-06	10	200	<2.00	<3.60	<4.80	<2.80	<5.60	<4.80	<2.40	<4.20	<1.80
		22-Sep-06	14	200	<2.00	<3.60	<4.80	<2.80	<5.60	<4.80	<2.40	<4.20	<1.80
		19-Jun-08	35	1.0	2.0	<1.0	<1.0	<1.0	<2.0	1.6	<1.0	1.2	<1.0
Injection Makeup Tank Water													
Tank Water	--	26-Jul-05	0	200	<3.40	<3.20	22 F	<7.00	<8.20	72.0 F	<4.80	<3.00	<2.40
Quality Assurance/Quality Control Samples													
DP98INJ-04	Dup of INJ-01	25-Jul-05	0	200	<3.40	<3.20	<5.0	<7.00	<8.20	44.0 F	<4.80	<3.00	<2.40
DP98MW-16	Dup of MW-06	22-Sep-05	2	200	<3.40	<3.20	68.0 F	<7.00	<8.20	480	32.0 F	28.0 F	34.0 F
DP98MW-02	Dup of INJ-02	2-Jun-06	10	200	<2.00	<3.60	<4.80	<2.80	<5.60	22.0F	<2.40	<4.20	<1.80
DP98INJ-11	Dup of INJ-01	21-Sep-06	14	500	<5.00	<9.00	<12.0	<7.00	<14.0	<12.0	<6.00	<10.5	<4.50
DP98INJ-12	Dup of INJ-02	19-Jun-08	35	1	1.6	<1.0	2.0	<1.0	<2.0	30	<1.0	6.2	3.9
TB-1	--	25-Jul-05	0	1	<0.5	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0
TB-2	--	20-Sep-05	2	1	<0.5	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0
TB-3	--	2-Jun-06	10	1	<0.5	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0
TB-4	--	21-Sep-06	14	1	<0.5	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0
TB-2-06-2008	--	19-Jun-08	35	1	<1.0	<1.0	<1.0	<1.0	<2.0	1.5	<1.0	<1.0	<1.0

^{a/} µg/L = micrograms per liter.

^{b/} F-flag indicates the concentration is below the quantification limit but above the method detection limit, and the concentration is estimated.

TABLE 9
DISSOLVED METALS IN GROUNDWATER
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Sample Location	Sample Date	Arsenic (mg/L) ^{a/}	Manganese (mg/L)	Selenium (mg/L)
	USEPA Standards ^{b/}	0.01	0.05	0.05
DP98MW-04	7/26/2005	<0.010	8.0	0.014 F ^{c/}
	6/2/2006	0.004 F	6.2 M ^{d/}	0.007 F
	6/19/2008	0.008 F	4.2 M	0.011 F
DP98INJ-02	7/26/2005	<0.010	9.3	0.013
	9/19/2005	0.012 M	13 M	0.018 F
	6/2/2006	0.018	19 M	0.019 F
	6/19/2008	0.036	25 M	0.019 F
DP98MW-05	6/19/2008	0.036	21 M	0.015 F
DP98MW-06	7/25/2005	0.016	21	0.0098 F
	9/20/2005	0.026 M	44 M	0.031
	6/1/2006	0.025	31 M	0.020 F
	6/19/2008	0.037	23 M	0.017 F
DP98MW-16 (dup MW-06)	9/20/2005	0.025 M	41 M	0.035
DP98MW-02 (dup INJ-02)	6/2/2006	0.021	19 M	0.021
DP98INJ-12 (dup INJ-02)	6/19/2008	0.037	25 M	0.022

^{a/} mg/L = milligrams per liter.

^{b/} Standards for arsenic and selenium are United States Environmental Protection Agency (USEPA) primary drinking water maximum contaminant levels (MCLs), and the standard for manganese is a secondary drinking water standard.

^{c/} F-flag indicates the concentration is below the laboratory reporting limit but above the method detection limit; the concentration is estimated.

^{d/} M = Recovery/RPD poor for MS/MSD or Sample/Duplicate.

TABLE 10
BIO-DECHLOR CENSUS SCREENING RESULTS
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Sample Identification	Sampling Location	Sample Date	Dehalococcoides species (cells/mL) ^{a/}	Functional Genes		
				TCE R-Dase (cells/mL)	BAV1 VC R-Dase (cells/mL)	VC R-Dase (cells/mL)
DP98 Groundwater Samples						
DP98MW-04	Upgradient	19-Jun-08	<2.0E+00	<2.0E+00	<2.0E+00	<2.0E+00
DP98INJ-02	Injection Zone	19-Jun-08	<2.5E+00	<2.5E+00	<2.5E+00	<2.5E+00
DP98INJ-12 (duplicate)		19-Jun-08	<2.5E+00	<2.5E+00	<2.5E+00	<2.5E+00
DP98MW-05	15' Downgradient	19-Jun-08	1.73E-01 (J) ^{b/}	<6.67E-01	<6.67E-01	<6.67E-01
Kenney Plume Samples						
403-WL-01	Injection Zone	18-Jun-08	<5.00E-01	<5.00E-01	<5.00E-01	<5.00E-01
OU5KINJ-02	Injection Zone	18-Jun-08	<3.33E-01	<3.33E-01	<3.33E-01	<3.33E-01
OU5KINJ-03	Injection Zone	17-Jun-08	<3.33E-01	<3.33E-01	<3.33E-01	<3.33E-01
OU5KMW-04	Downgradient	18-Jun-08	<1.0E+00	<1.0E+00	<1.0E+00	<1.0E+00

^{a/} cells/ml = cells per milliliter of sample.

^{b/} J-flag indicates the estimated gene copies are below the practical quantitation limit (PQL) but above the laboratory quantification limit (LQL).

TABLE 11
BIOMASS AND VOLATILE FATTY ACIDS IN GROUNDWATER
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Sample Location	Sample Date	Total Biomass (cells/ml) ^{a/}	Total Organic Carbon (mg/L) ^{b/}	Total VFAs (mg/L)	Volatile Fatty (Metabolic) Acids								
					Pyruvic (mg/L)	Lactic (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Butyric (mg/L)	Pentanoic (mg/L)	i-Pentanoic (mg/L)	Hexanoic (mg/L)	i-Hexanoic (mg/L)
Monitoring Wells													
DP98MW-04	26-Jul-05	2.88E+05	11	ND ^{c/}	<0.07	<0.10	0.34	<0.07	<0.07	<0.07	<0.07	<0.10	<0.10
	20-Sep-05	9.19E+05	8.9	ND	<0.70	<0.10	<0.70	<0.70	<0.07	<0.07	<0.07	<0.10	<0.10
	2-Jun-06	3.28E+05	8.6	ND	<10	<25	<1.0	<1.0	<1.0	-- ^{d/}	--	--	--
	21-Sep-06	2.18E+05	6.4	0.5	<10	<25	0.5 J	<1.0	<1.0	--	--	--	--
	19-Jun-08	--	1.9 F	ND	<10	<25	<1.0	<1.0	<1.0	--	--	--	--
DP98MW-05	25-Jul-05	2.78E+05	12	ND	<10	<25	<1.0	<1.0	<1.0	--	--	--	--
	20-Sep-05	6.71E+06	460	1,072	<10	<25	320	730	22	--	--	--	--
	2-Jun-06	9.31E+05	320	659	<0.70	<100	220	410	15	10	2.4	1.4 M	<0.10
	21-Sep-06	2.27E+06	96	272	6.1	1.1	98	150	7.1	5.4	3.5	0.69	<0.10
	19-Jun-08	--	10	1.2	<10	<25	1.2	<1.0	<1.0	--	--	--	--
DP98MW-06	25-Jul-05	--	19	ND	<10	<25	<1.0	<1.0	<1.0	--	--	--	--
	20-Sep-05	--	300	687	1.2J	<25	200	470	16	--	--	--	--
	1-Jun-06	--	100	145	<10	<25	58	86	1.1	--	--	--	--
	22-Sep-06	--	91	130	2.4	1.4	73	50	1.8	1.1	0.46	0.12	<0.10
	19-Jun-08	--	18	ND	<10	<25	<1.0	<1.0	<1.0	--	--	--	--
Injection Wells													
DP98INJ-01	25-Jul-05	--	8.9	ND	<10	<25	<1.0	<1.0	<1.0	--	--	--	--
	19-Sep-05	--	270	617	2.2J	53	180	380	1.9	--	--	--	--
	1-Jun-06	--	110	166	<10	<25	110	47	8.5	--	--	--	--
	21-Sep-06	--	110	179	<10	<25	130	42	6.9	--	--	--	--
	19-Jun-08	--	130	279	<10	<25	250	27	1.9	--	--	--	--
DP98INJ-02	26-Jul-05	2.43E+05	10	ND	<0.07	<0.10	0.272	<0.07	<0.07	<0.07	<0.07	<0.10	<0.10
	19-Sep-05	4.93E+06	240	740	<0.70	<0.10	242	498	<0.07	<0.07	<0.07	<0.10	<0.10
	2-Jun-06	2.37E+06	260	369	<7.0	<100	220	110	17	7.5 M	<0.07	14 M	<1.0
	21-Sep-06	1.78E+06	170	321	6.4	10 J	210	64	18	6.2	2.2	3.9	<0.10
	19-Jun-08	--	290	354	<10	<25	320	13	21	--	--	--	--
DP98INJ-03	26-Jul-05	--	10	ND	<10	<25	<1.0	<1.0	<1.0	--	--	--	--
	19-Sep-05	--	130	317	2.6J	26	88	200	0.88J	--	--	--	--
	31-May-06	--	110	163	<10	<25	110	46	7.3	--	--	--	--
	21-Sep-06	--	120	173	<10	<25	140	28	5.1	--	--	--	--
	10-Jun-08	--	100	214	<10	<25	200	12	1.9	--	--	--	--

TABLE 11 (Continued)
BIOMASS AND VOLATILE FATTY ACIDS IN GROUNDWATER
DP98 ENHANCED BIOREMEDIATION STUDY
ELMENDORF AFB, ALASKA

Sample Location	Sample Date	Total Biomass (cells/ml) ^{a/}	Total Organic Carbon (mg/L) ^{b/}	Total VFAs (mg/L)	Volatile Fatty (Metabolic) Acids								
					Pyruvic (mg/L)	Lactic (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Butyric (mg/L)	Pentanoic (mg/L)	i-Pentanoic (mg/L)	Hexanoic (mg/L)	i-Hexanoic (mg/L)
Quality Control - Duplicates													
DP98INJ-13	26-Jul-05	--	11	ND	<10	<25	<1.0	<1.0	<1.0	--	--	--	--
DP98MW-02	2-Jun-06	1.22E+06	240	454	<7.0	<100	310	110	20	7.2 M	<0.07	14 M	<1.0
DP98INJ-11	21-Sep-06	--	110	181	<10	<25	130	44	7	--	--	--	--
DP98INJ-12	19-Jun-08	--	290	664	<10	<25	630	13	21	--	--	--	--

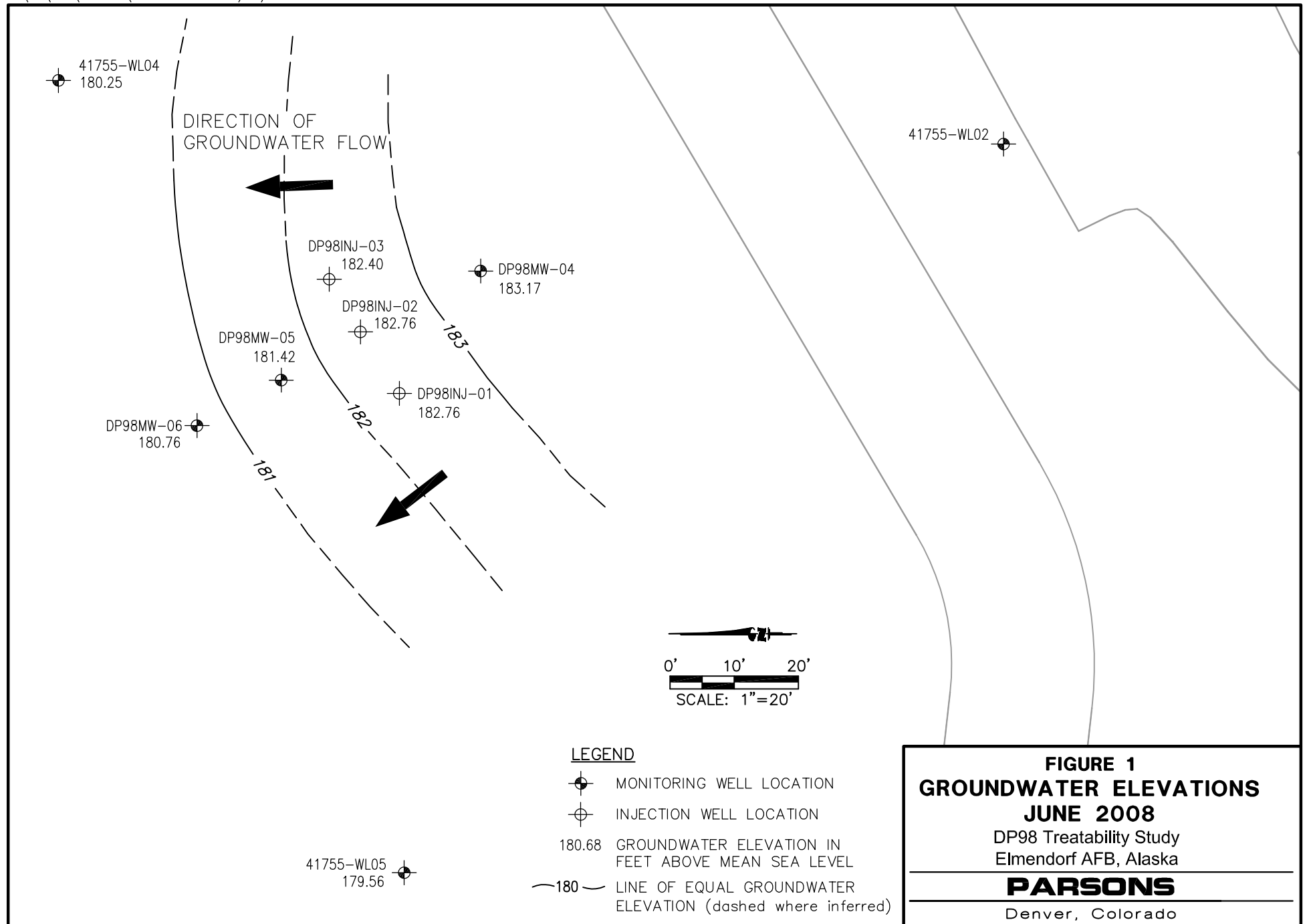
^{a/} cells/ml = cells per milliliter of sample.

^{b/} mg/L = milligrams per liter.

^{c/} ND = not detected.

^{d/} -- = not analyzed.

FIGURES



S:\ES\cod\744222\08DN0189.DWG 10/22/2008 10:16AM JLH

DATE	TCE	cDCE	VC
July 2005	2,680	3,850	<6.2
Sept 2005	2,140	3,740	<6.2
June 2006	386	6,950	<7.6
Sept 2006	688	4,670	<7.6
June 2008	360B	5,700B	15

DATE	TCE	cDCE	VC
July 2005	2,810	5,540	<6.2
Sept 2005	2,730	3,980	<6.2
June 2006	<13.5	10,100	<19.0
Sept 2006	<13.5	6,320	<19.0
June 2008	<10	5,500B	120

DATE	TCE	cDCE	VC
July 2005	2,040	2,880	<6.2
Sept 2005	5,680	2,430	<6.2
June 2006	4,370	4,330	<7.6
Sept 2006	4,340	2,840	<7.6
June 2008	3,200	3,300B	1.2

DATE	TCE	cDCE	VC
July 2005	2,000	5,730	<6.2
Sept 2005	1,220	6,630	<6.2
June 2006	294	12,400	<7.6
Sept 2006	<13.5	9,750	<19.0
June 2008	120	18,000B	75

DATE	TCE	cDCE	VC
July 2005	8,180	4,470	<6.2
Sept 2005	5,150	3,740	<6.2
June 2006	<5.4	10,100	<7.6
Sept 2006	<13.5	9,080	<19.0
June 2008	6.4	8,700B	<1.0

DATE	TCE	cDCE	VC
July 2005	140 F	4,440	<6.2
Sept 2005	92 F	5,430	<6.2
June 2006	<5.4	6,850	<7.6
Sept 2006	20 F	7,120	<7.6
June 2008	32	5,900B	45

DATE	TCE	cDCE	VC
July 2005	4,920	6,340	<6.2
Sept 2005	1,980	4,690	<6.2
June 2006	<5.4	11,100	74 F
Sept 2006	<13.5	7,820	<19.0
June 2008	15	11,000B	200

