ESTCP
Cost and Performance Report

(ER-0515)

Bioaugmentation for Groundwater Remediation

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ESTCP

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

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COST & PERFORMANCE REPORT
Project: ER-0515

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ACRONYMS AND ABBREVIATIONS

bgs	below ground surface
BMW	bioaugmentation monitoring well
C&P	cost and performance
cDCE	cis-1,2-dichloroethene
COR	contracting officer's representative
CVOC	chlorinated volatile organic compound
DHC	*Dehalococcoides* sp.
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
ESTCP	Environmental Security Technology Certification Program
EVO	emulsified vegetable oil
EX	extraction well
FRTR	Federal Remediation Technologies Roundtable
gpm	gallon per minute
GSA	General Services Administration
IPR	in-progress review
IW	injection well
MAG-1	Magazine 1 Area (Fort Dix, NJ)
MSL	mean sea level
NAVFAC ESC	Naval Facilities Engineering Command/Engineering Service Center
NJDEP	New Jersey Department of Environmental Protection
NPV	net present value
O&M	operation and maintenance
ORP	oxidation-reduction potential
PCE	tetrachloroethene
PCR	polymerase chain reaction
pH	activity of hydrogens
P&T	pump-and-treat
PLC	programmable logic controller
PRB	permeable reactive barrier
PVC	polyvinyl chloride

qPCR	quantitative polymerase chain reaction
SCADA	Supervisory Control and Data Acquisition
SDC-9	Shaw dechlorinating consortium
SERDP	Strategic Environmental Research and Development Program
TCE	trichloroethene
the Site	MAG-1 Area at Fort Dix, New Jersey
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VC	vinyl chloride
VFA	volatile fatty acid
VOC	volatile organic carbon

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Technical material contained in this report has been approved for public release.

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

The application of bioaugmentation technology has the potential to reduce both the time and cost associated with remediating groundwater contaminated with chlorinated volatile organic compounds (CVOC), and it has become widely used as an in situ treatment alternative. The primary goals of this field demonstration were to evaluate the amount of *Dehalococcoides* sp. (DHC)-containing bacterial culture needed to effectively remediate a CVOC-contaminated plume and to determine the effect of inoculum dose on remedial time. In addition, because of the low natural activity of hydrogens (pH) at the demonstration site, the ability to increase and maintain an elevated pH sufficient for successful bioremediation by adding buffers was evaluated.

A chlorinated ethene groundwater plume present in the MAG-1 Area, Fort Dix, NJ (MAG-1) was selected for the field demonstration component of this project. Bioaugmentation using Shaw Environmental, Inc.'s (Shaw) dechlorinating consortium (SDC-9) DHC-containing culture was performed in three separate groundwater recirculation loops, with one loop bioaugmented with 1 liter (L) of culture, the second loop bioaugmented with 10 L of culture, and the third loop bioaugmented with 100 L of culture. A fourth "control" loop was not bioaugmented. Groundwater monitoring was performed to evaluate DHC growth and migration, dechlorination kinetics, and aquifer geochemistry.

The results of the demonstration were used to develop, evaluate, and refine a one-dimensional bioaugmentation fate and transport screening model. The model developed during this project provided a reasonable prediction of the data generated during the field demonstration. The ability to predict results suggests that modeling potentially can serve as an effective tool for determining bioaugmentation dosage and predicting overall remedial time frames, thus providing the Department of Defense (DoD) with more efficient and less expensive approaches for treating CVOC-contaminated groundwater.

1.2 OBJECTIVES OF THE DEMONSTRATION

Primary objectives of the field demonstration were to evaluate the amount of culture needed to effectively remediate a CVOC-contaminated plume, to determine the effect of inoculum dose on remedial time, to evaluate the effect of site characteristics on the effectiveness of the technology, and to evaluate the ability to increase and maintain an elevated pH for successful bioremediation.

1.3 DEMONSTRATION RESULTS

The results of this project demonstrated that CVOC-contaminated aquifers can be effectively remediated by using active groundwater recirculation, bioaugmentation with Shaw's SDC-9, and pH adjustment. Results of this field demonstration have provided a detailed evaluation of the use of a groundwater recirculation design for the distribution of groundwater amendments (including a trichloroethene [TCE]-degrading microbial culture), use of buffering agents to control in situ pH, and an application model to allow practitioners to plan bioaugmentation applications and predict their performance. As such, critical design and implementation issues regarding

microbial dosage requirements, remedial time frames, and system optimization have been addressed and are being made available to environmental professionals and stakeholders.

Results for the loops inoculated with 1 L and 100 L of culture showed similar rates of dechlorination. TCE concentrations in the test loop performance monitoring wells declined significantly during the demonstration, with TCE decreases in these wells ranging from 90 to 100%. Concentrations of *cis*-1,2-dichloroethene (cDCE) in test loop performance monitoring wells declined between 73 and 99% and were generally trending downward at the end of the demonstration period, while cDCE concentrations in the control loop increased during the demonstration. Transient increases (followed by decreases) in vinyl chloride (VC) were observed in five of the six test loop performance wells, with VC in two of the wells below detection at the end of the demonstration. VC was not observed in the control loop monitoring wells. Ethene data collected during the demonstration clearly indicated that complete degradation was occurring within the three test loops that were bioaugmented with SDC-9 and not within the control loop that received only electron donor, buffer, and nutrients. Final DHC concentrations in these two test loops ranged from 1.8×10^7 to 2.0×10^9 cells/L. The greatest downgradient DHC concentrations were achieved in the test loop with the greater level of CVOC contamination, rather than the loop with the greatest inoculation.

Results of this demonstration also showed that many factors, including groundwater flow velocity, contaminant concentration, groundwater chemistry, and heterogeneity of the subsurface, can affect the amount of culture needed to effectively treat CVOC-contaminated aquifers. As a result, precisely determining the amount of culture needed for a given site still requires a site-by-site evaluation. The amount of culture needed cannot be reliably determined solely by estimating the volume of water to be treated, which is currently the approach commonly used by culture vendors. In this demonstration, significantly different amounts of DHC-containing culture were added to the test treatment loops, but the final treatment results were comparable. The lowest amount of culture, however, was added in a treatment loop with the greatest volatile organic carbon (VOC) concentration and in situ growth of the culture aided in distribution of DHC and efficient treatment of the aquifer. Conversely, the greater amount of culture was added in a treatment loop with lower CVOC concentrations, and growth of the added culture was limited by the rapid degradation of the needed electron acceptors (i.e., CVOCs); distribution of the culture was presumably dominated by transport of the added culture. Ultimately, distributed DHC concentrations in both treatment loops were similar, and in both loops treatment was effective. The loop inoculated with 10 L of culture showed slower dechlorination kinetics and DHC migration/growth compared to the other two test loops due to persistent low pH conditions that were not adequately adjusted by adding buffer.