LEGEND

MONITORING WELL LOCATION

INJECTION WELL LOCATION

ALL CONCENTRATIONS IN MICROGRAMS PER LITER

F-FLAG INDICATES CONCENTRATION IS ESTIMATED

B-FLAG INDICATES ANALYTE WAS DETECTED IN THE METHOD BLANK

41755-WL-05

DIRECTION OF
GROUNDWATER FLOW

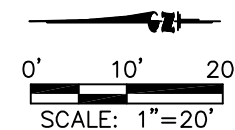


FIGURE 2
CONCENTRATIONS OF CHLORINATED
ETHENES OVER TIME

DP98 Treatability Study
Elmendorf AFB, Alaska

PARSONS

Denver, Colorado

FIGURE 3. CHANGES IN RELATIVE TOXICITY AT THE DP98 TREATABILITY STUDY SITE

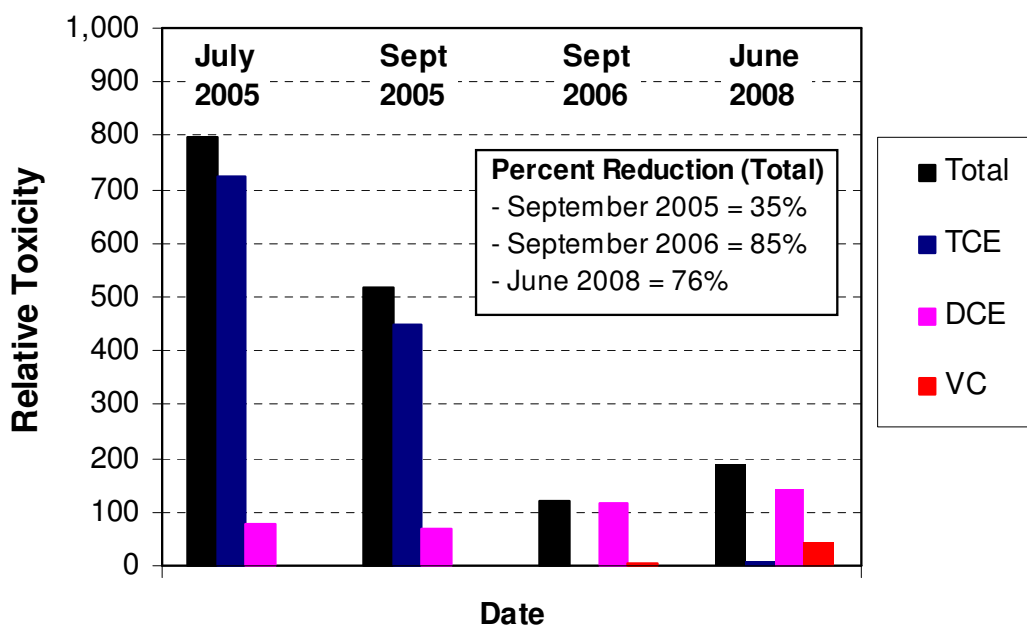


FIGURE 4. AVERAGE CONCENTRATIONS OF TOC AND TOTAL VFAs IN INJECTION AND DOWNGRADIENT MONITORING WELLS

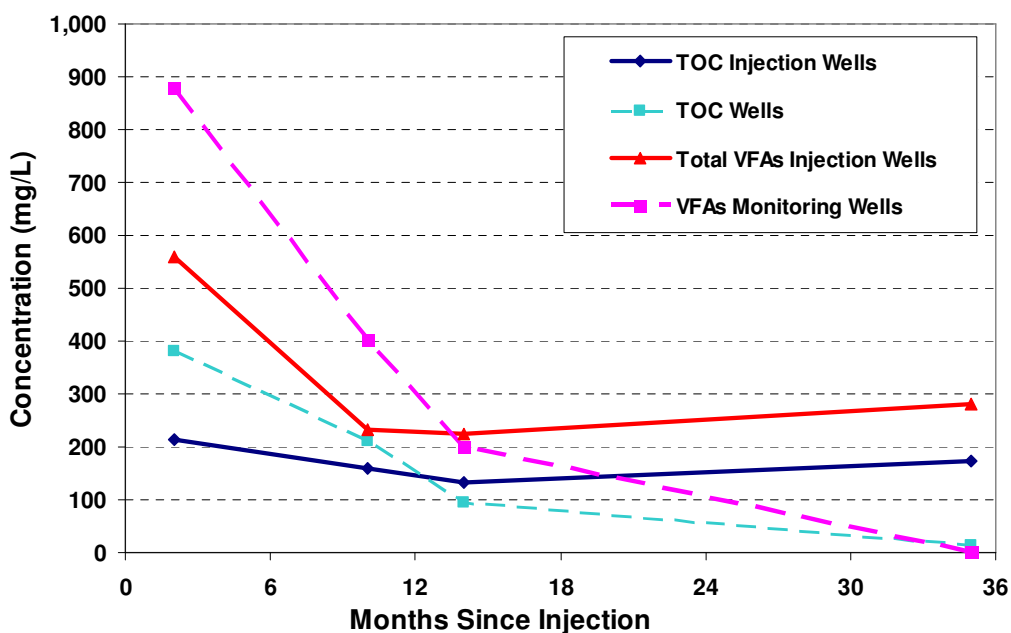
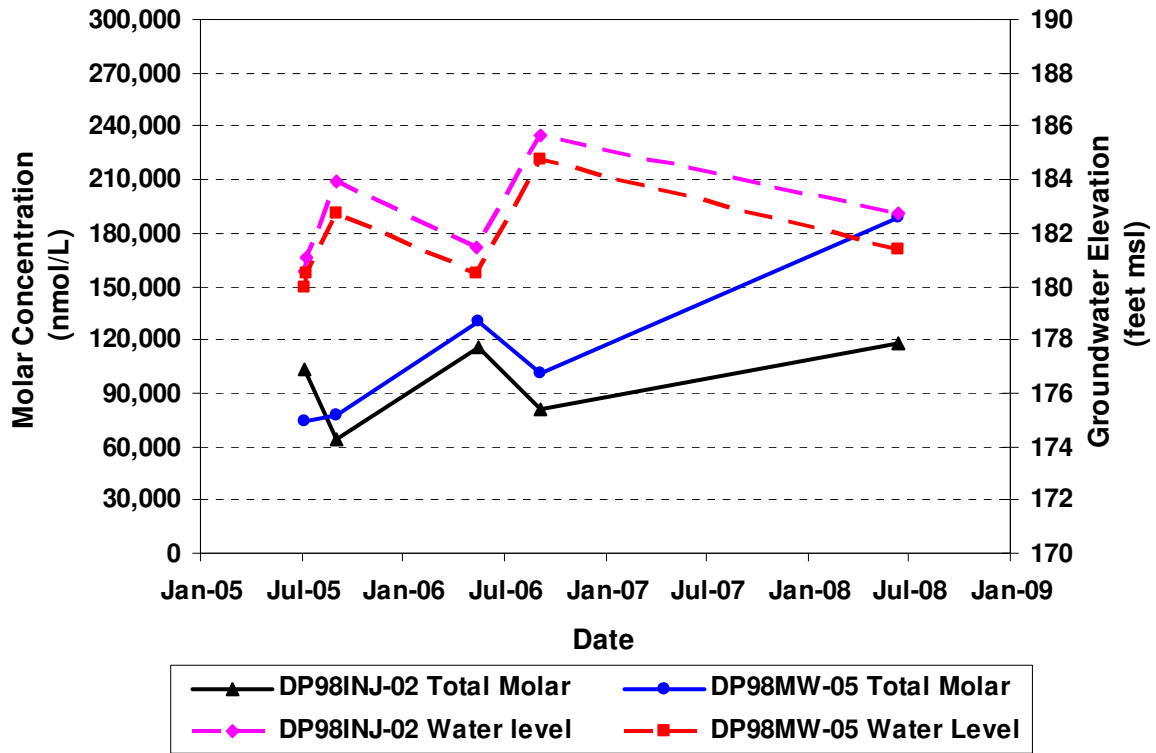


FIGURE 5. TOTAL MOLAR CONCENTRATION AND GROUNDWATER ELEVATION OVER TIME FOR DP98INJ-02 AND DP98MW-05



ATTACHMENT A
ADEC CHECKLIST AND
ANALYTICAL LABORATORY DATA REPORT

(Raw Data Package Provided on CD-ROM)

Laboratory Data Review Checklist

Completed by:

Title:

Date:

CS Report Name:

Report Date:

Consultant Firm:

Laboratory Name:

Laboratory Report Number:

ADEC File Number:

ADEC RecKey Number:

1. Laboratory

- a. Did an ADEC CS approved laboratory receive and perform all of the submitted sample analyses?

☒ Yes

☒ No

Comments:

All analyses were performed by Microseeps, Inc., as part of a technology demonstration project (ER-0627) for the Environmental Security Technology Certification Program, a nation-wide Department of Defense environmental research agency. Sampling at the DP98 site was for research purposes, and was not required for any ADEC or USEPA regulatory compliance program. This data is being provided to ADEC by the Air Force to further the understanding of enhanced in-situ bioremediation processes at Elmendorf AFB, Alaska. Microseeps has NELAP accreditation in Pennsylvania.

- b. If the samples were transferred to another “network” laboratory or sub-contracted to an alternate laboratory, was the laboratory performing the analyses ADEC CS approved?

☒ Yes

☒ No

Comments:

Microbial Insights performed dehalococcoides analyses

2. Chain of Custody (COC)

- a. COC information completed, signed, and dated (including released/received by)?

☒ Yes

☐ No

Comments:

- b. Correct analyses requested?

☒ Yes

☐ No

Comments:

SW8260B VOCs, SW9060 TOC, SW9056 Anions, Metals (Mn, As, Se) by SW6010B, Dissolved Gases (Methane, Ethane, Ethene) by Microseeps Method AM20GAX, Volatile Fatty Acids by Microseeps Method AM21G

3. Laboratory Sample Receipt Documentation

- a. Sample/cooler temperature documented and within range at receipt ($4^{\circ} \pm 2^{\circ} \text{C}$)?

☒ Yes

☐ No

Comments:

Sample storage log-in/log-out record provided in data package

- b. Sample preservation acceptable – acidified waters, Methanol preserved VOC soil (GRO, BTEX, Volatile Chlorinated Solvents, etc.)?

☒ Yes

☐ No

Comments:

- c. Sample condition documented – broken, leaking (Methanol), zero headspace (VOC vials)?

☐ Yes

☒ No

Comments:

- d. If there were any discrepancies, were they documented? For example, incorrect sample containers/preservation, sample temperature outside of acceptable range, insufficient or missing samples, etc.?

☐ Yes

☒ No

Comments:

n/a

- e. Data quality or usability affected? Explain.

Comments:

4. Case Narrative

a. Present and understandable?

☒ Yes ☐ No

Comments:

b. Discrepancies, errors or QC failures identified by the lab?

☒ Yes ☐ No

Comments:

MS/MSD QC acceptance criteria was not met for Mn (SW6010B) or Methane (AM20GAX) however, sample concentration was greater than 5x and 3x spike amount, respectively.

c. Were all corrective actions documented?

☒ Yes ☐ No

Comments:

n/a (none required)

d. What is the effect on data quality/usability according to the case narrative?

Comments:

All data usable. MS/MSD results had no (negative) affect on data quality. MS/MSD QC acceptance criteria was not met for Mn (SW6010B) or Methane (AM20GAX) however, sample concentration was greater than 5x and 3x spike amount, respectively.

5. Samples Results

a. Correct analyses performed/reported as requested on COC?

☒ Yes ☐ No

Comments:

b. All applicable holding times met?

☒ Yes ☐ No

Comments:

c. All soils reported on a dry weight basis?

☐ Yes ☒ No

Comments:

n/a - no soil analyses requested

- d. Are the reported PQLs less than the Cleanup Level or the minimum required detection level for the project?

☒ Yes ☐ No

Comments:

- e. Data quality or usability affected? Explain.

Comments:

6. QC Samples

- a. Method Blank

- i. One method blank reported per matrix, analysis and 20 samples?

☒ Yes ☐ No

Comments:

not required for analysis of dehalococcoides

- ii. All method blank results less than PQL?

☐ Yes ☒ No

Comments:

No. Cis-1,2-DCE (2.0 ug/L) >PQL (1.0 ug/L) in method blank for QC Batch M080709040 and Trichloroethene (11.0 ug/L) >PQL (1.0 ug/L) in method blank for QC Batch M080709040.

- iii. If above PQL, what samples are affected?

Comments:

Cis-1,2-DCE: DP98INJ-01, DP98INJ-02, DP98INJ-03, 41755-WL04, DP98MW-05, DP98MW-06, DE98MW-04, DE98MW-02, DP98MW-12.
Trichloroethene: 41755WL04 and DP98MW-04.

- iv. Do the affected sample(s) have data flags? If so, are the data flags clearly defined?

☒ Yes ☐ No

Comments:

"B" = "detected in blank"

- v. Data quality or usability affected? Explain.

Comments:

Sample results data quality not (negatively) affected by method blank result because all sample results for cis-1,2-DCE and TCE >5 times the method blank amount (times the dilution factor).

b. Laboratory Control Sample/Duplicate (LCS/LCSD)

- i. Organics – One LCS/LCSD reported per matrix, analysis and 20 samples? (LCS/LCSD required per AK methods, LCS required per SW846)

☒ Yes

☐ No

Comments:

- ii. Metals/Inorganics – one LCS and one sample duplicate reported per matrix, analysis and 20 samples?

☒ Yes

☐ No

Comments:

- iii. Accuracy – All percent recoveries (%R) reported and within method or laboratory limits? And project specified DQOs, if applicable. (AK Petroleum methods: AK101 60%-120%, AK102 75%-125%, AK103 60%-120%; all other analyses see the laboratory QC pages)

☒ Yes

☐ No

Comments:

- iv. Precision – All relative percent differences (RPD) reported and less than method or laboratory limits? And project specified DQOs, if applicable. RPD reported from LCS/LCSD, MS/MSD, and or sample/sample duplicate. (AK Petroleum methods 20%; all other analyses see the laboratory QC pages)

☒ Yes

☐ No

Comments:

- v. If %R or RPD is outside of acceptable limits, what samples are affected?

Comments:

- vi. Do the affected sample(s) have data flags? If so, are the data flags clearly defined?

☒ Yes

☐ No

Comments:

- vii. Data quality or usability affected? Explain.

Comments:

c. Surrogates – Organics Only

- i. Are surrogate recoveries reported for organic analyses – field, QC and laboratory samples?

☒ Yes ☐ No

Comments:

- ii. Accuracy – All percent recoveries (%R) reported and within method or laboratory limits? And project specified DQOs, if applicable. (AK Petroleum methods 50-150 %R; all other analyses see the laboratory report pages)

☒ Yes ☐ No

Comments:

- iii. Do the sample results with failed surrogate recoveries have data flags? If so, are the data flags clearly defined?

☒ Yes ☐ No

Comments:

- iv. Data quality or usability affected? Explain.

Comments:

d. Trip blank – Volatile analyses only (GRO, BTEX, Volatile Chlorinated Solvents, etc.): Water and Soil

- i. One trip blank reported per matrix, analysis and cooler?

☒ Yes ☐ No

Comments:

- ii. All results less than PQL?

☐ Yes ☒ No

Comments:

In Trip Blank, cis-1,2-DCE (18 ug/L) > PQL (1.0 ug/L)

- iii. If above PQL, what samples are affected?

Comments:

All samples.

iv. Data quality or usability affected? Explain.

Comments:

No. Sample results data quality not (negatively) affected by trip blank results. All cis-1,2-DCE sample results >7 times the trip blank amount (times the dilution factor); trip blank result (1.8 ug/L) was <5 times method blank amount (times the dilution factor) and so may be a false-positive result.

e. Field Duplicate

i. One field duplicate submitted per matrix, analysis and 10 project samples?

☒ Yes ☐ No

Comments:

ii. Submitted blind to lab?

☒ Yes ☐ No

Comments:

Yes, DP98INJ-12 was field duplicate of DP98INJ-02.

iii. Precision – All relative percent differences (RPD) less than specified DQOs?
(Recommended: 30% water, 50% soil)

$$\text{RPD (\%)} = \text{Absolute value of: } \frac{(R_1 - R_2)}{((R_1 + R_2)/2)} \times 100$$

Where R_1 = Sample Concentration
 R_2 = Field Duplicate Concentration

☒ Yes ☐ No

Comments:

iv. Data quality or usability affected? Explain.

Comments:

f. Decontamination or Equipment Blank (if applicable)

☐ Yes ☐ No ☒ Not Applicable

i. All results less than PQL?

☐ Yes ☐ No

Comments:

ii. If above PQL, what samples are affected?

Comments:

iii. Data quality or usability affected? Explain.

Comments:

7. Other Data Flags/Qualifiers (ACOE, AFCEE, Lab Specific, etc.)

a. Defined and appropriate?

☒ Yes

☐ No

Comments:

"M" = "recovery/RPD poor for MS/MSD, Samp/Dup"; "J" = estimated value (used when result >MDL, but less than PQL).



Client Name: Parsons Engineering Science
Contact: Bruce Henry
Address: 1700 Broadway
Suite 900
Denver, CO 80290

Page: Page 1 of 50
Lab Proj #: P0806357
Report Date: 07/09/08
Client Proj Name: Elmendorf
Client Proj #: 745255-30000

Laboratory Results

Total pages in data package: 548

<u>Lab Sample #</u>	<u>Client Sample ID</u>
P0806357-01	DP98INJ-01
P0806357-02	DP98INJ-03
P0806357-03	41755-WL04
P0806357-04	DP98MW-05
P0806357-05	DP98MW-06
P0806357-06	DP98MW-04
P0806357-07	DP98INJ-02
P0806357-08	DP98INJ-12
P0806357-09	TB-2-06-2008
P0806357-10	DP98MW-05 MS
P0806357-11	DP98MW-05 MSD

Microseeps test results meet all the requirements of the NELAC standards or provide reasons and/or justification if they do not

Approved By:

Debbie Hallo

Date:

7-10-08

Project Manager:

Debbie Hallo

The analytical results reported here are reliable and usable to the precision expressed in this report. As required by some regulating authorities, a full discussion of the uncertainty in our analytical results can be obtained at our web site or through customer service. Unless otherwise specified, all results are reported on a wet weight basis.

*As a valued client we would appreciate your comments on our service.
Please call customer service at (412)826-5245 or email customerservice@microseeps.com*

Client Name: Parsons Engineering Science
Contact: Bruce Henry
Address: 1700 Broadway
Suite 900
Denver, CO 80290

Page: Page 2 of 50
Lab Proj #: P0806357
Report Date: 07/09/08
Client Proj Name: Elmendorf
Client Proj #: 745255-30000

Case Narrative: The dehalococcoides analyses were performed by Microbial Insights. The batch spike analyses for manganese was outside of control limits. The unspiked sample concentration was greater than 5 times the spike added. All other QC analyses were acceptable. The percent recovery for the batch MSD analyses for methane was outside of control limits. The unspiked sample concentration was greater than 3 times the spike added. All other QC analyses were acceptable.



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 3 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received				
DP98INJ-01	Water	P0806357-01	19 Jun 08 9:15	23 Jun. 08 12:57				
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By	
WetChem								
N Chloride		49.00	1.00	mg/L	9056	6/24/08	21:24	md
N Sulfate		4.20	1.00	mg/L	9056	6/24/08	21:24	md
N Total Organic Carbon		130.0	5.0	mg/L	9060	6/28/08		md
Volatiles								
N 1,1,1,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,1,1-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,1,2,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,1,2-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,1-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,1-Dichloroethene		42.0	1	ug/L	8260B	6/27/08		hg
N 1,1-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2,3-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2,3-Trichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2,4-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2,4-Trimethylbenzene		1.5	1	ug/L	8260B	6/27/08		hg
N 1,2-Dibromo-3-chloropropane	U	< 5.0	5	ug/L	8260B	6/27/08		hg
N 1,2-Dibromoethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,3,5-Trimethylbenzene		7.6	1	ug/L	8260B	6/27/08		hg
N 1,3-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,3-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,4-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 2,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 2-Butanone	U	< 5.0	5	ug/L	8260B	6/27/08		hg
N 2-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 2-Hexanone	U	< 5.0	5	ug/L	8260B	6/27/08		hg
N 4-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 4-Methyl-2-pentanone	U	< 5.0	5	ug/L	8260B	6/27/08		hg
N Acetone		11.0	10	ug/L	8260B	6/27/08		hg
N Benzene		1.6	1	ug/L	8260B	6/27/08		hg
N Bromobenzene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N Bromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N Bromodichloromethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N Bromoform	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N Bromomethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N Carbon Disulfide	U	< 5.0	5	ug/L	8260B	6/27/08		hg
N Carbon tetrachloride	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N Chlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N Chloroethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N Chloroform	U	< 1.0	1	ug/L	8260B	6/27/08		hg



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
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Page: Page 4 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
DP98INJ-01	Water	P0806357-01	19 Jun 08 9:15	23 Jun 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
Volatiles							
N Chloromethane		26 0	1	ug/L	8260B	6/27/08	hg
N cis-1,2-Dichloroethene	B	8700 0	50 0	ug/L	8260B	7/1/08	cs
N cis-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromomethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dichlorodifluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Ethylbenzene		2.4	1	ug/L	8260B	6/27/08	hg
N Hexachlorobutadiene	U	< 2.0	2	ug/L	8260B	6/27/08	hg
N Isopropylbenzene		7.9	1	ug/L	8260B	6/27/08	hg
N m & p-Xylene	U	< 2.0	2	ug/L	8260B	6/27/08	hg
N Methylene Chloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Methyl-t-butyl ether	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Naphthalene		36 0	1	ug/L	8260B	6/27/08	hg
N n-Butylbenzene		5.0	1	ug/L	8260B	6/27/08	hg
N n-Propylbenzene		5.0	1	ug/L	8260B	6/27/08	hg
N o-Xylene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N p-Isopropyltoluene		3.6	1	ug/L	8260B	6/27/08	hg
N sec-Butylbenzene		6.0	1	ug/L	8260B	6/27/08	hg
N Styrene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N tert-Butyl alcohol	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N tert-Butylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Tetrachloroethene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Toluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N trans-1,2-Dichloroethene		25.0	1	ug/L	8260B	6/27/08	hg
N trans-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Trichloroethene		6.4	1	ug/L	8260B	6/27/08	hg
N Trichlorofluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Vinyl Chloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
SURROGATE:							
4-Bromofluorobenzene						112.00 %	
Dibromofluoromethane						116.00 %	
Toluene-d8						116.00 %	
RiskAnalysis							
N Ethane		0.390	0.025	ug/L	AM20GAX	7/3/08	rw
N Ethene		1.200	0.025	ug/L	AM20GAX	7/3/08	rw
N Methane	M	16000.000	0.100	ug/L	AM20GAX	7/3/08	rw
SemiVolatiles							
Acetic Acid		250.0	1.0	mg/L	AM21G	7/8/08	td
Butyric Acid		1.9	1.0	mg/L	AM21G	7/8/08	td
Lactic Acid	U	< 25.0	25.0	mg/L	AM21G	7/8/08	td
Propionic Acid		27.0	1.0	mg/L	AM21G	7/8/08	td



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 5 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

<u>Sample Description</u>	<u>Matrix</u>	<u>Lab Sample #</u>	<u>Sampled Date/Time</u>		<u>Received</u>		
DP98INJ-01	Water	P0806357-01	19 Jun 08 9:15		23 Jun. 08 12:57		
<u>Analyte(s)</u>	<u>Flag</u>	<u>Result</u>	<u>PQL</u>	<u>Units</u>	<u>Method #</u>	<u>Analysis Date</u>	<u>By</u>
SemiVolatiles							
Pyruvic Acid	U	< 10.0	10.0	mg/L	AM21G	7/8/08	td



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 6 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
DP98INJ-03	Water	P0806357-02	19 Jun 08 10:15	23 Jun 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
WetChem							
N Chloride		71.00	1.00	mg/L	9056	6/24/08 21:46	md
N Sulfate		3.30	1.00	mg/L	9056	6/24/08 21:46	md
N Total Organic Carbon		100.0	5.0	mg/L	9060	6/28/08	md
Volatiles							
N 1,1,1,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,1-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,2,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,2-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloroethene		24.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,3-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,3-Trichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,4-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,4-Trimethylbenzene	J	1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dibromo-3-chloropropane	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 1,2-Dibromoethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,3,5-Trimethylbenzene		3.2	1	ug/L	8260B	6/27/08	hg
N 1,3-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,3-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,4-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2-Butanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 2-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2-Hexanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 4-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 4-Methyl-2-pentanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N Acetone	J	6.6	10	ug/L	8260B	6/27/08	hg
N Benzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromodichloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromoform	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromomethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Carbon Disulfide	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N Carbon tetrachloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloroform	U	< 1.0	1	ug/L	8260B	6/27/08	hg



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 7 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #		Sampled Date/Time		Received	
DP98INJ-03	Water	P0806357-02		19 Jun 08 10:15		23 Jun 08 12:57	
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
Volatiles							
N Chloromethane		4.0	1	ug/L	8260B	6/27/08	hg
N cis-1,2-Dichloroethene	B	5500.0	50.0	ug/L	8260B	7/1/08	cs
N cis-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromomethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dichlorodifluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Ethylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Hexachlorobutadiene	U	< 2.0	2	ug/L	8260B	6/27/08	hg
N Isopropylbenzene		3.1	1	ug/L	8260B	6/27/08	hg
N m & p-Xylene	U	< 2.0	2	ug/L	8260B	6/27/08	hg
N Methylene Chloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Methyl-t-butyl ether	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Naphthalene		13.0	1	ug/L	8260B	6/27/08	hg
N n-Butylbenzene		4.6	1	ug/L	8260B	6/27/08	hg
N n-Propylbenzene		2.0	1	ug/L	8260B	6/27/08	hg
N o-Xylene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N p-Isopropyltoluene		3.2	1	ug/L	8260B	6/27/08	hg
N sec-Butylbenzene		4.6	1	ug/L	8260B	6/27/08	hg
N Styrene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N tert-Butyl alcohol	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N tert-Butylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Tetrachloroethene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Toluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N trans-1,2-Dichloroethene		13.0	1	ug/L	8260B	6/27/08	hg
N trans-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Trichloroethene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Trichlorofluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Vinyl Chloride		120.0	1	ug/L	8260B	6/27/08	hg
SURROGATE:							
4-Bromofluorobenzene						112.00 %	
Dibromofluoromethane						114.00 %	
Toluene-d8						116.00 %	
RiskAnalysis							
N Ethane		0.160	0.025	ug/L	AM20GAX	7/3/08	rw
N Ethene		0.960	0.025	ug/L	AM20GAX	7/3/08	rw
N Methane	M	16000.000	0.100	ug/L	AM20GAX	7/3/08	rw
SemiVolatiles							
Acetic Acid		200.0	1.0	mg/L	AM21G	7/8/08	td
Butyric Acid		1.9	1.0	mg/L	AM21G	7/8/08	td
Lactic Acid	U	< 25.0	25.0	mg/L	AM21G	7/8/08	td
Propionic Acid		12.0	1.0	mg/L	AM21G	7/8/08	td



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
Contact: Bruce Henry
Address: 1700 Broadway
Suite 900
Denver, CO 80290

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Lab Proj #: P0806357
Report Date: 07/09/08
Client Proj Name: Elmendorf
Client Proj #: 745255-30000

<u>Sample Description</u>	<u>Matrix</u>	<u>Lab Sample #</u>			<u>Sampled Date/Time</u>	<u>Received</u>	
DP98INJ-03	Water	P0806357-02			19 Jun. 08 10:15	23 Jun. 08 12:57	
<u>Analyte(s)</u>	<u>Flag</u>	<u>Result</u>	<u>PQL</u>	<u>Units</u>	<u>Method #</u>	<u>Analysis Date</u>	<u>By</u>
SemiVolatiles							
Pyruvic Acid	U	< 10.0	10.0	mg/L	AM21G	7/8/08	td



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
41755-WL04	Water	P0806357-03	19 Jun. 08 11:10	23 Jun. 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
WetChem							
N Chloride		97.00	1.00	mg/L	9056	6/24/08 22:08	md
N Sulfate		3.70	1.00	mg/L	9056	6/24/08 22:08	md
N Total Organic Carbon	J	2.5	5.0	mg/L	9060	6/28/08	md
Volatiles							
N 1,1,1,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,1-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,2,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,2-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloroethene		30.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,3-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,3-Trichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,4-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,4-Trimethylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dibromo-3-chloropropane	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 1,2-Dibromoethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,3,5-Trimethylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,3-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,3-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,4-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2-Butanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 2-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2-Hexanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 4-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 4-Methyl-2-pentanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N Acetone	U	< 10.0	10	ug/L	8260B	6/27/08	hg
N Benzene		2.0	1	ug/L	8260B	6/27/08	hg
N Bromobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromodichloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromoform	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromomethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Carbon Disulfide	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N Carbon tetrachloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloroform	U	< 1.0	1	ug/L	8260B	6/27/08	hg



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 10 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #		Sampled Date/Time		Received	
41755-WL04	Water	P0806357-03		19 Jun. 08 11:10		23 Jun. 08 12:57	
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
Volatiles							
N Chloromethane		2.2	1	ug/L	8260B	6/27/08	hg
N cis-1,2-Dichloroethene	B	5700.0	50.0	ug/L	8260B	7/1/08	cs
N cis-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromomethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dichlorodifluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Ethylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Hexachlorobutadiene	U	< 2.0	2	ug/L	8260B	6/27/08	hg
N Isopropylbenzene		1.2	1	ug/L	8260B	6/27/08	hg
N m & p-Xylene	U	< 2.0	2	ug/L	8260B	6/27/08	hg
N Methylene Chloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Methyl-t-butyl ether	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Naphthalene		1.6	1	ug/L	8260B	6/27/08	hg
N n-Butylbenzene		2.3	1	ug/L	8260B	6/27/08	hg
N n-Propylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N o-Xylene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N p-Isopropyltoluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N sec-Butylbenzene		4.3	1	ug/L	8260B	6/27/08	hg
N Styrene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N tert-Butyl alcohol	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N tert-Butylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Tetrachloroethene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Toluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N trans-1,2-Dichloroethene		9.3	1	ug/L	8260B	6/27/08	hg
N trans-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Trichloroethene	B	360.0	50.0	ug/L	8260B	7/1/08	cs
N Trichlorofluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Vinyl Chloride		15.0	1	ug/L	8260B	6/27/08	hg
SURROGATE.							
4-Bromofluorobenzene						110.00 %	
Dibromofluoromethane						116.00 %	
Toluene-d8						116.00 %	
Risk Analysis							
N Ethane		0.076	0.025	ug/L	AM20GAX	7/3/08	rw
N Ethene		0.370	0.025	ug/L	AM20GAX	7/3/08	rw
N Methane	M	5800.000	0.100	ug/L	AM20GAX	7/3/08	rw



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 11 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
DP98MW-05	Water	P0806357-04	19 Jun. 08 13:20	23 Jun. 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
WetChem							
N Chloride		48.00	1.00	mg/L	9056	6/24/08 22:30	md
N Sulfate		3.90	1.00	mg/L	9056	6/24/08 22:30	md
N Total Organic Carbon		10.0	5.0	mg/L	9060	6/28/08	md
Metals							
N Arsenic		0.036	0.010	mg/L	6010B	6/25/08	ak
N Manganese	M	21.000	0.050	mg/L	6010B	6/25/08	ak
N Selenium	J	0.015	0.020	mg/L	6010B	6/25/08	ak
Volatiles							
N 1,1,1,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,1-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,2,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,2-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloroethane		1.2	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloroethene		83.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,3-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,3-Trichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,4-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,4-Trimethylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dibromo-3-chloropropane	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 1,2-Dibromoethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,3,5-Trimethylbenzene		11.0	1	ug/L	8260B	6/27/08	hg
N 1,3-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,3-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,4-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2-Butanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 2-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2-Hexanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 4-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 4-Methyl-2-pentanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N Acetone	J	6.8	10	ug/L	8260B	6/27/08	hg
N Benzene		3.6	1	ug/L	8260B	6/27/08	hg
N Bromobenzene		2.0	1	ug/L	8260B	6/27/08	hg
N Bromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromodichloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromoform	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromomethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Carbon Disulfide	U	< 5.0	5	ug/L	8260B	6/27/08	hg



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 12 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmhendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
DP98MW-05	Water	P0806357-04	19 Jun 08 13:20	23 Jun 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
Volatiles							
N Carbon tetrachloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloroform	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloromethane		1.5	1	ug/L	8260B	6/27/08	hg
N cis-1,2-Dichloroethene		18000.0	200.0	ug/L	8260B	7/8/08	cs
N cis-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromomethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dichlorodifluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Ethylbenzene		15.0	1	ug/L	8260B	6/27/08	hg
N Hexachlorobutadiene	U	< 2.0	2	ug/L	8260B	6/27/08	hg
N Isopropylbenzene		24.0	1	ug/L	8260B	6/27/08	hg
N m & p-Xylene	J	1.3	2	ug/L	8260B	6/27/08	hg
N Methylene Chloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Methyl-t-butyl ether	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Naphthalene		16.0	1	ug/L	8260B	6/27/08	hg
N n-Butylbenzene		15.0	1	ug/L	8260B	6/27/08	hg
N n-Propylbenzene		20.0	1	ug/L	8260B	6/27/08	hg
N o-Xylene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N p-Isopropyltoluene		9.8	1	ug/L	8260B	6/27/08	hg
N sec-Butylbenzene		14.0	1	ug/L	8260B	6/27/08	hg
N Styrene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N tert-Butyl alcohol	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N tert-Butylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Tetrachloroethene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Toluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N trans-1,2-Dichloroethene		43.0	1	ug/L	8260B	6/27/08	hg
N trans-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Trichloroethene		120.0	1	ug/L	8260B	6/27/08	hg
N Trichlorofluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Vinyl Chloride		75.0	1	ug/L	8260B	6/27/08	hg

SURROGATE:

4-Bromofluorobenzene	114.00 %
Dibromofluoromethane	116.00 %
Toluene-d8	116.00 %

Risk Analysis

N Ethane		0.250	0.025	ug/L	AM20GAX	7/3/08	rw
N Ethene		0.950	0.025	ug/L	AM20GAX	7/3/08	rw
N Methane	M	8600.000	0.100	ug/L	AM20GAX	7/3/08	rw

Sample Receiving



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 13 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

<u>Sample Description</u>	<u>Matrix</u>	<u>Lab Sample #</u>	<u>Sampled Date/Time</u>	<u>Received</u>				
DP98MW-05	Water	P0806357-04	19 Jun. 08 13:20	23 Jun 08 12:57				
<u>Analyte(s)</u>	<u>Flag</u>	<u>Result</u>	<u>PQL</u>	<u>Units</u>	<u>Method #</u>	<u>Analysis Date</u>	<u>By</u>	
SampleReceiving								
Dehalococcoides	L	Done	0.0	NONE	DHC	6/21/08 13:29	mi	
SemiVolatiles								
Acetic Acid		1.2	1.0	mg/L	AM21G	7/8/08	td	
Butyric Acid	U	< 1.0	1.0	mg/L	AM21G	7/8/08	td	
Lactic Acid	U	< 25.0	25.0	mg/L	AM21G	7/8/08	td	
Propionic Acid	U	< 1.0	1.0	mg/L	AM21G	7/8/08	td	
Pyruvic Acid	U	< 10.0	10.0	mg/L	AM21G	7/8/08	td	



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 14 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
DP98MW-06	Water	P0806357-05	19 Jun 08 12:00	23 Jun 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
WetChem							
N Chloride		24.00	1.00	mg/L	9056	6/24/08	md
N Sulfate		3.40	1.00	mg/L	9056	6/24/08	md
N Total Organic Carbon		18.0	5.0	mg/L	9060	6/28/08	md
Metals							
N Arsenic		0.037	0.010	mg/L	6010B	6/25/08	ak
N Manganese	M	23.000	0.050	mg/L	6010B	6/25/08	ak
N Selenium	J	0.017	0.020	mg/L	6010B	6/25/08	ak
Volatiles							
N 1,1,1,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,1-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,2,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,2-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloroethene		29.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,3-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,3-Trichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,4-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,4-Trimethylbenzene		50.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dibromo-3-chloropropane	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 1,2-Dibromoethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,3,5-Trimethylbenzene		110.0	1	ug/L	8260B	6/27/08	hg
N 1,3-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,3-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,4-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2-Butanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 2-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2-Hexanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 4-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 4-Methyl-2-pentanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N Acetone	J	3.6	10	ug/L	8260B	6/27/08	hg
N Benzene		2.0	1	ug/L	8260B	6/27/08	hg
N Bromobenzene		18.0	1	ug/L	8260B	6/27/08	hg
N Bromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromodichloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromoform	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromomethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Carbon Disulfide	U	< 5.0	5	ug/L	8260B	6/27/08	hg