Because the results of this study demonstrated that many factors affect the amount of culture needed for effective treatment, and that selecting the amount of culture needed cannot reliably be based solely on the amount of groundwater to be treated, we developed a 1-dimensional model to aid practitioners in determining the amount of culture needed. Importantly, the 1-dimensional model reasonably described the results of the demonstration. Consequently, the model appears suitable for evaluating the effect of different DHC dosages on treatment times and effectiveness, and it will be a useful design tool for planning bioaugmentation applications. To make the

model more accessible to remediation practitioners, it is currently being incorporated into a widely used fate and transport model package, and it will be widely available in the near future.

1.4 IMPLEMENTATION ISSUES

The two major challenges encountered during the demonstration were pH adjustment of the aquifer and injection well fouling. pH adjustment, however, may not be required during most applications provided the aquifer has sufficient natural buffering capacity. Well fouling typically is of less concern during passive or semi-active application of the technology, and it may be reduced in aquifers that do not require extensive buffer addition or by using an improved injection well design.

In addition, as observed during performance of model simulations, a DHC attachment-detachment factor plays a significant role in determining the relative importance of DHC dosage on bioaugmentation kinetics (Schaefer et al., 2009). Thus, the impact of DHC dosage on bioaugmentation performance likely will need to be evaluated on a site-by-site basis. However, the model developed during this project can assist in predicting the effect of different cell dosages on in situ performance of the cultures.

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2.0 INTRODUCTION

The application of bioaugmentation technology has the potential to reduce both the time and cost associated with remediating groundwater contaminated with CVOCs. The primary goals of this field demonstration, funded by the ESTCP were to evaluate the amount of bacterial culture needed to effectively remediate a CVOC-contaminated plume and to determine the effect of inoculum dose on remedial time. The field demonstration involved the construction and operation of four groundwater recirculation loops, three of which were inoculated with a different amount of Shaw's SDC-9 dechlorinating culture. CVOC biodegradation and growth of the added organisms were monitored. In addition, because of the low natural pH at the site, the ability to increase and maintain an elevated pH sufficient for successful bioremediation by adding buffers was evaluated.

The demonstration project was performed by Shaw at the MAG-1 Area at Fort Dix, NJ. Shaw has prepared this Cost and Performance (C&P) Report to summarize the project's activities, results, conclusions, and cost information. The results of the demonstration were also used to validate a bioaugmentation treatment model and to assist the DoD in the production of a bioaugmentation guidance document. Points of contact involved in the demonstration, including investigators and sponsors, are provided in Appendix A.

2.1 BACKGROUND

Bioremediation applications for CVOCs have been applied in situ at many DoD facilities. Although bioaugmentation is gaining acceptance as a remedial technology and despite the fact that continuing field application of the technology is producing useful data to aid in its maturation, critical questions exist that can only be answered by careful laboratory research and multicondition, science-based field demonstrations. One key question addressed during this demonstration is how many organisms must be added to a site for successful application of the technology. The amount of microorganisms needed depends on contaminant concentrations, site hydrogeochemical conditions, competition by indigenous microorganisms, the relative concentration of DHC in the bioaugmentation culture, in situ growth, transport and decay of the bioaugmented culture, and various other site-specific factors, including access and shipping costs. Answers to these questions were explored through laboratory studies with site samples and by field testing the SDC-9 culture under a range of concentrations to determine a minimum required concentration. This field-scale demonstration also allowed assessment of delivery methods, distribution of the cultures in situ, and survival and growth of the culture in the subsurface.

2.2 OBJECTIVES OF THE DEMONSTRATION

Primary objectives of the pilot-scale field demonstration were to evaluate the amount of culture needed to effectively remediate a CVOC-contaminated plume, to determine the effect of inoculum dose on remedial time, and to evaluate the affect of site characteristics on the effectiveness of the technology. Critical design and implementation issues regarding microbial dosage requirements, remedial time frames, and system optimization have been addressed and are being made available to environmental professionals and stakeholders.

2.3 REGULATORY DRIVERS

Tetrachloroethylene (PCE) and TCE are suspected carcinogens, both with a current Federal Drinking Water Standard of 5 microgram per liter (µg/L). The current Federal Drinking Water Standard for cDCE is 70 µg/L (U.S. Environmental Protection Agency [USEPA], 2009). State groundwater standards are often more stringent. For example, in New Jersey (the location of the demonstration) the groundwater quality standards for PCE, TCE, and cDCE are 0.4 µg/L, 1 µg/L and 10 µg/L, respectively (New Jersey Department of Environmental Protection [NJDEP], 2008).

3.0 TECHNOLOGY

Bioaugmentation, which consists of adding exogenous microorganisms to enhance degradation of contaminants, has been utilized as a treatment technology in various settings over the past 10 years. In the case of chlorinated ethene remediation, the most accepted form of bioaugmentation involves the use of mixed anaerobic cultures containing DHC that can reductively dechlorinate the chlorinated ethenes. Currently, bioaugmentation cultures are being marketed by several vendors, but many questions remain about the technology, limiting its selection by site managers as a valid treatment alternative.

3.1 TECHNOLOGY DESCRIPTION

The predominant biodegradation pathway for chlorinated ethenes under anaerobic conditions is via microbial-mediated reductive dechlorination. During reductive dechlorination, chlorinated ethenes are used as electron acceptors, not as a source of carbon, and a chlorine atom on the ethene backbone is removed and replaced with a hydrogen atom (McCarty, 1997). Sequential dechlorination of PCE proceeds to TCE, cDCE, VC, and innocuous ethene. Because the chlorinated ethenes are used as electron acceptors during reductive dechlorination, there must be an appropriate source of electrons and a carbon source for microbial growth in order for this process to occur (Bouwer, 1994). Incomplete reductive dechlorination often results in an accumulation of cDCE and VC, indicating that the carbon source is depleted and/or that microorganisms capable of complete anaerobic reductive dechlorination are not present. Bioaugmentation is applicable to sites where adequate microbial populations are absent, as well as to sites where relatively rapid cleanup times are desired. Bioaugmentation can accelerate the reductive dechlorination process and provide dechlorinating microorganisms to areas not populated with native DHC microorganisms.

Key design criteria for applying bioaugmentation for remediating chlorinated ethene-contaminated sites include identification of a microbial culture, large-scale growth of the culture, injection the culture, and distribution optimization. A schematic of the bioaugmentation process is provided in Figure 1.