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmhurst
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
DP98MW-06	Water	P0806357-05	19 Jun 08 12:00	23 Jun 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
Volatiles							
N Carbon tetrachloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloroform	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloromethane		1.6	1	ug/L	8260B	6/27/08	hg
N cis-1,2-Dichloroethene	B	5900.0	50.0	ug/L	8260B	7/1/08	cs
N cis-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromomethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dichlorodifluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Ethylbenzene		58.0	1	ug/L	8260B	6/27/08	hg
N Hexachlorobutadiene	U	< 2.0	2	ug/L	8260B	6/27/08	hg
N Isopropylbenzene		46.0	1	ug/L	8260B	6/27/08	hg
N m & p-Xylene		16.0	2	ug/L	8260B	6/27/08	hg
N Methylene Chloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Methyl-t-butyl ether	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Naphthalene		300.0	50.0	ug/L	8260B	7/1/08	cs
N n-Butylbenzene		19.0	1	ug/L	8260B	6/27/08	hg
N n-Propylbenzene		44.0	1	ug/L	8260B	6/27/08	hg
N o-Xylene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N p-Isopropyltoluene		20.0	1	ug/L	8260B	6/27/08	hg
N sec-Butylbenzene		15.0	1	ug/L	8260B	6/27/08	hg
N Styrene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N tert-Butyl alcohol		6.8	5	ug/L	8260B	6/27/08	hg
N tert-Butylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Tetrachloroethene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Toluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N trans-1,2-Dichloroethene		21.0	1	ug/L	8260B	6/27/08	hg
N trans-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Trichloroethene		32.0	1	ug/L	8260B	6/27/08	hg
N Trichlorofluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Vinyl Chloride		45.0	1	ug/L	8260B	6/27/08	hg

SURROGATE:

4-Bromofluorobenzene	114.00 %
Dibromofluoromethane	116.00 %
Toluene-d8	118.00 %

Risk Analysis

Risk Analysis							
N Ethane		0.130	0.025	ug/L	AM20GAX	7/3/08	rw
N Ethene		0.820	0.025	ug/L	AM20GAX	7/3/08	rw
N Methane	M	12000.000	0.100	ug/L	AM20GAX	7/3/08	rw

SemiVolatiles



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 16 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

<u>Sample Description</u>	<u>Matrix</u>	<u>Lab Sample #</u>			<u>Sampled Date/Time</u>	<u>Received</u>	
DP98MW-06	Water	P0806357-05			19 Jun 08 12:00	23 Jun 08 12:57	
<u>Analyte(s)</u>	<u>Flag</u>	<u>Result</u>	<u>PQL</u>	<u>Units</u>	<u>Method #</u>	<u>Analysis Date</u>	<u>By</u>
SemiVolatiles							
Acetic Acid	U	< 1.0	1.0	mg/L	AM21G	7/8/08	td
Butyric Acid	U	< 1.0	1.0	mg/L	AM21G	7/8/08	td
Lactic Acid	U	< 25.0	25.0	mg/L	AM21G	7/8/08	td
Propionic Acid	U	< 1.0	1.0	mg/L	AM21G	7/8/08	td
Pyruvic Acid	U	< 10.0	10.0	mg/L	AM21G	7/8/08	td



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 17 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
DP98MW-04	Water	P0806357-06	19 Jun 08 15:00	23 Jun 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
WetChem							
N Chloride		26.00	1.00	mg/L	9056	6/24/08 23:14	md
N Sulfate		8.10	1.00	mg/L	9056	6/24/08 23:14	md
N Total Organic Carbon	J	1.9	5.0	mg/L	9060	6/28/08	md
Metals							
N Arsenic	J	0.008	0.010	mg/L	6010B	6/25/08	ak
N Manganese	M	4.200	0.010	mg/L	6010B	6/25/08	ak
N Selenium	J	0.011	0.020	mg/L	6010B	6/25/08	ak
Volatiles							
N 1,1,1,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,1-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,2,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,2-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloroethene		16.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,3-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,3-Trichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,4-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,4-Trimethylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dibromo-3-chloropropane	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 1,2-Dibromoethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,3,5-Trimethylbenzene	J	1.0	1	ug/L	8260B	6/27/08	hg
N 1,3-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,3-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,4-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2-Butanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 2-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2-Hexanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 4-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 4-Methyl-2-pentanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N Acetone	U	< 10.0	10	ug/L	8260B	6/27/08	hg
N Benzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromodichloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromoform	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromomethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Carbon Disulfide	U	< 5.0	5	ug/L	8260B	6/27/08	hg



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 18 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
DP98MW-04	Water	P0806357-06	19 Jun. 08 15:00	23 Jun 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
Volatiles							
N Carbon tetrachloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloroform	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloromethane		1.2	1	ug/L	8260B	6/27/08	hg
N cis-1,2-Dichloroethene	B	3300.0	50.0	ug/L	8260B	7/1/08	cs
N cis-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromomethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dichlorodifluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Ethylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Hexachlorobutadiene	U	< 2.0	2	ug/L	8260B	6/27/08	hg
N Isopropylbenzene		1.4	1	ug/L	8260B	6/27/08	hg
N m & p-Xylene	U	< 2.0	2	ug/L	8260B	6/27/08	hg
N Methylene Chloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Methyl-t-butyl ether	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Naphthalene		20.0	1	ug/L	8260B	6/27/08	hg
N n-Butylbenzene		6.1	1	ug/L	8260B	6/27/08	hg
N n-Propylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N o-Xylene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N p-Isopropyltoluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N sec-Butylbenzene		7.4	1	ug/L	8260B	6/27/08	hg
N Styrene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N tert-Butyl alcohol	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N tert-Butylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Tetrachloroethene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Toluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N trans-1,2-Dichloroethene		5.0	1	ug/L	8260B	6/27/08	hg
N trans-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Trichloroethene	B	3200.0	50.0	ug/L	8260B	7/1/08	cs
N Trichlorofluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Vinyl Chloride		1.2	1	ug/L	8260B	6/27/08	hg

SURROGATE:

4-Bromofluorobenzene	112.00 %
Dibromofluoromethane	116.00 %
Toluene-d8	116.00 %

Risk Analysis

N Ethane		0.210	0.025	ug/L	AM20GAX	7/3/08	rw
N Ethene		0.420	0.025	ug/L	AM20GAX	7/3/08	rw
N Methane	M	150.000	0.100	ug/L	AM20GAX	7/3/08	rw

Sample Receiving



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank. S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 19 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

<u>Sample Description</u>	<u>Matrix</u>	<u>Lab Sample #</u>	<u>Sampled Date/Time</u>	<u>Received</u>				
DP98MW-04	Water	P0806357-06	19 Jun. 08 15:00	23 Jun. 08 12:57				
<u>Analyte(s)</u>	<u>Flag</u>	<u>Result</u>	<u>PQL</u>	<u>Units</u>	<u>Method #</u>	<u>Analysis Date</u>	<u>By</u>	
SampleReceiving								
Dehalococcoides	L	Done	0.0	NONE	DHC	6/21/08 13:29	mi	
SemiVolatiles								
Acetic Acid	U	< 1.0	1.0	mg/L	AM21G	7/8/08	td	
Butyric Acid	U	< 1.0	1.0	mg/L	AM21G	7/8/08	td	
Lactic Acid	U	< 25.0	25.0	mg/L	AM21G	7/8/08	td	
Propionic Acid	U	< 1.0	1.0	mg/L	AM21G	7/8/08	td	
Pyruvic Acid	U	< 10.0	10.0	mg/L	AM21G	7/8/08	td	



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 20 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
DP98INJ-02	Water	P0806357-07	19 Jun 08 16:30	23 Jun 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
WetChem							
N Chloride		47.00	1.00	mg/L	9056	6/24/08	md
N Sulfate		3.50	1.00	mg/L	9056	6/24/08	md
N Total Organic Carbon		290.0	25.0	mg/L	9060	6/30/08	md
Metals							
N Arsenic		0.036	0.010	mg/L	6010B	6/25/08	ak
N Manganese	M	25.000	0.050	mg/L	6010B	6/25/08	ak
N Selenium	J	0.019	0.020	mg/L	6010B	6/25/08	ak
Volatiles							
N 1,1,1,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,1-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,2,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1,2-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloroethane		1.2	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloroethene		44.0	1	ug/L	8260B	6/27/08	hg
N 1,1-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,3-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,3-Trichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,4-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2,4-Trimethylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dibromo-3-chloropropane	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 1,2-Dibromoethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,3,5-Trimethylbenzene		4.2	1	ug/L	8260B	6/27/08	hg
N 1,3-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,3-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 1,4-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2-Butanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 2-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 2-Hexanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N 4-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N 4-Methyl-2-pentanone	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N Acetone	J	2.7	10	ug/L	8260B	6/27/08	hg
N Benzene		1.7	1	ug/L	8260B	6/27/08	hg
N Bromobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromodichloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromoform	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Bromomethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Carbon Disulfide	U	< 5.0	5	ug/L	8260B	6/27/08	hg



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 21 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #		Sampled Date/Time		Received	
DP98INJ-02	Water	P0806357-07		19 Jun. 08 16:30		23 Jun. 08 12:57	
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
Volatiles							
N Carbon tetrachloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloroform	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloromethane		9.0	1	ug/L	8260B	6/27/08	hg
N cis-1,2-Dichloroethene	B	11000.0	50.0	ug/L	8260B	7/1/08	cs
N cis-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromomethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dichlorodifluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Ethylbenzene		1.9	1	ug/L	8260B	6/27/08	hg
N Hexachlorobutadiene	U	< 2.0	2	ug/L	8260B	6/27/08	hg
N Isopropylbenzene		6.0	1	ug/L	8260B	6/27/08	hg
N m & p-Xylene	U	< 2.0	2	ug/L	8260B	6/27/08	hg
N Methylene Chloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Methyl-t-butyl ether	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Naphthalene		31.0	1	ug/L	8260B	6/27/08	hg
N n-Butylbenzene		6.4	1	ug/L	8260B	6/27/08	hg
N n-Propylbenzene		3.7	1	ug/L	8260B	6/27/08	hg
N o-Xylene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N p-Isopropyltoluene		3.4	1	ug/L	8260B	6/27/08	hg
N sec-Butylbenzene		6.0	1	ug/L	8260B	6/27/08	hg
N Styrene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N tert-Butyl alcohol	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N tert-Butylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Tetrachloroethene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Toluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N trans-1,2-Dichloroethene		24.0	1	ug/L	8260B	6/27/08	hg
N trans-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Trichloroethene		15.0	1	ug/L	8260B	6/27/08	hg
N Trichlorofluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Vinyl Chloride		200.0	50.0	ug/L	8260B	7/1/08	cs

SURROGATE:

4-Bromofluorobenzene	112.00 %
Dibromofluoromethane	114.00 %
Toluene-d8	116.00 %

Risk Analysis

N Ethane		0.180	0.025	ug/L	AM20GAX	7/3/08	rw
N Ethene		1.200	0.025	ug/L	AM20GAX	7/3/08	rw
N Methane	M	15000.000	0.100	ug/L	AM20GAX	7/3/08	rw

Sample Receiving



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 22 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

<u>Sample Description</u>	<u>Matrix</u>	<u>Lab Sample #</u>			<u>Sampled Date/Time</u>	<u>Received</u>		
DP98INJ-02	Water	P0806357-07			19 Jun 08 16:30	23 Jun 08 12:57		
<u>Analyte(s)</u>	<u>Flag</u>	<u>Result</u>	<u>PQL</u>	<u>Units</u>	<u>Method #</u>	<u>Analysis Date</u>	<u>By</u>	
SampleReceiving								
Dehalococcoides	L	Done	0 0	NONE	DHC	6/21/08	13:29	mi
SemiVolatiles								
Acetic Acid		320 0	1 0	mg/L	AM21G	7/8/08		td
Butyric Acid		21 0	1 0	mg/L	AM21G	7/8/08		td
Lactic Acid	U	< 25 0	25 0	mg/L	AM21G	7/8/08		td
Propionic Acid		13 0	1 0	mg/L	AM21G	7/8/08		td
Pyruvic Acid	U	< 10 0	10 0	mg/L	AM21G	7/8/08		td



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page. Page 23 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #			Sampled Date/Time	Received		
DP98INJ-12	Water	P0806357-08			19 Jun 08 17:10	23 Jun 08 12:57		
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date		By
WetChem								
N Chloride		47.00	1.00	mg/L	9056	6/24/08	23:58	md
N Sulfate		3.50	1.00	mg/L	9056	6/24/08	23:58	md
N Total Organic Carbon		290.0	25.0	mg/L	9060	6/30/08		md
Metals								
N Arsenic		0.037	0.010	mg/L	6010B	6/25/08		ak
N Manganese	M	25.000	0.050	mg/L	6010B	6/25/08		ak
N Selenium		0.022	0.020	mg/L	6010B	6/25/08		ak
Volatiles								
N 1,1,1,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,1,1-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,1,2,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,1,2-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,1-Dichloroethane		1.2	1	ug/L	8260B	6/27/08		hg
N 1,1-Dichloroethene		44.0	1	ug/L	8260B	6/27/08		hg
N 1,1-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2,3-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2,3-Trichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2,4-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2,4-Trimethylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2-Dibromo-3-chloropropane	U	< 5.0	5	ug/L	8260B	6/27/08		hg
N 1,2-Dibromoethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,3,5-Trimethylbenzene		4.3	1	ug/L	8260B	6/27/08		hg
N 1,3-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,3-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 1,4-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 2,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 2-Butanone	U	< 5.0	5	ug/L	8260B	6/27/08		hg
N 2-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 2-Hexanone	U	< 5.0	5	ug/L	8260B	6/27/08		hg
N 4-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N 4-Methyl-2-pentanone	U	< 5.0	5	ug/L	8260B	6/27/08		hg
N Acetone	U	< 10.0	10	ug/L	8260B	6/27/08		hg
N Benzene		1.6	1	ug/L	8260B	6/27/08		hg
N Bromobenzene	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N Bromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N Bromodichloromethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N Bromoform	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N Bromomethane	U	< 1.0	1	ug/L	8260B	6/27/08		hg
N Carbon Disulfide	U	< 5.0	5	ug/L	8260B	6/27/08		hg



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 24 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #			Sampled Date/Time	Received	
DP98INJ-12	Water	P0806357-08			19 Jun. 08 17:10	23 Jun. 08 12:57	
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
Volatiles							
N Carbon tetrachloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chlorobenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloroethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloroform	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Chloromethane		4.7	1	ug/L	8260B	6/27/08	hg
N cis-1,2-Dichloroethene		12000.0	100.0	ug/L	8260B	7/8/08	cs
N cis-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromochloromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dibromomethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Dichlorodifluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Ethylbenzene		2.0	1	ug/L	8260B	6/27/08	hg
N Hexachlorobutadiene	U	< 2.0	2	ug/L	8260B	6/27/08	hg
N Isopropylbenzene		6.2	1	ug/L	8260B	6/27/08	hg
N m & p-Xylene	U	< 2.0	2	ug/L	8260B	6/27/08	hg
N Methylene Chloride	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Methyl-t-butyl ether	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Naphthalene		30.0	1	ug/L	8260B	6/27/08	hg
N n-Butylbenzene		6.3	1	ug/L	8260B	6/27/08	hg
N n-Propylbenzene		3.9	1	ug/L	8260B	6/27/08	hg
N o-Xylene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N p-Isopropyltoluene		3.5	1	ug/L	8260B	6/27/08	hg
N sec-Butylbenzene		6.2	1	ug/L	8260B	6/27/08	hg
N Styrene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N tert-Butyl alcohol	U	< 5.0	5	ug/L	8260B	6/27/08	hg
N tert-Butylbenzene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Tetrachloroethene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Toluene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N trans-1,2-Dichloroethene		23.0	1	ug/L	8260B	6/27/08	hg
N trans-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Trichloroethene		4.4	1	ug/L	8260B	6/27/08	hg
N Trichlorofluoromethane	U	< 1.0	1	ug/L	8260B	6/27/08	hg
N Vinyl Chloride		200.0	50	ug/L	8260B	7/1/08	cs

SURROGATE:

4-Bromofluorobenzene	112.00 %
Dibromofluoromethane	116.00 %
Toluene-d8	118.00 %

Risk Analysis

N Ethane		0.170	0.025	ug/L	AM20GAX	7/3/08	rw
N Ethene		1.200	0.025	ug/L	AM20GAX	7/3/08	rw
N Methane	M	14000.000	0.100	ug/L	AM20GAX	7/3/08	rw

Sample Receiving

Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

<u>Sample Description</u>	<u>Matrix</u>	<u>Lab Sample #</u>	<u>Sampled Date/Time</u>	<u>Received</u>				
DP98INJ-12	Water	P0806357-08	19 Jun 08 17:10	23 Jun. 08 12:57				
<u>Analyte(s)</u>	<u>Flag</u>	<u>Result</u>	<u>PQL</u>	<u>Units</u>	<u>Method #</u>	<u>Analysis Date</u>	<u>By</u>	
SampleReceiving								
Dehalococcoides	L	Done	0.0	NONE	DHC	6/21/08 13:29	mi	
SemiVolatiles								
Acetic Acid		630.0	10.0	mg/L	AM21G	7/8/08	td	
Butyric Acid		21.0	1	mg/L	AM21G	7/8/08	td	
Lactic Acid	U	< 25.0	25	mg/L	AM21G	7/8/08	td	
Propionic Acid		13.0	1	mg/L	AM21G	7/8/08	td	
Pyruvic Acid	U	< 10.0	10	mg/L	AM21G	7/8/08	td	



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
TB-2-06-2008	Water	P0806357-09	19 Jun. 08 17:30	23 Jun. 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
Volatiles							
N 1,1,1,2-Tetrachloroethane		2.7	1	ug/L	8260B	6/30/08	CS
N 1,1,1-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,1,2,2-Tetrachloroethane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,1,2-Trichloroethane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,1-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,1-Dichloroethene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,1-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,2,3-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,2,3-Trichloropropane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,2,4-Trichlorobenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,2,4-Trimethylbenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,2-Dibromo-3-chloropropane	U	< 5.0	5	ug/L	8260B	6/30/08	CS
N 1,2-Dibromoethane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,2-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,2-Dichloroethane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,3,5-Trimethylbenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,3-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,3-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 1,4-Dichlorobenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 2,2-Dichloropropane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 2-Butanone	U	< 5.0	5	ug/L	8260B	6/30/08	CS
N 2-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 2-Hexanone	U	< 5.0	5	ug/L	8260B	6/30/08	CS
N 4-Chlorotoluene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N 4-Methyl-2-pentanone	U	< 5.0	5	ug/L	8260B	6/30/08	CS
N Acetone	U	< 10.0	10	ug/L	8260B	6/30/08	CS
N Benzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Bromobenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Bromochloromethane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Bromodichloromethane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Bromoform	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Bromomethane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Carbon Disulfide	U	< 5.0	5	ug/L	8260B	6/30/08	CS
N Carbon tetrachloride	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Chlorobenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Chloroethane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Chloroform	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Chloromethane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N cis-1,2-Dichloroethene	B	1.8	1.0	ug/L	8260B	7/1/08	CS
N cis-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/30/08	CS



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
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 Address: 1700 Broadway
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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
TB-2-06-2008	Water	P0806357-09	19 Jun 08 17:30	23 Jun. 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
Volatiles							
N Dibromochloromethane		5.6	1	ug/L	8260B	6/30/08	CS
N Dibromomethane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Dichlorodifluoromethane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Ethylbenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Hexachlorobutadiene	U	< 2.0	2	ug/L	8260B	6/30/08	CS
N Isopropylbenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N m & p-Xylene	U	< 2.0	2	ug/L	8260B	6/30/08	CS
N Methylene Chloride	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Methyl-t-butyl ether	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Naphthalene		1.5	1	ug/L	8260B	6/30/08	CS
N n-Butylbenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N n-Propylbenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N o-Xylene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N p-Isopropyltoluene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N sec-Butylbenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Styrene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N tert-Butyl alcohol	U	< 5.0	5	ug/L	8260B	6/30/08	CS
N tert-Butylbenzene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Tetrachloroethene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Toluene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N trans-1,2-Dichloroethene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N trans-1,3-Dichloropropene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Trichloroethene	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Trichlorofluoromethane	U	< 1.0	1	ug/L	8260B	6/30/08	CS
N Vinyl Chloride	U	< 1.0	1	ug/L	8260B	6/30/08	CS

SURROGATE:

4-Bromofluorobenzene	104.00 %
Dibromofluoromethane	108.00 %
Toluene-d8	112.00 %



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
DP98MW-05 MS	Water	P0806357-10	19 Jun. 08 13:20	23 Jun. 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
Volatiles							
N 1,1,1,2-Tetrachloroethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,1,1-Trichloroethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,1,2,2-Tetrachloroethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,1,2-Trichloroethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,1-Dichloroethane	J	1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,1-Dichloroethene		120.0	1.0	ug/L	8260B	6/30/08	CS
N 1,1-Dichloropropene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,2,3-Trichlorobenzene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,2,3-Trichloropropane		21.0	1.0	ug/L	8260B	6/30/08	CS
N 1,2,4-Trichlorobenzene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,2,4-Trimethylbenzene		1.1	1.0	ug/L	8260B	6/30/08	CS
N 1,2-Dibromo-3-chloropropane	U	< 5.0	5.0	ug/L	8260B	6/30/08	CS
N 1,2-Dibromoethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,2-Dichlorobenzene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,2-Dichloroethane		1.1	1.0	ug/L	8260B	6/30/08	CS
N 1,2-Dichloropropane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,3,5-Trimethylbenzene		12.0	1.0	ug/L	8260B	6/30/08	CS
N 1,3-Dichlorobenzene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,3-Dichloropropane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,4-Dichlorobenzene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 2,2-Dichloropropane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 2-Butanone	J	4.1	5.0	ug/L	8260B	6/30/08	CS
N 2-Chlorotoluene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 2-Hexanone	U	< 5.0	5.0	ug/L	8260B	6/30/08	CS
N 4-Chlorotoluene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 4-Methyl-2-pentanone	U	< 5.0	5.0	ug/L	8260B	6/30/08	CS
N Acetone	J	4.0	10.0	ug/L	8260B	6/30/08	CS
N Benzene		51.0	1.0	ug/L	8260B	6/30/08	CS
N Bromobenzene		2.2	1.0	ug/L	8260B	6/30/08	CS
N Bromochloromethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Bromodichloromethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Bromoform	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Bromomethane	B	1.6	1.0	ug/L	8260B	6/30/08	CS
N Carbon Disulfide	U	< 5.0	5.0	ug/L	8260B	6/30/08	CS
N Carbon tetrachloride	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Chlorobenzene		50.0	1.0	ug/L	8260B	6/30/08	CS
N Chloroethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Chloroform	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Chloromethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N cis-1,2-Dichloroethene	E	1700.0	1.0	ug/L	8260B	6/30/08	CS
N cis-1,3-Dichloropropene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
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 Denver, CO 80290

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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
DP98MW-05 MS	Water	P0806357-10	19 Jun 08 13:20	23 Jun 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
Volatiles							
N Dibromochloromethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Dibromomethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Dichlorodifluoromethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Ethylbenzene		16.0	1.0	ug/L	8260B	6/30/08	CS
N Hexachlorobutadiene	U	< 2.0	2.0	ug/L	8260B	6/30/08	CS
N Isopropylbenzene		25.0	1.0	ug/L	8260B	6/30/08	CS
N m & p-Xylene	J	1.5	2.0	ug/L	8260B	6/30/08	CS
N Methylene Chloride	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Methyl-t-butyl ether	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Naphthalene		17.0	1.0	ug/L	8260B	6/30/08	CS
N n-Butylbenzene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N n-Propylbenzene		22.0	1.0	ug/L	8260B	6/30/08	CS
N o-Xylene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N p-Isopropyltoluene		11.0	1.0	ug/L	8260B	6/30/08	CS
N sec-Butylbenzene		15.0	1.0	ug/L	8260B	6/30/08	CS
N Styrene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N tert-Butyl alcohol	U	< 5.0	5.0	ug/L	8260B	6/30/08	CS
N tert-Butylbenzene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Tetrachloroethene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Toluene		50.0	1.0	ug/L	8260B	6/30/08	CS
N trans-1,2-Dichloroethene		33.0	1.0	ug/L	8260B	6/30/08	CS
N trans-1,3-Dichloropropene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Trichloroethene		160.0	1.0	ug/L	8260B	6/30/08	CS
N Trichlorofluoromethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Vinyl Chloride		63.0	1.0	ug/L	8260B	6/30/08	CS

SURROGATE:

4-Bromofluorobenzene	106.00 %
Dibromofluoromethane	108.00 %
Toluene-d8	112.00 %



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

Page: Page 30 of 50
 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #	Sampled Date/Time	Received			
DP98MW-05 MSD	Water	P0806357-11	19 Jun 08 13:20	23 Jun 08 12:57			
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
Volatiles							
N 1,1,1,2-Tetrachloroethane		1.9	1.0	ug/L	8260B	6/30/08	CS
N 1,1,1-Trichloroethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,1,2,2-Tetrachloroethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,1,2-Trichloroethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,1-Dichloroethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,1-Dichloroethene		120.0	1.0	ug/L	8260B	6/30/08	CS
N 1,1-Dichloropropene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,2,3-Trichlorobenzene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,2,3-Trichloropropane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,2,4-Trichlorobenzene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,2,4-Trimethylbenzene		1.1	1.0	ug/L	8260B	6/30/08	CS
N 1,2-Dibromo-3-chloropropane	U	< 5.0	5.0	ug/L	8260B	6/30/08	CS
N 1,2-Dibromoethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,2-Dichlorobenzene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,2-Dichloroethane		1.2	1.0	ug/L	8260B	6/30/08	CS
N 1,2-Dichloropropane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,3,5-Trimethylbenzene		12.0	1.0	ug/L	8260B	6/30/08	CS
N 1,3-Dichlorobenzene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,3-Dichloropropane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 1,4-Dichlorobenzene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 2,2-Dichloropropane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 2-Butanone	J	4.1	5.0	ug/L	8260B	6/30/08	CS
N 2-Chlorotoluene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 2-Hexanone	U	< 5.0	5.0	ug/L	8260B	6/30/08	CS
N 4-Chlorotoluene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N 4-Methyl-2-pentanone	U	< 5.0	5.0	ug/L	8260B	6/30/08	CS
N Acetone	J	4.0	10.0	ug/L	8260B	6/30/08	CS
N Benzene		52.0	1.0	ug/L	8260B	6/30/08	CS
N Bromobenzene		2.2	1.0	ug/L	8260B	6/30/08	CS
N Bromochloromethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Bromodichloromethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Bromoform	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Bromomethane	B	1.3	1.0	ug/L	8260B	6/30/08	CS
N Carbon Disulfide	U	< 5.0	5.0	ug/L	8260B	6/30/08	CS
N Carbon tetrachloride	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Chlorobenzene		52.0	1.0	ug/L	8260B	6/30/08	CS
N Chloroethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Chloroform	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Chloromethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N cis-1,2-Dichloroethene	E	1600.0	1.0	ug/L	8260B	6/30/08	CS
N cis-1,3-Dichloropropene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Sample Description	Matrix	Lab Sample #			Sampled Date/Time		Received
DP98MW-05 MSD	Water	P0806357-11			19 Jun 08 13.20		23 Jun 08 12.57
Analyte(s)	Flag	Result	PQL	Units	Method #	Analysis Date	By
Volatiles							
N Dibromochloromethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Dibromomethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Dichlorodifluoromethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Ethylbenzene		16.0	1.0	ug/L	8260B	6/30/08	CS
N Hexachlorobutadiene	U	< 2.0	2.0	ug/L	8260B	6/30/08	CS
N Isopropylbenzene		25.0	1.0	ug/L	8260B	6/30/08	CS
N m & p-Xylene	J	1.6	2.0	ug/L	8260B	6/30/08	CS
N Methylene Chloride	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Methyl-t-butyl ether	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Naphthalene		20.0	1.0	ug/L	8260B	6/30/08	CS
N n-Butylbenzene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N n-Propylbenzene		21.0	1.0	ug/L	8260B	6/30/08	CS
N o-Xylene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N p-Isopropyltoluene		11.0	1.0	ug/L	8260B	6/30/08	CS
N sec-Butylbenzene		15.0	1.0	ug/L	8260B	6/30/08	CS
N Styrene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N tert-Butyl alcohol	U	< 5.0	5.0	ug/L	8260B	6/30/08	CS
N tert-Butylbenzene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Tetrachloroethene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Toluene		50.0	1.0	ug/L	8260B	6/30/08	CS
N trans-1,2-Dichloroethene		30.0	1.0	ug/L	8260B	6/30/08	CS
N trans-1,3-Dichloropropene	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Trichloroethene		160.0	1.0	ug/L	8260B	6/30/08	CS
N Trichlorofluoromethane	U	< 1.0	1.0	ug/L	8260B	6/30/08	CS
N Vinyl Chloride		60.0	1.0	ug/L	8260B	6/30/08	CS
SURROGATE:							
4-Bromofluorobenzene						106.00 %	
Dibromofluoromethane						108.00 %	
Toluene-d8						110.00 %	



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmhurst
 Client Proj #: 745255-30000

Prep Method: Acid Digestions of Aqueous samples and extracts for tc
Analysis Method: Inductively Coupled Plasma-Atomic Emission Spectrometry

M080625016-MB

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>RDL</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Arsenic	< 0.010 mg/L		0.010		- NA
Manganese	< 0.010 mg/L		0.010		- NA
Selenium	< 0.020 mg/L		0.020		- NA

M080625016-LCS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Arsenic	0.510 mg/L	0.50	102.00	80 - 120
Manganese	2.300 mg/L	2.50	92.00	80 - 120
Selenium	0.490 mg/L	0.50	98.00	80 - 120

P0806357-04A-DUP

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>	<u>RPD</u>	<u>RPD Ctl Limits</u>
Arsenic	0.037 mg/L			- NA	2.74	0 - 20
Manganese	20.000 mg/L			- NA	4.88	0 - 20
Selenium	0.016 mg/L			- NA	0.00	0 - 20

P0806357-04A-MS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Arsenic	2.200 mg/L	2.00	108.00	75 - 125
Manganese	21.000 mg/L	0.50	0.00	75 - 125
Selenium	2.000 mg/L	2.00	99.00	75 - 125

 Outlined Results indicate results outside of Control limits



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Prep Method: Anions by ion chromatography
Analysis Method: Anions by ion chromatography

M080627010-MB

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>RDL</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Chloride	< 1 00 mg/L		1 00		- NA
Sulfate	< 1 00 mg/L		1 00		- NA

M080627010-LCS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Chloride	11 00 mg/L	10.00	110 00	80 - 120
Sulfate	11 00 mg/L	10 00	110 00	80 - 120

P0806373-01A-DUP

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>	<u>RPD</u>	<u>RPD Ctl Limits</u>
Chloride	4.60 mg/L			- NA	0.00	0 - 20
Sulfate	3 50 mg/L			- NA	0 00	0 - 20

P0806376-01A-DUP

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>	<u>RPD</u>	<u>RPD Ctl Limits</u>
Chloride	46.00 mg/L			- NA	4 44	0 - 20
Sulfate	49 00 mg/L			- NA	0 00	0 - 20

P0806373-01A-MS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Chloride	52 00 mg/L	50.00	95 00	70 - 130
Sulfate	49 00 mg/L	50.00	91 00	70 - 130

P0806376-01A-MS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Chloride	91 00 mg/L	50.00	94 00	70 - 130
Sulfate	95 00 mg/L	50.00	92 00	70 - 130

 Outlined Results indicate results outside of Control limits



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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Prep Method: Total Organic Carbon
Analysis Method: Total Organic Carbon

M080629004-MB

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>RDL</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Total Organic Carbon	< 5.0 mg/L		5.0		- NA

M080629004-LCS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Total Organic Carbon	55.0 mg/L	55.30	99.00	70 - 130

P0806305-01A-DUP

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>	<u>RPD</u>	<u>RPD Ctl Limits</u>
Total Organic Carbon	2.6 mg/L			- NA	0.00	0 - 20

P0806357-06A-DUP

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>	<u>RPD</u>	<u>RPD Ctl Limits</u>
Total Organic Carbon	1.8 mg/L			- NA	0.00	0 - 20

P0806305-02A-MS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Total Organic Carbon	54.0 mg/L	50.00	101.00	70 - 130

Outlined Results indicate results outside of Control limits



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
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 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Prep Method: Total Organic Carbon
Analysis Method: Total Organic Carbon

M080701004-MB

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>RDL</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Total Organic Carbon	< 5.0 mg/L		5.0		- NA

M080701004-LCS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Total Organic Carbon	56.0 mg/L	55.30	101.00	70 - 130

P0806373-01A-DUP

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>	<u>RPD</u>	<u>RPD Ctl Limits</u>
Total Organic Carbon	< 5.0 mg/L			- NA	0.00	0 - 20

P0806389-01A-DUP

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>	<u>RPD</u>	<u>RPD Ctl Limits</u>
Total Organic Carbon	< 5.0 mg/L			- NA	0.00	0 - 20

P0806373-02A-MS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Total Organic Carbon	51.0 mg/L	50.00	102.00	70 - 130

P0806389-02A-MS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Total Organic Carbon	56.0 mg/L	50.00	112.00	70 - 130

 Outlined Results indicate results outside of Control limits



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Lab Proj #: P0806357
Report Date: 07/09/08
Client Proj Name: Elmendorf
Client Proj #: 745255-30000

Prep Method: Dehalococcoides

Analysis Method: Dehalococcoides

There are no QC Samples in this Batch



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

☐ Outlined Results indicate results outside of Control limits

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Prep Method: Analysis of Volatile Fatty Acids in Water
Analysis Method: Analysis of Volatile Fatty Acids in Water

M080703013-MB

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>RDL</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Acetic Acid	< 1.0 mg/L		1.0		- NA
Propionic Acid	< 1.0 mg/L		1.0		- NA
Butyric Acid	< 1.0 mg/L		1.0		- NA
Lactic Acid	< 25.0 mg/L		25.0		- NA
Pyruvic Acid	< 10.0 mg/L		10.0		- NA

M080703013-LCS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Acetic Acid	110.0 mg/L	100.00	110.00	70 - 130
Propionic Acid	110.0 mg/L	100.00	110.00	70 - 130
Butyric Acid	120.0 mg/L	100.00	120.00	70 - 130
Lactic Acid	87.0 mg/L	100.00	87.00	70 - 130
Pyruvic Acid	120.0 mg/L	100.00	120.00	70 - 130

P0806325-01A-MS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Acetic Acid	120.0 mg/L	100.00	106.00	70 - 130
Propionic Acid	110.0 mg/L	100.00	110.00	70 - 130
Butyric Acid	110.0 mg/L	100.00	110.00	70 - 130
Lactic Acid	85.0 mg/L	100.00	85.00	70 - 130
Pyruvic Acid	120.0 mg/L	100.00	120.00	70 - 130

P0806325-01A-MSD

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>	<u>RPD</u>	<u>RPD Ctl Limits</u>
Acetic Acid	120.0 mg/L	100.00	106.00	70 - 130	0.00	0 - 20
Propionic Acid	110.0 mg/L	100.00	110.00	70 - 130	0.00	0 - 20
Butyric Acid	110.0 mg/L	100.00	110.00	70 - 130	0.00	0 - 20
Lactic Acid	85.0 mg/L	100.00	85.00	70 - 130	0.00	0 - 20
Pyruvic Acid	120.0 mg/L	100.00	120.00	70 - 130	0.00	0 - 20

 Outlined Results indicate results outside of Control limits



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Prep Method: Light Hydrocarbons (C1-C4) in Water
Analysis Method: Light Hydrocarbons (C1-C4) in Water

M080703016-MB

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>RDL</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Ethane	< 0.025 ug/L		0.025		- NA
Ethene	< 0.025 ug/L		0.025		- NA
Methane	< 0.100 ug/L		0.100		- NA

M080703016-LCS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Ethane	47.000 ug/L	41.68	113.00	75 - 125
Ethene	46.000 ug/L	38.89	118.00	75 - 125
Methane	840.000 ug/L	822.80	102.00	75 - 125