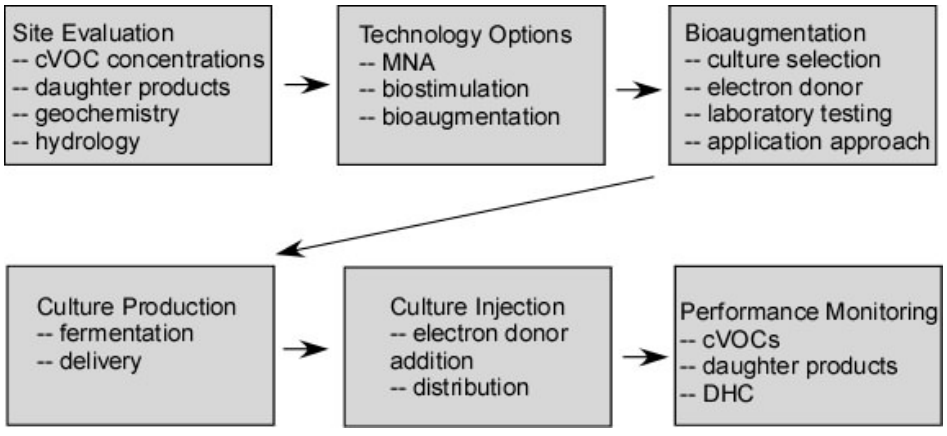

Figure 1. Bioaugmentation process.

3.1.1 Previous Testing of the Technology

The first field demonstration of pilot-scale in situ bioaugmentation with DHC was conducted by the Remediation Technologies Development Forum at Dover Air Force Base, DE (Ellis et al., 2000). A microbial consortium containing DHC enriched from soil and groundwater samples from the U.S. Department of Energy's (DOE) Pinellas site in Largo, FL, was injected into the pilot-test area. After a 90-day lag period, VC and ethene began to appear in select monitoring wells. A microcosm study and pilot-scale field test was conducted at Kelly Air Force Base in Texas (Major et al., 2002). The pilot test area was amended with methanol and acetate to establish reducing conditions and then injected with 13 L of the bioaugmentation culture. Within 200 days, the concentrations of PCE, TCE, and cDCE were reduced to below 5 grams per liter (g/L) and ethene production accounted for the observed loss in mass.

In a recent bioaugmentation application by Shaw at Naval Station Treasure Island in San Francisco, CA, a dechlorinating culture was grown to a high cell density (>4 x 10^9 cells DHC per liter) in a 750-L fermentor and injected into a recirculation loop at the site. PCE, TCE, and cDCE concentrations in the treated aquifer decreased from approximately 2 mg/L to below detection in about 70 days. VC and cDCE produced from PCE and TCE were also degraded rapidly (180 days) in the bioaugmentation test plot. Less biodegradation was observed in the test plot that received only lactate. The enriched culture used by Shaw at Treasure Island is marketed as SDC-9™, has now been used for bioaugmentation at more than 195 sites, and is marketed by six distributors under a variety of trade names.

3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The main advantages of anaerobic bioaugmentation with DHC are (1) complete reductive dechlorination of chlorinated ethenes to the innocuous by-product ethene, (2) reduced cleanup times, and (3) cost-effective remediation. In addition, bioaugmentation is a "green" and "sustainable" technology that can be performed with renewable materials (lactate, soy oil, molasses, etc.) and with minimal energy consumption. It can be applied in a wide range of aquifers and can treat even very high concentrations of chlorinated solvents. This technology has now been successfully demonstrated at full-scale at multiple sites, and commercially available bioaugmentation cultures are now widely available from multiple vendors.

One potential limitation to bioaugmentation is that effective treatment is contingent upon adequate distribution of the degradative bacteria within the treatment area. Before implementing bioaugmentation, or any in situ technology, an evaluation is necessary to consider site-specific characteristics and to determine the most effective treatment technology based on current contaminant and hydrogeochemical conditions and site access. A second potential limitation for successful bioaugmentation is that unfavorable aquifer conditions such as low pH, low temperatures, elevated dissolved oxygen (DO) levels, or lack of adequate organic carbon may limit the activity of the bioaugmentation culture or necessitate additional treatments like pH adjustment or pre-treatment to reduce DO levels. In addition, excessively low concentrations of chlorinated ethenes may not provide a sufficient source of electron acceptors needed to support halorespiration, thereby limiting in situ growth of the added culture. Excessively high concentrations of chlorinated ethenes may have a toxic effect on the added DHC population, and

the presence of some co-contaminants like chloroform (Duhamel et al., 2002) and chlorinated ethanes (Grostern and Edwards, 2006) may inhibit some dehalogenating cultures.

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4.0 PERFORMANCE OBJECTIVES

Performance objectives were established for this demonstration to provide a basis for evaluating the performance and costs of anaerobic bioaugmentation. The primary performance objectives for this demonstration are summarized in Table 1.

Table 1. Performance objectives.

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Determine the amount of SDC-9 culture required for effective remediation	Baseline, demonstration, and post-demonstration contaminant and DHC concentrations in groundwater	• DHC concentrations >10^7 cells/L at downgradient monitoring wells	• An effective 1-D model was developed for determining the amount of culture needed to effectively treat aquifers
Compare SDC-9 dechlorination to dechlorination in the presence of existing microorganisms only (biostimulation)	Baseline, demonstration, and post-demonstration contaminant and DHC concentrations in groundwater	• Complete dechlorination of TCE and cDCE to ethene in the 3 SDC-9 test loops • Slow or incomplete dechlorination of TCE and cDCE in control loop	• Ethene observed in all 3 test loops • DHC concentrations orders of magnitude higher in test loops • "DCE stall" observed in control loop
Effectively distribute electron donor throughout all 4 loops	Volatile fatty acid (VFA) concentrations in groundwater during demonstration	• VFA concentrations >5 mg/L at downgradient monitoring wells	• Objective fully achieved in all 4 demonstration loops
Adjust and maintain acceptable groundwater pH for dechlorination to occur	Baseline and demonstration field pH measurements	• Increase and maintain groundwater pH levels between 5.5 and 8.0 standard units	• pH increased from ~4.5 to >5.5 during most of demonstration • Temporary drops in pH below 5.5 observed at some wells • Spike in pH to >pH 9 occurred during pH adjustment efforts.
Determine remedial effectiveness of bioaugmentation with SDC-9	Baseline, demonstration, and post-demonstration contaminant concentrations in groundwater	• >90% reduction of TCE and cDCE considered successful • Complete dechlorination of TCE and cDCE to ethene	• 90-100% reduction of TCE, and 73-99% reduction of cDCE observed in test loops • Ethene observed in all 3 test loops

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5.0 SITE DESCRIPTION

The field demonstration was performed at the Magazine 1 Area (MAG-1) at Fort Dix, NJ (Figure 2). The MAG-1 Area groundwater plume met many of the selection criteria for a field demonstration site, based on the following: (1) TCE concentrations >250 µg/L with no VC or ethene; (2) shallow sand or silty sand aquifer (less than 30 ft below ground surface[bgs]); (3) sufficient area to allow operation of four approximately 30 ft long by 20-25-ft wide recirculation loops; and (4) proximity to a Shaw office and vendors used to support the field demonstration.

One potentially challenging issue identified with the MAG-1 site was the low natural pH (<5). Laboratory studies demonstrated that the SDC-9 culture used for the demonstration is inhibited at pH values less than 5.5 (Vainberg et al., 2009), and as discussed in Section 6.3, microcosm and column studies showed that pH adjustment would be required to facilitate bioremediation at the site.

5.1 SITE LOCATION

Fort Dix is located in Burlington and Ocean counties, approximately 25 miles southeast of Trenton. MAG-1 is in the northern part of the Cantonment Area at Fort Dix (Figure 2).

5.2 SITE GEOLOGY/HYDROLOGY

As shown in Figure 3, the geology underlying the field demonstration site consists of unconsolidated materials from the Kirkwood and Manasquan Formations. The Kirkwood Formation is the uppermost unit in the immediate vicinity of MAG-1. The shallow soils of this formation (down to ~104 ft mean sea level [MSL]) are a mixture of silty and clayey sands. Kirkwood Formation soils from approximately 104 to 90 ft MSL consist of saturated, light gray silty fine sands. A 4- to 8-inch Interface Zone, consisting of fine to coarse sands and fine gravel, is present at the base of this unit. This zone exhibits significantly higher permeability than the formations above and below and appears to limit downward groundwater flow by creating a highly conductive horizontal flow path. Vertical contaminant distribution (Sections 5.3 and 6.2.1) and bromide tracer testing results (Section 6.6.2) seem to confirm this assertion. Soils of the Manasquan Formation (down to at least 70 ft MSL) consist of saturated, greenish-gray fine sands. The demonstration was performed within the Kirkwood aquifer.

5.3 CONTAMINANT DISTRIBUTION

TCE and cDCE are the main chlorinated solvents detected in the MAG-1 groundwater. The field demonstration area was located in the plume area with the highest CVOC concentrations. Based on the CVOCs observed during site characterization activities (Figure 3) and at wells within the demonstration area, the highest total CVOC concentrations are in the 90- to 100-MSL range (i.e. Kirkwood Formation). Significantly lower concentrations observed in the Manasquan Formation suggest that the formation interface existing near 90 ft MSL inhibits downward groundwater flow and mixing.

Figure 2. Site location map.

Figure 3. Geologic cross section A-A', direct-push investigation.

6.0 TEST DESIGN

6.1 CONCEPTUAL EXPERIMENTAL DESIGN

The field demonstration involved the construction and operation of four groundwater recirculation loops. Three of the loops (test loops) were inoculated with a different amount of Shaw's SDC-9 dechlorinating culture, while the fourth loop (control loop) received only electron donor, buffer, and nutrients. The demonstration layout is provided in Figure 4 and a cross section of Loop 3 is provided in Figure 5. CVOC biodegradation and growth of the added organisms were monitored. In addition, because of the low natural pH at the site, the ability to increase and maintain an elevated pH sufficient for successful bioremediation by adding buffers was evaluated. The results of the demonstration were used to evaluate and refine the one-dimensional bioaugmentation fate and transport screening model that was generated from laboratory experiments performed during the project (Schaefer et al., 2009).

6.2 BASELINE CHARACTERIZATION

6.2.1 SITE CHARACTERIZATION

Extensive site characterization data were collected from January to March 2007 and used to prepare the final design of the field demonstration layout. These pre-design activities included:

- A direct-push (Geoprobe®) investigation to improve delineation of the stratigraphy in the field demonstration test area and to further evaluate the vertical and lateral contaminant distribution
- Installation of nested piezometers to facilitate evaluation of hydraulic conductivities within the Kirkwood and Manasquan formations, as well as the higher permeability Interface Zone (Figures 4 and 5)
- Performance of rising and falling head slug tests at selected demonstration area monitoring wells and piezometers to verify and/or estimate the hydraulic conductivity in the various stratigraphic layers within the demonstration area (Table 2)
- Performance of short-term aquifer pump tests to evaluate vertical hydraulic conductivities and extraction well radius of influence within the demonstration area.

Information obtained during these activities was ultimately used to determine well spacing and pumping rates for the demonstration. Based on these results and the contaminant distribution, it was determined that the treatment zone for the demonstration would be within the Kirkwood formation.

Table 2. Summary of slug testing and pump testing analysis data.

Well	Screen Interval	From Pump Test					From Slug Test
		T (ft^2/day)	K (ft/day)	S	Sy	K_z/K_r	K (ft/day)
PZ-1	98.7 -- 103.7	93.0	**1.9**	1.0E-03	0.021	0.45	**2.1**
PZ-2	88.3 -- 93.3	63.6	**1.3**	1.0E-03	0.021	0.045	**5.5**
MAG-113P	82.5 -- 92.5	254	**5.1**	2.0E-03	0.030	0.005	**2.7**
MAG-112P	75.3 -- 85.3	560	**11.2**	5.5E-05	0.0034	1.00	**2.8**
MAG-66	72.4 -- 82.4	452	**9.0**	2.1E-05	0.0028	1.00	**3.5**

6.2.2 Baseline Groundwater Sampling

Baseline groundwater sampling events were conducted in October and November 2007. These samples were used to establish the baseline conditions of groundwater quality and biogeochemistry prior to system start-up and tracer testing. The following summarizes baseline sampling results:

6.2.2.1 Chlorinated Ethenes and Ethene

Figure 4 shows the baseline chlorinated ethene (TCE, cDCE, and VC) concentrations within the demonstration area. TCE concentrations within the Kirkwood aquifer ranged from 17 µg/L to 1800 µg/L. Concentrations of cDCE within the Kirkwood aquifer ranged from 45 µg/L to 1400 µg/L. Concentrations were generally higher in Loops 2 and 3, located within the center of the demonstration area. Vinyl chloride and ethene were not detected in any of the wells sampled during either of the baseline events.

6.2.2.2 DHC

Data collected during the two baseline sampling events indicated that DHC concentrations ranged from nondetect to 3.92×10^5 cells per liter.

6.2.2.3 Field Parameters

The key field parameters were collected during baseline sampling. The pH ranged from 4.1 to 5.4 standard units, indicating that the groundwater was acidic. Specific conductivity ranged from 19 µS/cm to 236 µS/cm. Oxidation-reduction potential (ORP) ranged from +19 millivolts (mV) to +219 mV, indicating oxygen and nitrate reduction may have been occurring in portions of the aquifer. Dissolved oxygen ranged from 0.3 mg/L to 3.4 mg/L and was generally below 1.0 mg/L, indicating that the aquifer was anaerobic to anoxic.