M080703016-LCSD

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>	<u>RPD</u>	<u>RPD Ctl Limits</u>
Ethane	46.000 ug/L	41.68	110.00	75 - 125	2.15	0 - 20
Ethene	45.000 ug/L	38.89	116.00	75 - 125	2.2	0 - 20
Methane	810.000 ug/L	822.80	98.00	75 - 125	3.64	0 - 20

P0806439-19A-MS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Ethane	47.000 ug/L	41.68	113.00	70 - 130
Ethene	47.000 ug/L	38.89	120.00	70 - 130
Methane	17000.000 ug/L	822.80	122.00	70 - 130

P0806439-19A-MSD

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>	<u>RPD</u>	<u>RPD Ctl Limits</u>
Ethane	46.000 ug/L	41.68	110.00	70 - 130	2.15	0 - 20
Ethene	47.000 ug/L	38.89	120.00	70 - 130	0	0 - 20
Methane	14000.000 ug/L	822.80	0.00	70 - 130	19.35	0 - 20

Outlined Results indicate results outside of Control limits



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Lab Proj #: P0806357
Report Date: 07/09/08
Client Proj Name: Elmendorf
Client Proj #: 745255-30000

Prep Method: Analysis of Volatile Fatty Acids in Water
Analysis Method: Analysis of Volatile Fatty Acids in Water

There are no QC Samples in this Batch



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Prep Method: Purge and trap for aqueous samples
Analysis Method: Low Level 8260

M080709031-MB

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>RDL</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Acetone	2.9 ug/L		10.0		- NA
1,1,1,2-Tetrachloroethane	< 1.0 ug/L		1.0		- NA
Benzene	< 1.0 ug/L		1.0		- NA
Bromochloromethane	< 1.0 ug/L		1.0		- NA
Bromodichloromethane	< 1.0 ug/L		1.0		- NA
Bromoform	< 1.0 ug/L		1.0		- NA
Bromomethane	< 1.0 ug/L		1.0		- NA
2-Butanone	< 5.0 ug/L		5.0		- NA
Carbon Disulfide	< 5.0 ug/L		5.0		- NA
Carbon tetrachloride	< 1.0 ug/L		1.0		- NA
Chlorobenzene	< 1.0 ug/L		1.0		- NA
Dibromochloromethane	< 1.0 ug/L		1.0		- NA
Chloroethane	< 1.0 ug/L		1.0		- NA
Chloroform	< 1.0 ug/L		1.0		- NA
Methylene Chloride	< 1.0 ug/L		1.0		- NA
Chloromethane	< 1.0 ug/L		1.0		- NA
1,2-Dibromo-3-chloropropane	< 5.0 ug/L		5.0		- NA
1,2-Dibromoethane	< 1.0 ug/L		1.0		- NA
Dibromomethane	< 1.0 ug/L		1.0		- NA
1,2-Dichlorobenzene	< 1.0 ug/L		1.0		- NA
1,3-Dichlorobenzene	< 1.0 ug/L		1.0		- NA
1,4-Dichlorobenzene	< 1.0 ug/L		1.0		- NA
Dichlorodifluoromethane	< 1.0 ug/L		1.0		- NA
1,1-Dichloroethane	< 1.0 ug/L		1.0		- NA
1,2-Dichloroethane	< 1.0 ug/L		1.0		- NA
1,1-Dichloroethene	< 1.0 ug/L		1.0		- NA
trans-1,2-Dichloroethene	< 1.0 ug/L		1.0		- NA
1,2-Dichloropropane	< 1.0 ug/L		1.0		- NA
cis-1,3-Dichloropropene	< 1.0 ug/L		1.0		- NA
trans-1,3-Dichloropropene	< 1.0 ug/L		1.0		- NA
Ethylbenzene	< 1.0 ug/L		1.0		- NA
2-Hexanone	< 5.0 ug/L		5.0		- NA
Isopropylbenzene	< 1.0 ug/L		1.0		- NA
4-Methyl-2-pentanone	< 5.0 ug/L		5.0		- NA
Naphthalene	< 1.0 ug/L		1.0		- NA



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

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 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

M080709031-MB

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>RDL</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Styrene	< 1.0 ug/L		1.0		- NA
1,1,2,2-Tetrachloroethane	< 1.0 ug/L		1.0		- NA
Tetrachloroethene	< 1.0 ug/L		1.0		- NA
Toluene	< 1.0 ug/L		1.0		- NA
1,2,4-Trichlorobenzene	< 1.0 ug/L		1.0		- NA
1,1,1-Trichloroethane	< 1.0 ug/L		1.0		- NA
1,1,2-Trichloroethane	< 1.0 ug/L		1.0		- NA
Trichloroethene	< 1.0 ug/L		1.0		- NA
Trichlorofluoromethane	< 1.0 ug/L		1.0		- NA
1,2,3-Trichloropropane	< 1.0 ug/L		1.0		- NA
Vinyl Chloride	< 1.0 ug/L		1.0		- NA
o-Xylene	< 1.0 ug/L		1.0		- NA
m & p-Xylene	< 2.0 ug/L		2.0		- NA
Bromobenzene	< 1.0 ug/L		1.0		- NA
tert-Butyl alcohol	< 5.0 ug/L		5.0		- NA
n-Butylbenzene	< 1.0 ug/L		1.0		- NA
cis-1,2-Dichloroethene	< 1.0 ug/L		1.0		- NA
sec-Butylbenzene	< 1.0 ug/L		1.0		- NA
tert-Butylbenzene	< 1.0 ug/L		1.0		- NA
2-Chlorotoluene	< 1.0 ug/L		1.0		- NA
4-Chlorotoluene	< 1.0 ug/L		1.0		- NA
1,3-Dichloropropane	< 1.0 ug/L		1.0		- NA
2,2-Dichloropropane	< 1.0 ug/L		1.0		- NA
1,1-Dichloropropene	< 1.0 ug/L		1.0		- NA
p-Isopropyltoluene	< 1.0 ug/L		1.0		- NA
Methyl-t-butyl ether	< 1.0 ug/L		1.0		- NA
n-Propylbenzene	< 1.0 ug/L		1.0		- NA
1,2,3-Trichlorobenzene	< 1.0 ug/L		1.0		- NA
1,2,4-Trimethylbenzene	< 1.0 ug/L		1.0		- NA
1,3,5-Trimethylbenzene	< 1.0 ug/L		1.0		- NA
Hexachlorobutadiene	< 2.0 ug/L		2.0		- NA

M080709031-LCS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Benzene	61.0 ug/L	50.00	122.00	79 - 118
Chlorobenzene	54.0 ug/L	50.00	108.00	79 - 116
1,1-Dichloroethene	63.0 ug/L	50.00	126.00	53 - 121
Toluene	61.0 ug/L	50.00	122.00	73 - 123
Trichloroethene	52.0 ug/L	50.00	104.00	66 - 118



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

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 Client Proj #: 745255-30000

P0806357-04A-MS

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Benzene	51.0	ug/L	50.00	95.00	70 - 130
Chlorobenzene	50.0	ug/L	50.00	100.00	70 - 130
1,1-Dichloroethene	120.0	ug/L	50.00	74.00	70 - 130
Toluene	50.0	ug/L	50.00	100.00	70 - 130
Trichloroethene	160.0	ug/L	50.00	80.00	70 - 130

P0806357-04A-MSD

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>	<u>RPD</u>	<u>RPD Ctl Limits</u>
Benzene	52.0	ug/L	50.00	97.00	70 - 130	1.94	0 - 20
Chlorobenzene	52.0	ug/L	50.00	104.00	70 - 130	3.92	0 - 20
1,1-Dichloroethene	120.0	ug/L	50.00	74.00	70 - 130	0	0 - 20
Toluene	50.0	ug/L	50.00	100.00	70 - 130	0	0 - 20
Trichloroethene	160.0	ug/L	50.00	80.00	70 - 130	0	0 - 20

Outlined Results indicate results outside of Control limits



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

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P0806357-01A

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	56.0 ug/L		50.00	112.00	70 - 130
Toluene-d8	58.0 ug/L		50.00	116.00	70 - 130
Dibromofluoromethane	58.0 ug/L		50.00	116.00	70 - 130

P0806357-02A

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	56.0 ug/L		50.00	112.00	70 - 130
Toluene-d8	58.0 ug/L		50.00	116.00	70 - 130
Dibromofluoromethane	57.0 ug/L		50.00	114.00	70 - 130

P0806357-03A

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	55.0 ug/L		50.00	110.00	70 - 130
Toluene-d8	58.0 ug/L		50.00	116.00	70 - 130
Dibromofluoromethane	58.0 ug/L		50.00	116.00	70 - 130

P0806357-04A

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	57.0 ug/L		50.00	114.00	70 - 130
Toluene-d8	58.0 ug/L		50.00	116.00	70 - 130
Dibromofluoromethane	58.0 ug/L		50.00	116.00	70 - 130

P0806357-05A

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	57.0 ug/L		50.00	114.00	70 - 130
Toluene-d8	59.0 ug/L		50.00	118.00	70 - 130
Dibromofluoromethane	58.0 ug/L		50.00	116.00	70 - 130

P0806357-06A

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	56.0 ug/L		50.00	112.00	70 - 130
Toluene-d8	58.0 ug/L		50.00	116.00	70 - 130
Dibromofluoromethane	58.0 ug/L		50.00	116.00	70 - 130

P0806357-07A

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	56.0 ug/L		50.00	112.00	70 - 130
Toluene-d8	58.0 ug/L		50.00	116.00	70 - 130
Dibromofluoromethane	57.0 ug/L		50.00	114.00	70 - 130

P0806357-08A

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P0806357-08A

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	56.0	ug/L.	50.00	112.00	70 - 130
Toluene-d8	59.0	ug/L.	50.00	118.00	70 - 130
Dibromofluoromethane	58.0	ug/L.	50.00	116.00	70 - 130

P0806357-10A

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	53.0	ug/L.	50.00	106.00	70 - 130
Toluene-d8	56.0	ug/L.	50.00	112.00	70 - 130
Dibromofluoromethane	54.0	ug/L.	50.00	108.00	70 - 130

P0806357-11A

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	53.0	ug/L.	50.00	106.00	70 - 130
Toluene-d8	55.0	ug/L.	50.00	110.00	70 - 130
Dibromofluoromethane	54.0	ug/L.	50.00	108.00	70 - 130

M080709031-MB

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	56.0	ug/L.	50.00	112.00	70 - 130
Toluene-d8	58.0	ug/L.	50.00	116.00	70 - 130
Dibromofluoromethane	57.0	ug/L.	50.00	114.00	70 - 130

M080709031-LCS

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	55.0	ug/L.	50.00	110.00	70 - 130
Toluene-d8	58.0	ug/L.	50.00	116.00	70 - 130
Dibromofluoromethane	57.0	ug/L.	50.00	114.00	70 - 130

P0806357-04A-MS

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	53.0	ug/L.	50.00	106.00	70 - 130
Toluene-d8	56.0	ug/L.	50.00	112.00	70 - 130
Dibromofluoromethane	55.0	ug/L.	50.00	110.00	70 - 130

P0806357-04A-MSD

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	53.0	ug/L.	50.00	106.00	70 - 130
Toluene-d8	55.0	ug/L.	50.00	110.00	70 - 130
Dibromofluoromethane	54.0	ug/L.	50.00	108.00	70 - 130

Outlined Results indicate results outside of Control limits



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

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 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Prep Method: Purge and trap for aqueous samples
Analysis Method: Low Level 8260

M080709038-MB

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>RDL</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Acetone	< 10.0 ug/L		10.0	-	NA
1,1,1,2-Tetrachloroethane	< 1.0 ug/L		1.0	-	NA
Benzene	< 1.0 ug/L		1.0	-	NA
Bromochloromethane	< 1.0 ug/L		1.0	-	NA
Bromodichloromethane	< 1.0 ug/L		1.0	-	NA
Bromoform	< 1.0 ug/L		1.0	-	NA
Bromomethane	< 1.0 ug/L		1.0	-	NA
2-Butanone	< 5.0 ug/L		5.0	-	NA
Carbon Disulfide	< 5.0 ug/L		5.0	-	NA
Carbon tetrachloride	< 1.0 ug/L		1.0	-	NA
Chlorobenzene	< 1.0 ug/L		1.0	-	NA
Dibromochloromethane	< 1.0 ug/L		1.0	-	NA
Chloroethane	< 1.0 ug/L		1.0	-	NA
Chloroform	< 1.0 ug/L		1.0	-	NA
Methylene Chloride	< 1.0 ug/L		1.0	-	NA
Chloromethane	< 1.0 ug/L		1.0	-	NA
1,2-Dibromo-3-chloropropane	< 5.0 ug/L		5.0	-	NA
1,2-Dibromoethane	< 1.0 ug/L		1.0	-	NA
Dibromomethane	< 1.0 ug/L		1.0	-	NA
1,2-Dichlorobenzene	< 1.0 ug/L		1.0	-	NA
1,3-Dichlorobenzene	< 1.0 ug/L		1.0	-	NA
1,4-Dichlorobenzene	< 1.0 ug/L		1.0	-	NA
Dichlorodifluoromethane	< 1.0 ug/L		1.0	-	NA
1,1-Dichloroethane	< 1.0 ug/L		1.0	-	NA
1,2-Dichloroethane	< 1.0 ug/L		1.0	-	NA
1,1-Dichloroethene	< 1.0 ug/L		1.0	-	NA
trans-1,2-Dichloroethene	< 1.0 ug/L		1.0	-	NA
1,2-Dichloropropane	< 1.0 ug/L		1.0	-	NA
cis-1,3-Dichloropropene	< 1.0 ug/L		1.0	-	NA
trans-1,3-Dichloropropene	< 1.0 ug/L		1.0	-	NA
Ethylbenzene	< 1.0 ug/L		1.0	-	NA
2-Hexanone	< 5.0 ug/L		5.0	-	NA
Isopropylbenzene	< 1.0 ug/L		1.0	-	NA
4-Methyl-2-pentanone	< 5.0 ug/L		5.0	-	NA
Naphthalene	< 1.0 ug/L		1.0	-	NA



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

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M080709038-MB

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>RDL</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Styrene	< 1.0 ug/L		1.0		- NA
1,1,2,2-Tetrachloroethane	< 1.0 ug/L		1.0		- NA
Tetrachloroethene	< 1.0 ug/L		1.0		- NA
Toluene	< 1.0 ug/L		1.0		- NA
1,2,4-Trichlorobenzene	< 1.0 ug/L		1.0		- NA
1,1,1-Trichloroethane	< 1.0 ug/L		1.0		- NA
1,1,2-Trichloroethane	< 1.0 ug/L		1.0		- NA
Trichloroethene	< 1.0 ug/L		1.0		- NA
Trichlorofluoromethane	< 1.0 ug/L		1.0		- NA
1,2,3-Trichloropropane	< 1.0 ug/L		1.0		- NA
Vinyl Chloride	< 1.0 ug/L		1.0		- NA
o-Xylene	< 1.0 ug/L		1.0		- NA
m & p-Xylene	< 2.0 ug/L		2.0		- NA
Bromobenzene	< 1.0 ug/L		1.0		- NA
tert-Butyl alcohol	< 5.0 ug/L		5.0		- NA
n-Butylbenzene	< 1.0 ug/L		1.0		- NA
cis-1,2-Dichloroethene	< 1.0 ug/L		1.0		- NA
sec-Butylbenzene	< 1.0 ug/L		1.0		- NA
tert-Butylbenzene	< 1.0 ug/L		1.0		- NA
2-Chlorotoluene	< 1.0 ug/L		1.0		- NA
4-Chlorotoluene	< 1.0 ug/L		1.0		- NA
1,3-Dichloropropane	< 1.0 ug/L		1.0		- NA
2,2-Dichloropropane	< 1.0 ug/L		1.0		- NA
1,1-Dichloropropene	< 1.0 ug/L		1.0		- NA
p-Isopropyltoluene	< 1.0 ug/L		1.0		- NA
Methyl-t-butyl ether	< 1.0 ug/L		1.0		- NA
n-Propylbenzene	< 1.0 ug/L		1.0		- NA
1,2,3-Trichlorobenzene	< 1.0 ug/L		1.0		- NA
1,2,4-Trimethylbenzene	< 1.0 ug/L		1.0		- NA
1,3,5-Trimethylbenzene	< 1.0 ug/L		1.0		- NA
Hexachlorobutadiene	< 2.0 ug/L		2.0		- NA

M080709038-LCS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Benzene	50.0 ug/L	50.00	100.00	79 - 118
Chlorobenzene	54.0 ug/L	50.00	108.00	79 - 116
1,1-Dichloroethene	51.0 ug/L	50.00	102.00	53 - 121
Toluene	51.0 ug/L	50.00	102.00	73 - 123
Trichloroethene	44.0 ug/L	50.00	88.00	66 - 118



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

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☐ Outlined Results indicate results outside of Control limits



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

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P0806357-09A

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	52.0 ug/L		50.00	104.00	70 - 130
Toluene-d8	56.0 ug/L		50.00	112.00	70 - 130
Dibromofluoromethane	54.0 ug/L		50.00	108.00	70 - 130

M080709038-MB

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	52.0 ug/L		50.00	104.00	70 - 130
Toluene-d8	55.0 ug/L		50.00	110.00	70 - 130
Dibromofluoromethane	54.0 ug/L		50.00	108.00	70 - 130

M080709038-LCS

	<u>Result</u>		<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
4-Bromofluorobenzene	52.0 ug/L		50.00	104.00	70 - 130
Toluene-d8	55.0 ug/L		50.00	110.00	70 - 130
Dibromofluoromethane	54.0 ug/L		50.00	108.00	70 - 130

Outlined Results indicate results outside of Control limits



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

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 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Prep Method: Purge and trap for aqueous samples
Analysis Method: Low Level 8260

M080709041-MB

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>RDL</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
cis-1,2-Dichloroethene	0.6 ug/L		1.0		- NA