6.2.2.4 Groundwater Elevation and Flow

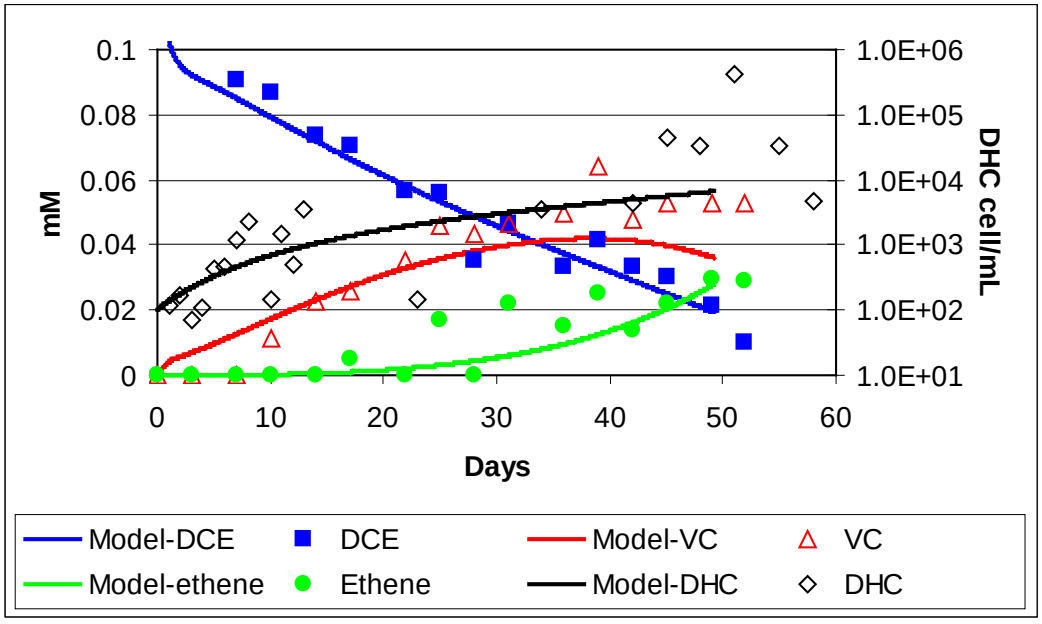
Baseline groundwater elevation data indicated that the groundwater flow direction is generally to the southwest and the hydraulic gradient across the demonstration area was approximately 0.012 for the Kirkwood aquifer. Using the hydraulic conductivity data derived from the pump test and assuming an effective porosity of 25%, the groundwater velocity within the Kirkwood formation was estimated at approximately 0.08 ft/day.

Figure 4. Demonstration well layout and baseline chlorinated ethene concentrations.

Figure 5. Geologic cross section of Loop 3.

6.3 TREATABILITY AND LABORATORY STUDY RESULTS

Laboratory studies included two separate microcosm tests and two separate column tests. Results of the laboratory microcosms testing showed that biostimulation alone was insufficient for treating TCE in the demonstration area and that addition of DHC was needed to biodegrade the chlorinated ethenes. Preliminary column tests evaluated SDC-9 transport, growth, and chlorinated ethene degradation kinetics through a sandy soil (MAG-1 soil and groundwater were not used in these preliminary tests). The rates of increase in measured DHC concentrations, as well as the rate of chlorinated ethene decreases, were well predicted by a Monod kinetic model that had been previously calibrated to results obtained from batch experiments. Column data, along with the corresponding model simulations, are shown in Figure 6. Thus, these column studies demonstrated our ability to predict chlorinated ethene biodegradation rates and DHC distribution during bioaugmentation. The Monod model also was validated as a useful tool for selecting DHC dosages for the bioaugmentation demonstration (Schaefer et al., 2009).



Results are shown for 6 cm from the column influent.

Figure 6. Results of laboratory column testing.

Additional laboratory column testing was performed to verify results of the microcosm and preliminary column testing and to evaluate microbial distribution, growth, and dechlorination activity through site soils.

6.4 FIELD TESTING

Installation of the field demonstration wells and equipment was performed between June and September 2007. Field testing began in November 2007 and lasted for approximately 14 months. Testing was performed in three operational phases: 1) system testing, 2) system start-up and tracer testing, and 3) bioaugmentation, system operation, and performance monitoring.

6.4.1 System Installation

Four recirculation loops were installed, with an orientation parallel to groundwater flow. The layout includes approximately 25 ft of separation between each recirculation loop. The distance between the injection well (IW) and extraction well (EX) in each loop was approximately 30 ft. Two performance bioaugmentation monitoring wells (BMW) were installed along each of the injection/extraction well transects at distances of approximately 10 and 20 ft from the injection well, respectively. Each of the injection/extraction well pairs, along with the two intermediate monitoring wells, consisted of a recirculation loop. The four loops allowed the following amendment dosages to be tested:

- Loop 1: Lactate, buffer, nutrients, and 100 L of SDC-9 injected
- Loop 2: Lactate, buffer, nutrients, and 10 L of SDC-9 injected
- Loop 3: Lactate, buffer, nutrients, and 1 L of SDC-9 injected
- Loop 4: Lactate, buffer, and nutrients only (control loop).

Three additional performance monitoring wells (BMW-9 through BMW-11) were installed side-gradient of the Loop 1 injection/extraction well transect (Figure 4) to monitor lateral distribution of amendments and possible cross flow between loops. A cross-sectional view of Loop 3 is shown in Figure 5. The groundwater recirculation and amendment injection systems consisted of electron donor and buffer metering pumps controlled by a Supervisory Control and Data Acquisition (SCADA) system.

6.4.2 System Testing

The recirculation system was successfully tested between November 8 through November 14, 2007 to insure proper operation of pumps and controls. Additionally, brief testing of the electron donor and buffer injection systems was performed using potable water to check for leaks and allow for selection of proper flow rates and pressures. Water levels were measured manually in demonstration area monitoring wells and extraction wells, and automatically at the injection wells by the SCADA system during this period to determine the impacts of groundwater extraction and injection on local water table elevations.

6.4.3 System Start-Up and Tracer Testing

The system start-up period lasted for 10 weeks. Operation of the four recirculation loops began on November 15, 2007. Operation of the amendment injection systems began on November 16, 2007. Groundwater extraction rates for each extraction well were reduced incrementally from 0.5 gallons per minute (gpm) to 0.3 gpm during the start-up period to minimize injection pressures at the injection wells.

During this period, lactate, buffer (sodium bicarbonate or sodium carbonate), and nutrients (diammonium phosphate and yeast extract) were injected into each of the four injection wells in equal amounts. The groundwater recirculation and amendment delivery systems operated nearly continuously (except for brief operation and maintenance [O&M] shutdown periods) during the start-up period. All four injection wells were redeveloped between December 20 and 26, 2007.

A tracer test was performed during the start-up period to evaluate and verify local hydrogeologic characteristics. Tracer injection occurred relatively continuously for a 28-day period. During the system start-up and tracer testing phase, six groundwater sampling events were performed at select monitoring locations within the demonstration area to monitor migration of tracers and lactate, to determine the appropriate changes in aquifer geochemical conditions, to evaluate changes in dissolved chlorinated ethene concentrations due to system mixing, and to determine baseline conditions prior to bioaugmentation.