Outlined Results indicate results outside of Control limits



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Client Name: Parsons Engineering Science
 Contact: Bruce Henry
 Address: 1700 Broadway
 Suite 900
 Denver, CO 80290

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 Lab Proj #: P0806357
 Report Date: 07/09/08
 Client Proj Name: Elmendorf
 Client Proj #: 745255-30000

Prep Method: Purge and trap for aqueous samples
Analysis Method: Low Level 8260

M080709040-MB

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>RDL</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Naphthalene	1 ug/L		1.0		- NA
Trichloroethene	1.1 ug/L		1.0		- NA
Vinyl Chloride	< 1.0 ug/L		1.0		- NA
cis-1,2-Dichloroethene	2.0 ug/L		1.0		- NA

M080709040-LCS

	<u>Result</u>	<u>TrueSpikeConc.</u>	<u>%Recovery</u>	<u>Ctl Limits</u>
Trichloroethene	40.0 ug/L	50.00	80.00	66 - 118

Outlined Results indicate results outside of Control limits



Data Qualifiers: J - estimated value, U - Non detect, R - Poor surrogate recovery, M - Recovery/RPD poor for MS/MSD, SAMP/DUP, B - detected in blank, S - field sample as received did not meet NELAC sample acceptance criteria, L - Subcontracted Lab used, N - NELAC certified analysis

Chain of Custody Documents

Client Name:

Client Project Number:

Bottle Type Circle or Highlight (Sample Receiving Only)		Sulfide	Nutrient	TIC	Oxygenates	D - Metals
Phenol					VFA	
G. Chem.		Coliform	Semi-VOA	Soils	LLVFA	HEM
TOC/DOC		Cations	VOA	Diss. Gas	Hydrogen	SGT-HEM
Cyanide		Anions	TPH	Vapor	AMIBA	T - Metals

Sample Receiving only to mark above dotted line

[illegible]

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Enter Bottle Type From List Above In Proper Column