6.4.4 Bioaugmentation, System Operation, and Performance Monitoring

Two bioaugmentation events, continued operation of the groundwater recirculation and amendment delivery systems, and twelve rounds of performance monitoring were performed during this phase of the demonstration. These activities are summarized in the following subsections.

6.4.4.1 Bioaugmentation

The first of two bioaugmentation injection events was conducted on January 24, 2008. The SDC-9 culture used for the bioaugmentation was grown at Shaw's fermentation facility in Lawrenceville, NJ, immediately prior to injection. The DHC concentration in the culture was measured at 2.17×10^{10} cells/L. A total of 100 L, 10 L, and 1 L of culture were injected into injection wells IW-1, IW-2 and IW-3, respectively. It is believed that high pH levels (>10 standard units) measured in injection wells IW-1 through IW-3 shortly after the first bioaugmentation injection may have adversely affected the injected SDC-9 culture, as no substantial dechlorination or downgradient migration of DHC were observed over a 12-week period (see Section 5.6.4). Therefore, a second bioaugmentation event was conducted on May 1, 2008. Unlike the first injection, the culture was injected into the first downgradient monitoring well within Loops 1 through 3 to prevent high pH levels in the injection wells from impacting the injected culture. A total of 100 L, 10 L, and 1 L were injected into injection wells BMW-1, BMW-3 and BMW-5, respectively. The DHC concentration in the injected culture was measured at 1.45×10^{12} cells/L (approximately two orders of magnitude higher than the first injected culture).

6.4.4.2 System Operation

The system operation phase lasted for 9½ months (January 24 through November 5, 2008). The groundwater recirculation and amendment delivery systems were operated continuously from January 24 through March 3, 2008 (39 days). Between March 3, 2008, and November 5, 2008, the systems were operated in an "active-passive" mode. During active cycles, groundwater was continuously recirculated, and lactate, buffer, and nutrients were continuously injected into the aquifer. During passive cycles, the systems were not operated, and the injected amendments were allowed to move naturally with the groundwater. Each individual active and passive period lasted generally 1-2 weeks. The systems were operated in active mode approximately 50 days. All four injection wells were redeveloped for a second time between June 25 and June 29, 2008.

6.4.4.3 Performance Monitoring

A total of 12 performance monitoring groundwater sampling events were conducted in the demonstration area between January 30, 2008, and January 5, 2009, to monitor treatment performance. Analyses of groundwater collected included VOCs, reduced gases, VFAs, anions (including nitrate and sulfate), dissolved iron and manganese, and DHC. Groundwater elevation measurements were also collected during this phase of the demonstration to evaluate changes in hydraulic gradients induced by operation of the injection/extraction well system in the Demonstration Area.

6.5 SAMPLING METHODS

6.5.1 Site Characterization Sampling

During the direct-push (Geoprobe®) investigation, a total of 26 aqueous samples (including one equipment blank) were collected using a discrete sampler and analyzed for VOCs.

6.5.2 Demonstration Groundwater Sampling

Demonstration groundwater samples were collected from monitoring wells using low-flow sampling techniques. Analyses of groundwater collected included VOCs, reduced gases, VFAs, anions, dissolved iron and manganese, and DHC.

6.6 SAMPLING RESULTS

A total of 21 groundwater sampling events were conducted during the demonstration, including:

- Two baseline sampling events
- Six system start-up and tracer testing groundwater sampling events
- One pre-bioaugmentation sampling event
- Twelve performance monitoring sampling events.

Baseline groundwater data were compared to data collected during the start-up/tracer testing phase, and the performance monitoring (system operation) phase.

6.6.1 Water Level Measurements

Baseline groundwater elevation measurements indicated that groundwater flow direction was to the southwest, the hydraulic gradient across the demonstration area was approximately 0.012, and the groundwater velocity was approximately 0.08 ft/day for the Kirkwood aquifer. During system operation (0.5 gpm pumping rate), the hydraulic gradient increased approximately ten-fold to 0.10 in the middle of the test plots (between performance monitoring wells) and was significantly greater still in the vicinity of the injection and extraction wells. Based on this data, the groundwater velocity between performance monitoring wells was estimated at 0.65 ft/day. Reduction of pumping rates during the demonstration period reduced gradients in the middle of the test plots to approximately 0.02 (a five-fold decrease), or an estimated groundwater velocity of 0.13 ft/day.

6.6.2 Tracer Testing

Sampling results from the tracer testing indicated that the bromide tracer was distributed through Loops 1 and 3 quickly. Analysis of the data indicated that the estimated travel time of the bromide tracer through these loops (from the injection to the extraction well) was approximately 30 to 40 days (an average groundwater velocity of 0.75 to 1.0 ft/day based on groundwater extraction/reinjection rates of 0.5 gpm per loop). However, groundwater extraction rates were gradually reduced to 0.1 gpm over the course of the demonstration, therefore increasing travel times through the loops to greater than 120 days.

Bromide tracer data, coupled with data from the Geoprobe investigation, slug tests, and pump test, indicate that the higher permeability formation interface provides preferential horizontal flow and most likely inhibits downward groundwater flow and mixing. Fluoride tracer data indicated that fluoride was reacting or sorbing to materials within the aquifer. Therefore, data from the fluoride tracer test could not be used to determine hydrogeologic characteristics (travel times, etc.) within Loops 2 and 4.

6.6.3 System Start-Up Sampling

Six tracer sampling events and one pre-bioaugmentation sampling event were performed at select monitoring locations within the demonstration area during the start-up phase of the demonstration. VOC data indicated that while some fluctuations in CVOC concentrations were observed, few significant increases or decreases (>two-fold) were observed in any of demonstration area monitoring wells. VFA data indicated that electron donor was quickly distributed throughout all four recirculation loops. However, it took longer for the impacts of the injected buffer (i.e., increased pH) to be seen downgradient. By the end of the start-up period, pH levels in most of the monitoring wells had increased to >5.5 from baseline levels of approximately 4.5 standard units. Field and laboratory data (ORP, DO, metals) indicated reducing conditions had been successfully established in the aquifer during the start-up period.

6.6.4 Performance Sampling

Twelve performance monitoring sampling events were performed at select monitoring locations within the demonstration area after bioaugmentation with SDC-9. The first five sampling events were performed between the first and second bioaugmentation events, while the next five sampling events were performed after the second bioaugmentation event. The following summarizes key data collected during this period.

6.6.4.1 Chlorinated Ethenes and Ethene

Figure 7 provides chlorinated ethene and ethene trend graphs for demonstration area monitoring wells along the four loop transects. TCE concentrations in the three test loops and the control loop declined between 90 and 100% during the demonstration. TCE decreases were expected in the control loop, as the addition of electron donor in the microcosm studies (Section 6.3) stimulated degradation of TCE (but not cDCE). Concentrations of cDCE in the three test loops declined between 73 and 99% and were generally trending downward at the end of the demonstration period (Figure 7). Transient increases (followed by decreases) in VC were

observed in five of the six monitoring wells, with two of the wells (BMW-1 and BMW-2) below detection at the end of the demonstration. Concentrations of cDCE in Control Loop monitoring well BMW-7 increased by 67%, and concentrations in well BMW-8 during the demonstration were generally above baseline. VC and ethene were not observed in the control plot monitoring wells during the demonstration, indicating that degradation of TCE had "stalled" at DCE in the absence of bioaugmentation.

Ethene concentration trends (Figure 7) indicated that complete dechlorination of TCE was occurring within the three test loops bioaugmented with SDC-9, and not within the control loop (Loop 4) that received only electron donor, buffer, and nutrients. The data indicate that greater than 95% of the TCE and cDCE observed at three of the six test loop monitoring wells had been converted to ethene. Loop 2 (which had issues with the pH dropping below 5.5) had the lowest ethene conversion rates. Additionally, reductions in TCE concentrations, VC and ethene concentration trends, and increased DHC concentrations (discussed below) in extraction wells EX-1, EX-2, and EX-3 indicated that degradation was occurring through the entire lengths of the three test loops.

6.6.4.2 Volatile Fatty Acids

VFA concentrations were observed in the test loop and control loop performance monitoring wells throughout most of the demonstration and generally ranged from 50 mg/L to 2000 mg/L. VFAs were generally not detected in wells BMW-10 and BMW-11 (outside the treatment zone) during the demonstration. VFAs were observed at concentrations between 50 and 1000 mg/L at all four extraction wells. These data indicate that lactate injection rates provided effective distribution of electron donor throughout all four recirculation loops during the demonstration.

6.6.4.3 DHC

Quantitative polymerase chain reaction (qPCR) analysis was used to measure DHC concentration as a function of time and distance from the injection wells during the demonstration. DHC trend graphs for demonstration area monitoring wells along the four loop transects are provided in Figure 7.

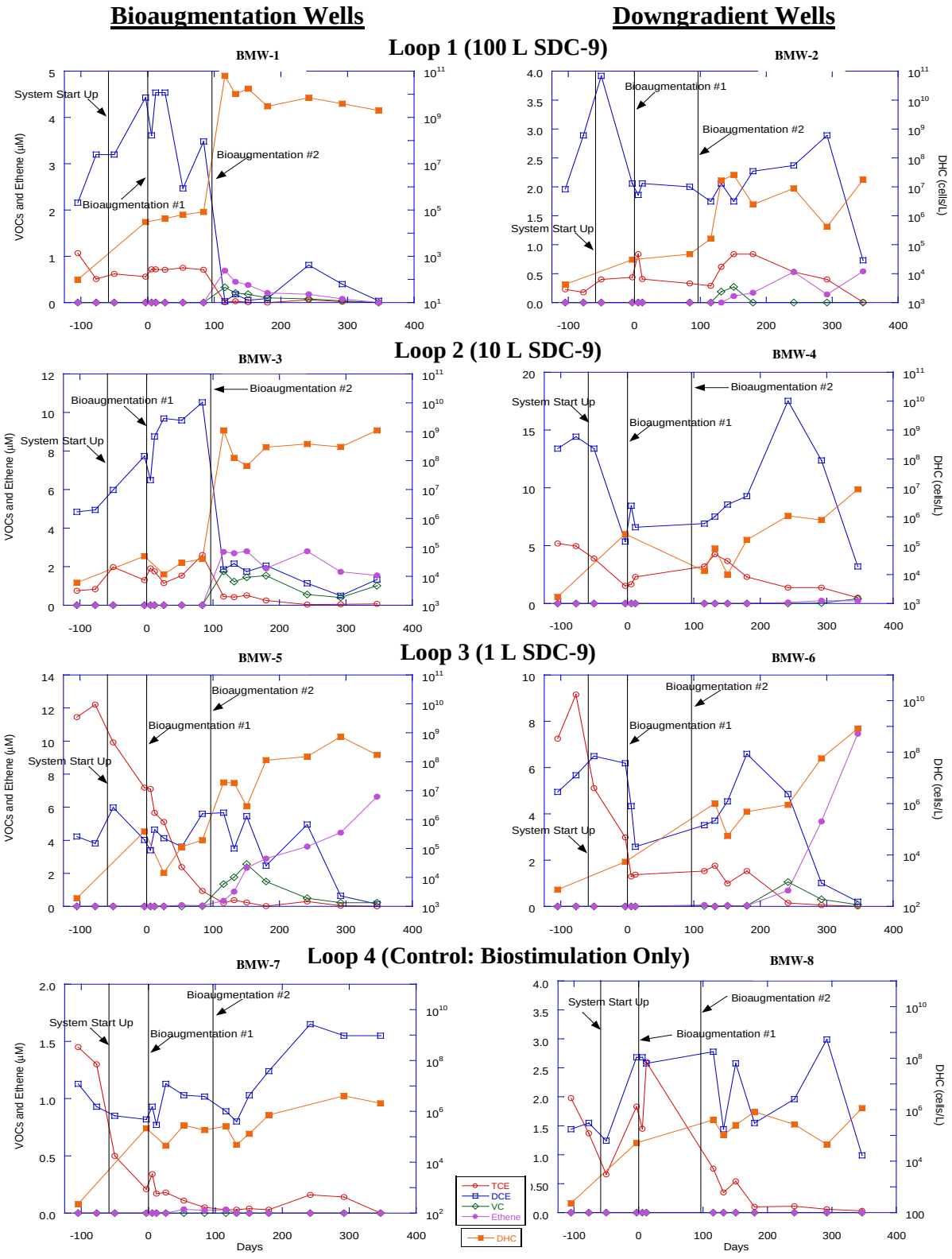


Figure 7. Chlorinated ethenes, ethane, and DHC graphs.

The following observations were made based on DHC and CVOC data collected during the demonstration:

- Vinyl chloride and ethene were generally observed when aqueous DHC concentrations reached a level of approximately 1.0×10^7 cells/L, or greater. These data indicate that the complete degradation of TCE occurs readily at (and above) this cell concentration at this site. These results are consistent with the findings of Lu et al. (2006).
- Aqueous DHC concentrations in the three test loops tended to reach and maintain an apparent equilibrium of approximately 10^8 to 10^9 cells/L (Figure 7).
- There did not appear to be a correlation between DHC dosage and downgradient DHC transport. The data suggest that DHC concentration increased downgradient of the injection wells at similar rates, likely because of differences in CVOC concentrations and resulting DHC growth in the test loops.