P0806357

ATTACHMENT B

CONCENTRATION AND MOLAR FRACTION PLOTS

**FIGURE B.1A - CONCENTRATIONS OF CHLOROETHENES
AT UPGRADIENT LOCATION DP98MW-04**

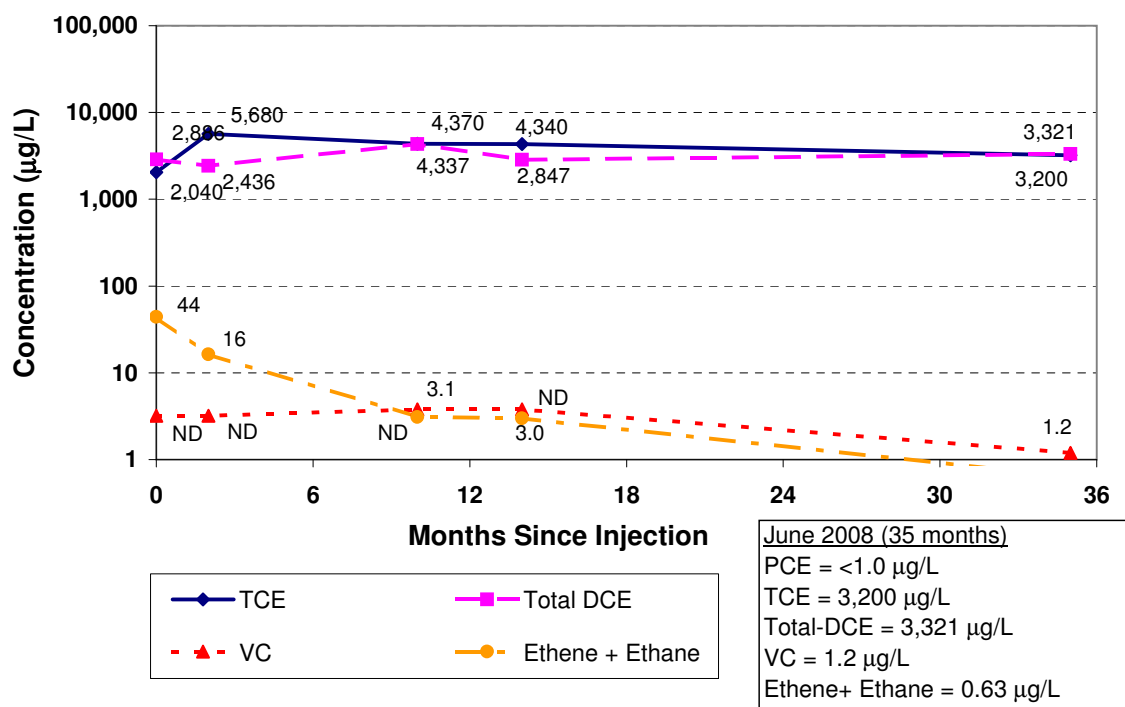


**FIGURE B1.B - MOLAR FRACTION AND TOTAL MOLAR
CHLOROETHENES AT UPGRADIENT LOCATION DP98MW-04**

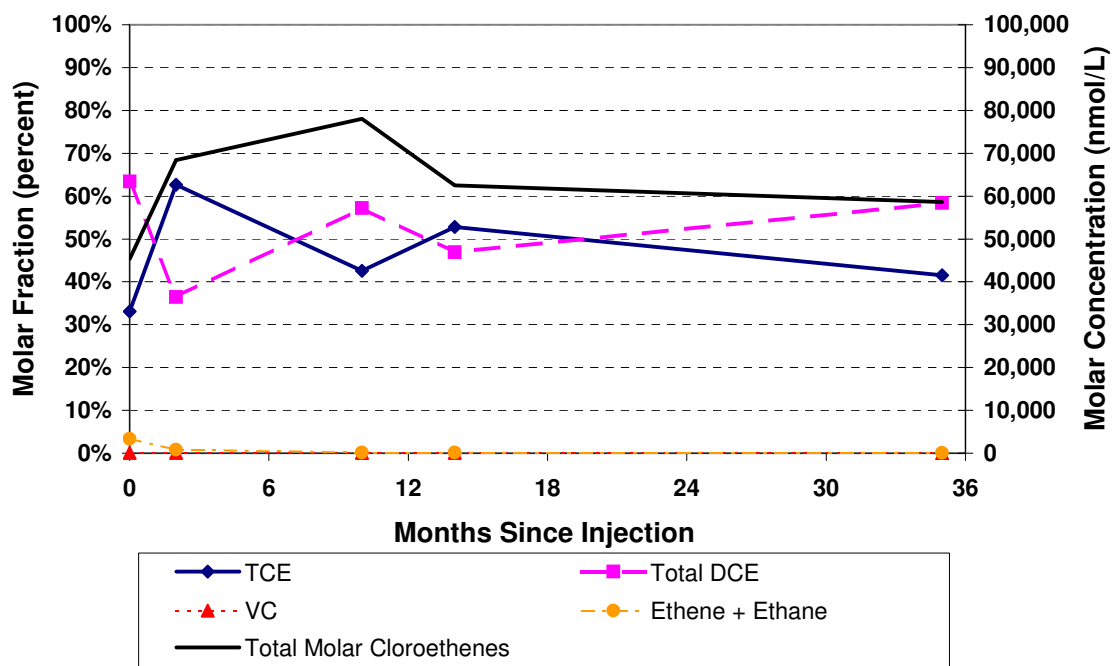


**FIGURE B.2A - CONCENTRATIONS OF CHLOROETHENES
AT INJECTION LOCATION DP98INJ-01**

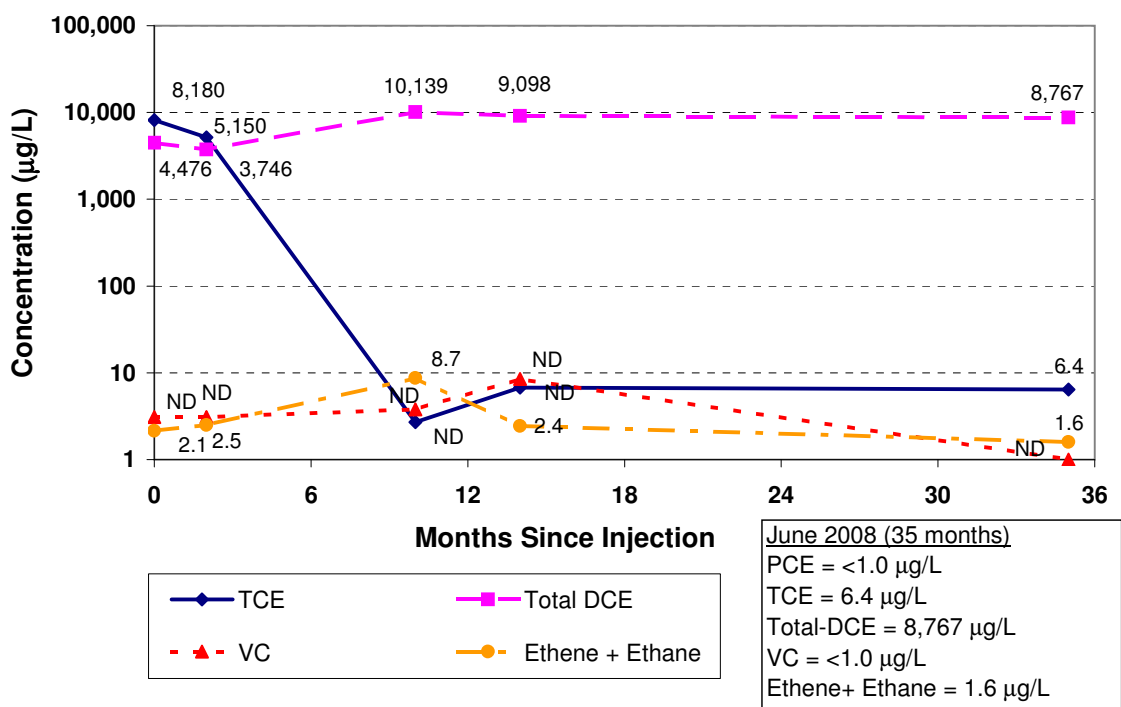


**FIGURE B.1B - MOLAR FRACTION AND TOTAL MOLAR
CHLOROETHENES AT INJECTION LOCATION DP98INJ-01**

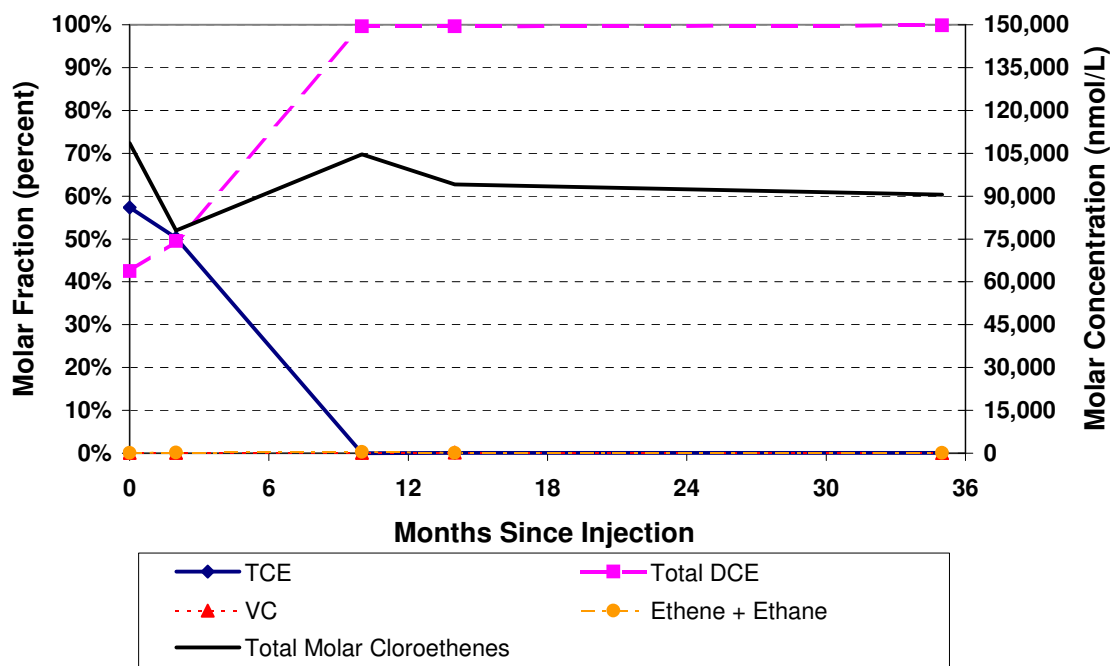


**FIGURE B.3A - CONCENTRATIONS OF CHLOROETHENES
AT INJECTION LOCATION DP98INJ-02**

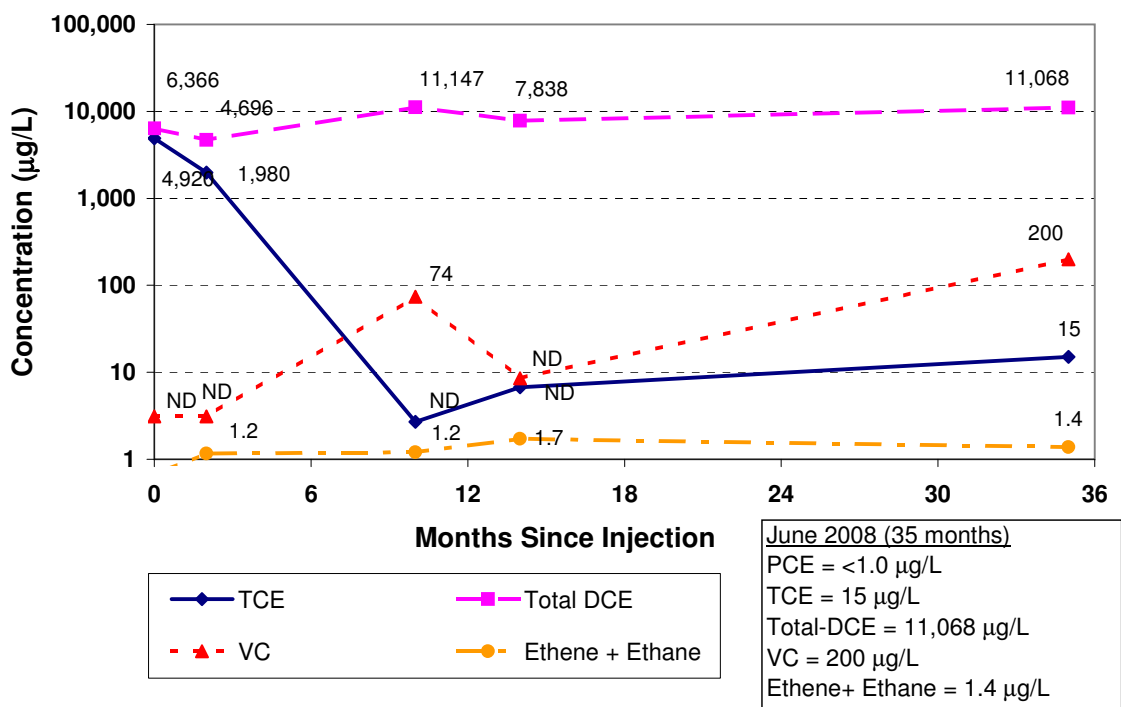


**FIGURE B.3B - MOLAR FRACTION AND TOTAL MOLAR
CHLOROETHENES AT INJECTION LOCATION DP98INJ-02**

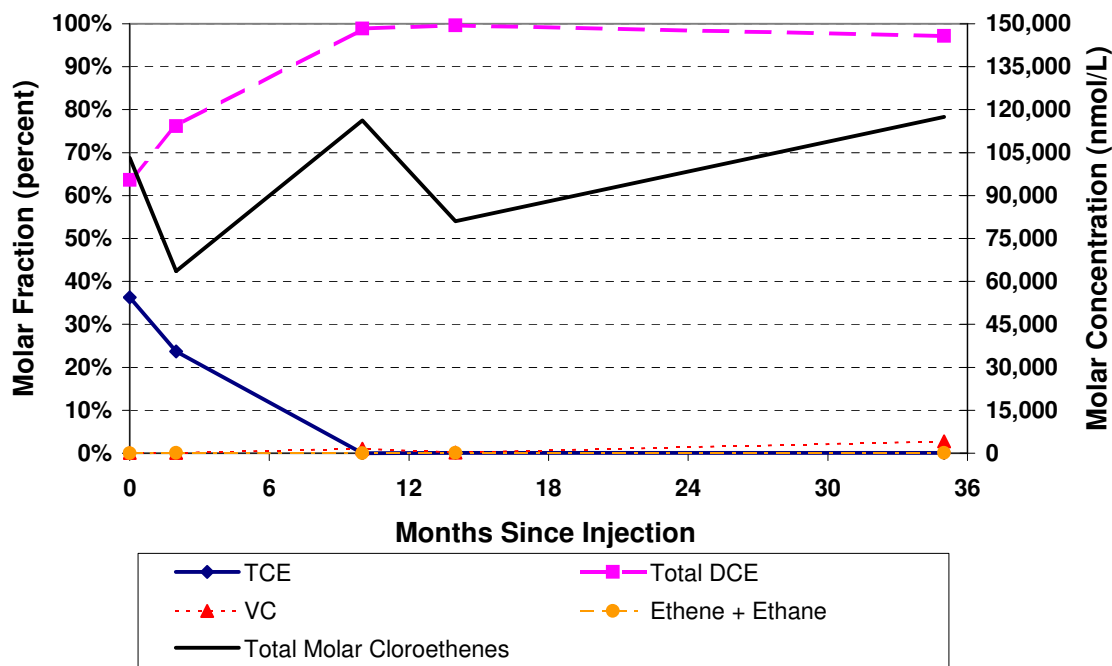


**FIGURE B.4A - CONCENTRATIONS OF CHLOROETHENES
AT INJECTION LOCATION DP98INJ-03**

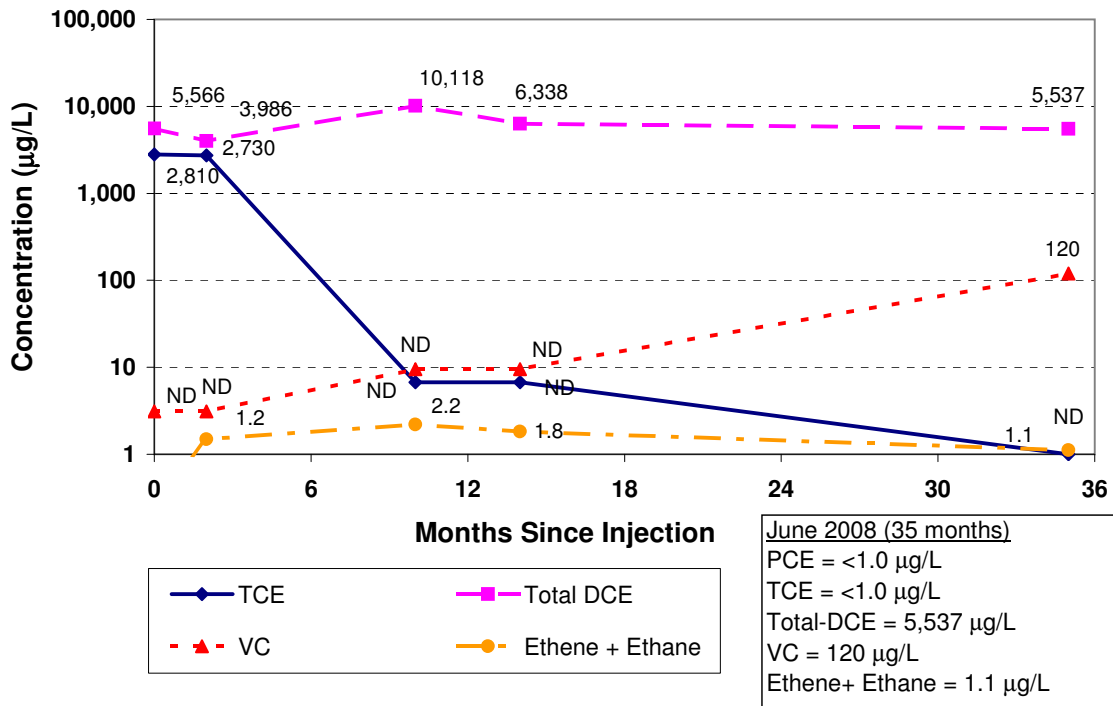


**FIGURE B.4B - MOLAR FRACTION AND TOTAL MOLAR
CHLOROETHENES AT INJECTION LOCATION DP98INJ-03**

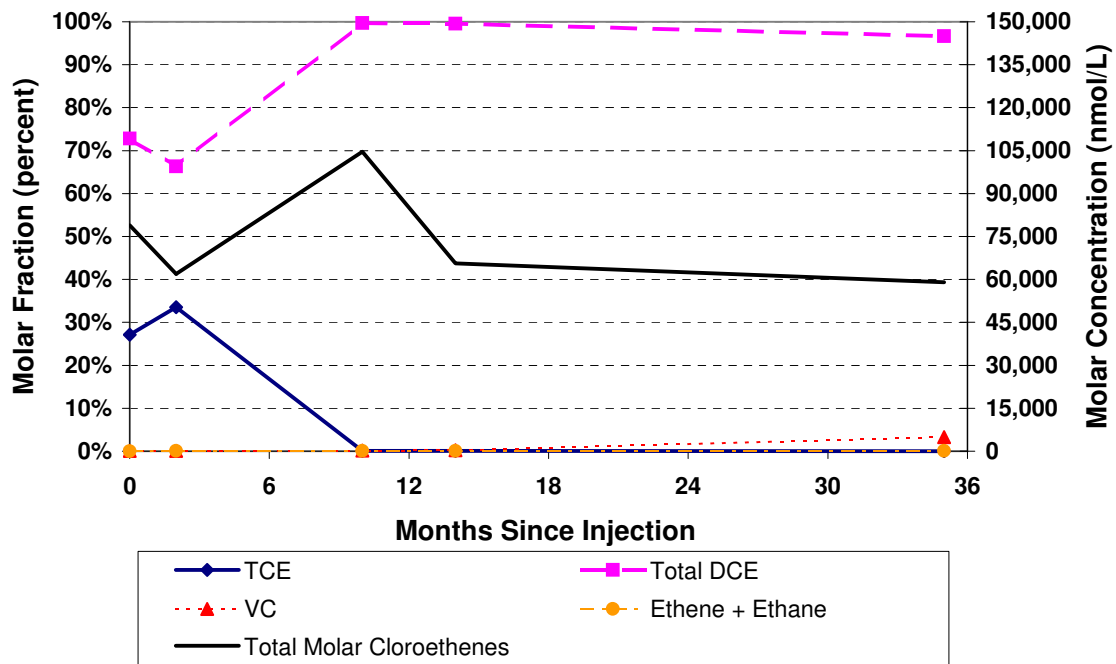


**FIGURE B.5A - CONCENTRATIONS OF CHLOROETHENES
AT DOWNGRADIENT LOCATION DP98MW-05**

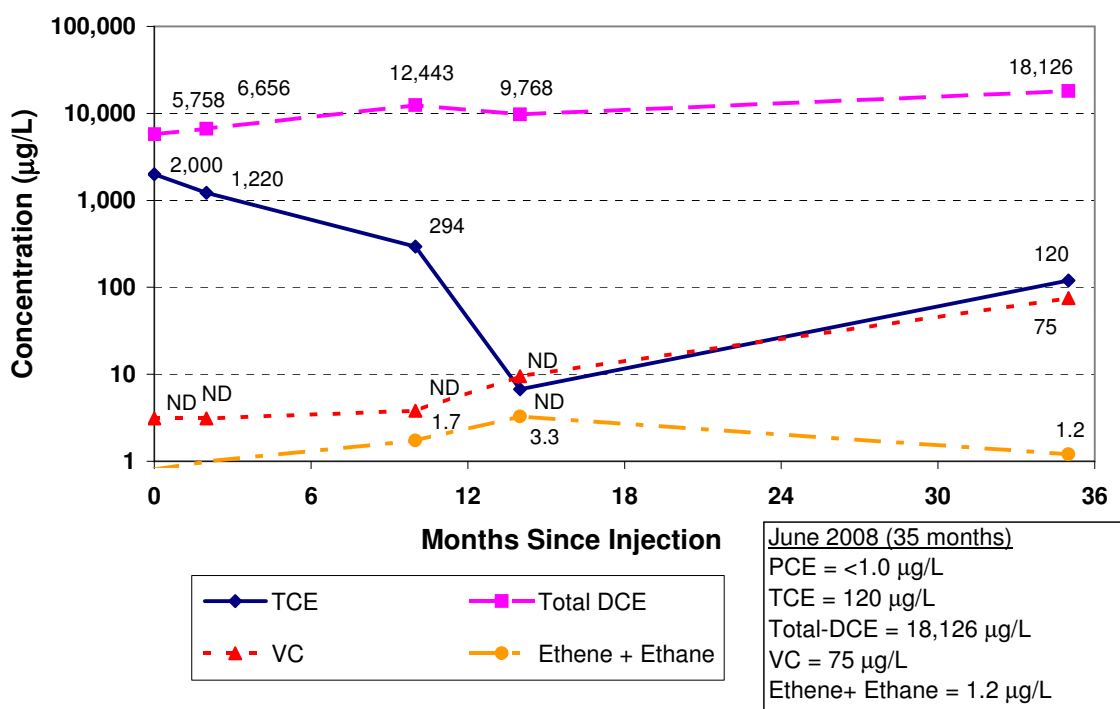


**FIGURE B.5B - MOLAR FRACTION AND TOTAL MOLAR
CHLOROETHENES AT DOWNGRADIENT LOCATION DP98MW-05**

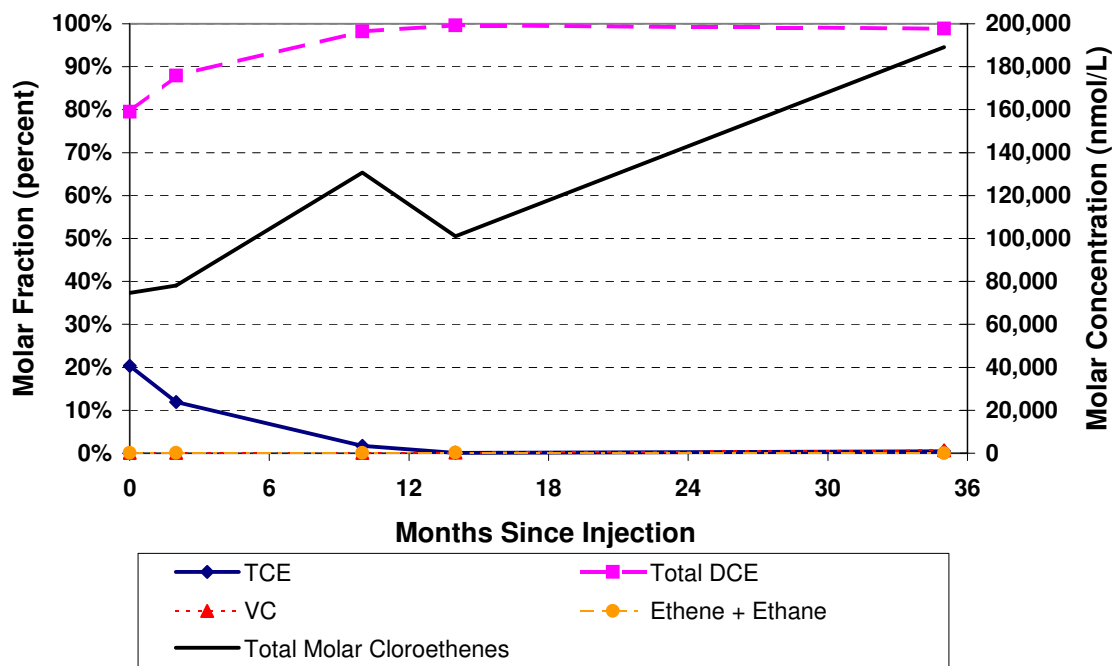


**FIGURE B.6A - CONCENTRATIONS OF CHLOROETHENES
AT DOWNGRADIANT LOCATION DP98MW-06**

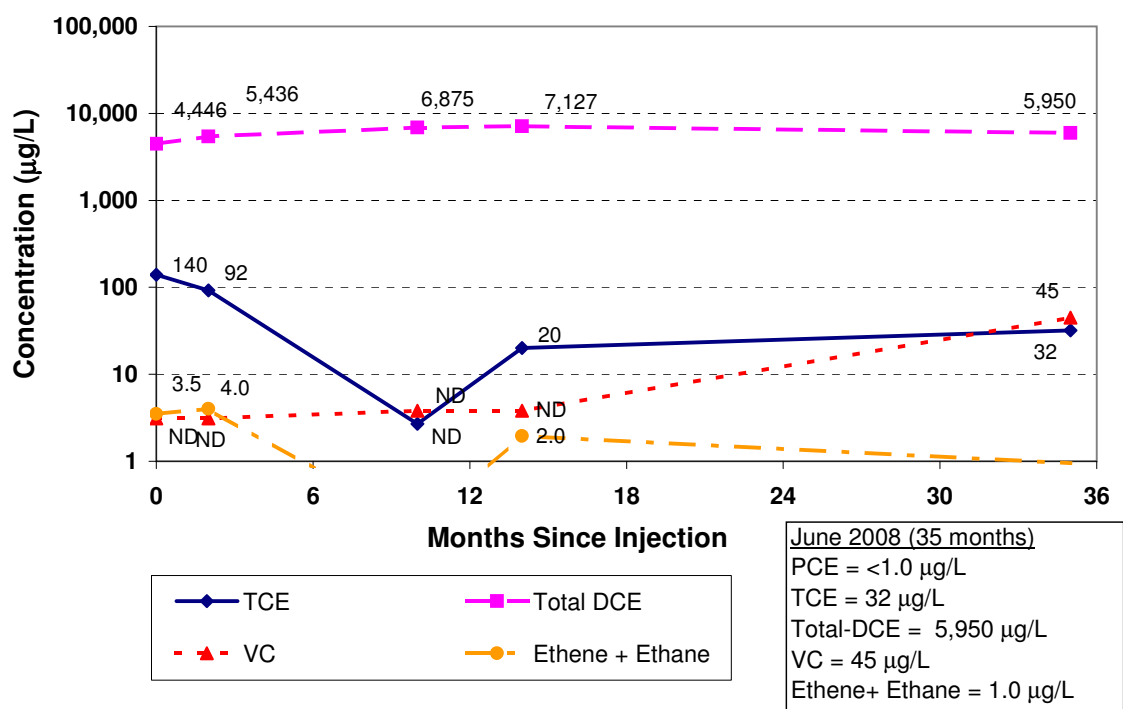


**FIGURE B.6B - MOLAR FRACTION AND TOTAL MOLAR
CHLOROETHENES AT DOWNGRADIANT LOCATION DP98MW-06**

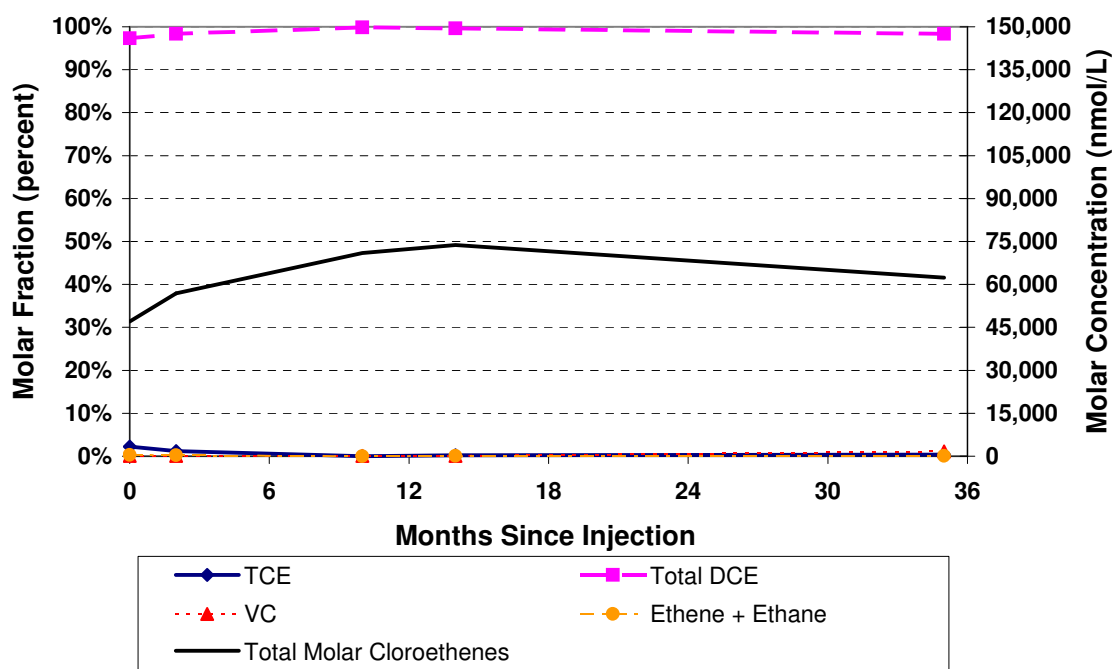


**FIGURE B.7A - CONCENTRATIONS OF CHLOROETHENES
AT DOWNGRADIENT LOCATION 41755-WL04**

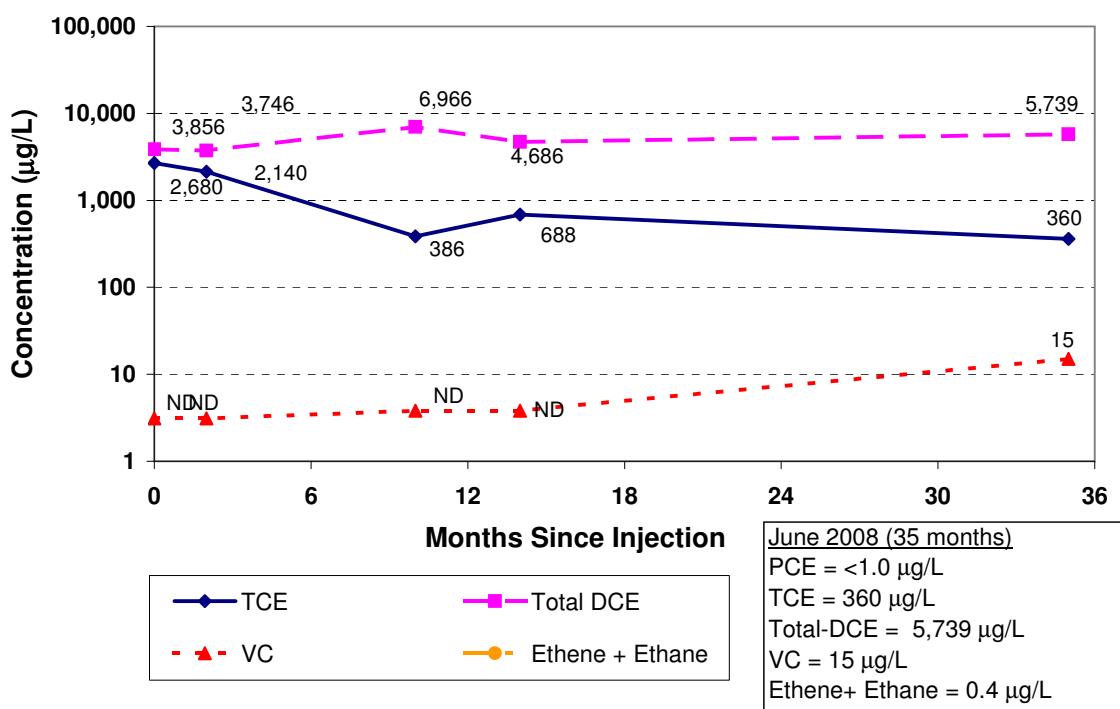


**FIGURE B.7B - MOLAR FRACTION AND TOTAL MOLAR
CHLOROETHENES AT DOWNGRADIENT LOCATION 41755-WL04**