6.6.5 System Operation

There were no significant mechanical problems during the demonstration. A total of approximately 333,000 L (88,000 gallons) (an estimated 6.5 pore volumes) of groundwater were extracted and re-injected within each of the four loops during the demonstration. A total of 2290 L (605 gallons) of 60% sodium lactate solution, 114 kg (250 lb) of diammonium phosphate, and 68 kg (150 lb) of yeast extract were injected evenly into the four loops during the 12 months of system operation. A total of 3180 kg (7000 lb) of sodium bicarbonate and 4360 kg (9600 lb) of sodium carbonate (including the bulk injections) were injected into the four loops during the 12 months of system operation. The mixing of buffer solutions was the most time-intensive O&M component. All four injection wells were redeveloped in December 2007 during the start-up phase, and again in June 2008 during the system operation phase.

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7.0 PERFORMANCE ASSESSMENT

The established performance objectives were generally met during the demonstration. The following subsections provide an assessment of the performance objectives, including to what extent the success criteria were achieved.

7.1 DHC DOSAGE COMPARISON

The key objective of this demonstration was to determine the DHC dosage required to effectively remediate a chlorinated-ethene contaminated site. The current industry standard for estimating the amount of culture involves estimating the volume of water in the treatment zone by multiplying the length, width, and thickness of the contaminated saturating zone by the estimated porosity (L x W x thickness x porosity), and then adding enough culture to achieve 107 DHC/L, assuming even distribution of the added culture. We evaluated 40 successful field-scale bioaugmentation applications performed by Shaw at DoD facilities. The average volume of aquifer treated during these projects was approximately 29,000 m^3, and the average volume of culture applied was 115 L. The culture contained 10^{11} DHC/L. Assuming an average of 25% porosity, the volume of treated water was 7.7×10^6 L. This equates to an inoculum dosage of 0.2×10^7 DHC/L of treated groundwater, which is within the range predicted to be effective by Lu et al. (2006) and similar to the industry standard of 10^7 DHC/L. This approach, however, does not account for differences in contaminant concentration that can affect the growth of the added organisms, or the hydrogeology of the aquifer, which can affect distribution of the bacteria.

For this project, bioaugmentation using Shaw's SDC-9 DHC-containing culture was performed in three separate groundwater re-circulation loops, with one loop bioaugmented with 1 L of culture, the second loop bioaugmented with 10 L of culture, and the third loop bioaugmented with 100 L of culture. A fourth "control" loop was not bioaugmented. Based on the estimated volume of groundwater within each treatment loop, and assuming an even distribution of the added organisms throughout the groundwater, this represented target final DHC concentrations of 5×10^5, 5×10^6, 5×10^7, and 0 DHC/L, respectively. Due to high pH in the injection wells caused by buffer addition, a second bioaugmentation was performed at the first downgradient monitoring well within each loop. This represented target final DHC concentrations of 5×10^7, 5×10^8, 5×10^9, and 0 DHC/L, respectively. Groundwater monitoring was performed to evaluate DHC growth and migration, dechlorination kinetics, and aquifer geochemistry.

The loop inoculated with 10 L of culture (Loop 2) showed slower dechlorination kinetics and DHC migration/growth compared to the other two test loops. This relatively poor performance was attributed to low pH conditions that were not effectively controlled by the addition of buffer. Results for the loops inoculated with 1 L (Loop 3) and 100 L (Loop 1) of culture showed similar rates of dechlorination, as measured at a monitoring well approximately 10 ft downgradient of the DHC injection well (as well as the injection and extraction wells and other monitoring wells).

To provide a first level evaluation of in situ dechlorination kinetics and DHC growth, the 1-dimensional screening level bioaugmentation model developed during the project (Schaefer et al., 2009) for the SDC-9 culture was applied to demonstration Loops 1 and 3. This model employs Monod kinetics to describe DHC growth and dechlorination kinetics (determined for the SDC-9 culture in batch kinetic studies) and applies an attachment-detachment type model to

describe DHC migration through soil. Immobile and mobile DHC near the bioaugmentation injection well, and mobile DHC migrating downgradient from the bioaugmentation injection well, contribute to contaminant dechlorination. Model predictions for Loops 1 and 3 are shown in Figures 8 and 9. While intended to serve as only a semi-quantitative tool, the model provided a reasonable prediction of the time frame for DCE treatment at each of the monitoring wells in these treatment loops. In addition, the model provided a reasonable prediction of the DHC concentrations in groundwater, although the elevated DHC levels at BMW-2 at 40 to 50 days after bioaugmentation are not readily explained. Most importantly, the model showed that treatment kinetics at BMW-2 and BMW-6 were similar despite a 100-fold difference in DHC bioaugmentation dosage at BMW-1 and BMW-5. It also showed that in situ DHC growth in Loop 3 was greater than the DHC growth in Loop 1. The rapid decrease in chlorinated ethene concentrations in BMW-1, which resulted from the large DHC inoculation dosage in this well, limits the subsequent rate of DHC growth within this treatment loop. Thus, in situ growth in Loop 3 acted to compensate for the decreased DHC inoculation dosage, and explains why results for these two treatment loops are similar despite the 100-fold difference in bioaugmentation dosage.

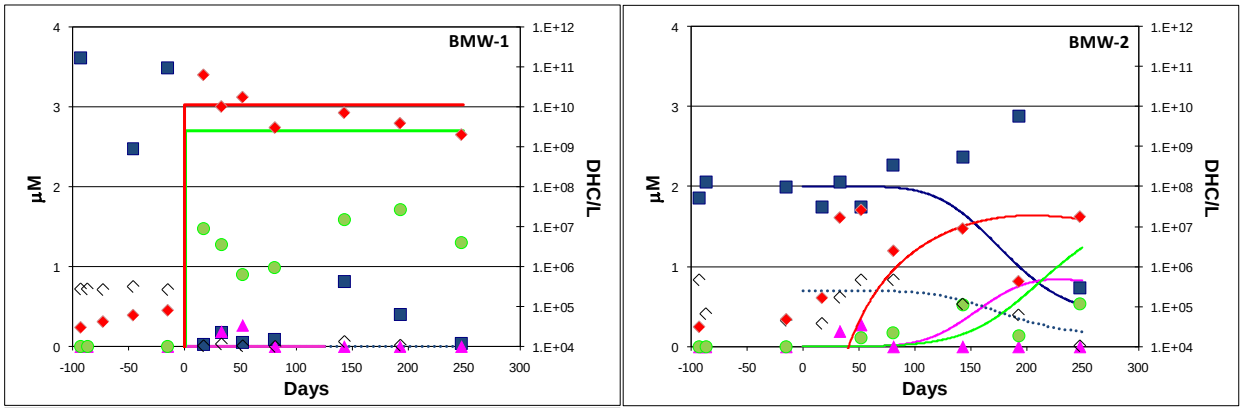


Figure 8. Ethenes and DHC concentrations plotted as a function of time for Loop 1.
Bioaugmentation was performed at 0 days. ◇ - TCE, ■- DCE, ▲-VC, ● - ethene, ◆ - DHC
Solid and dotted lines represent corresponding model simulations.
Simulated DHC concentrations in the bioaugmentation injection well (BMW-1) include the total (mobile and immobile) DHC.

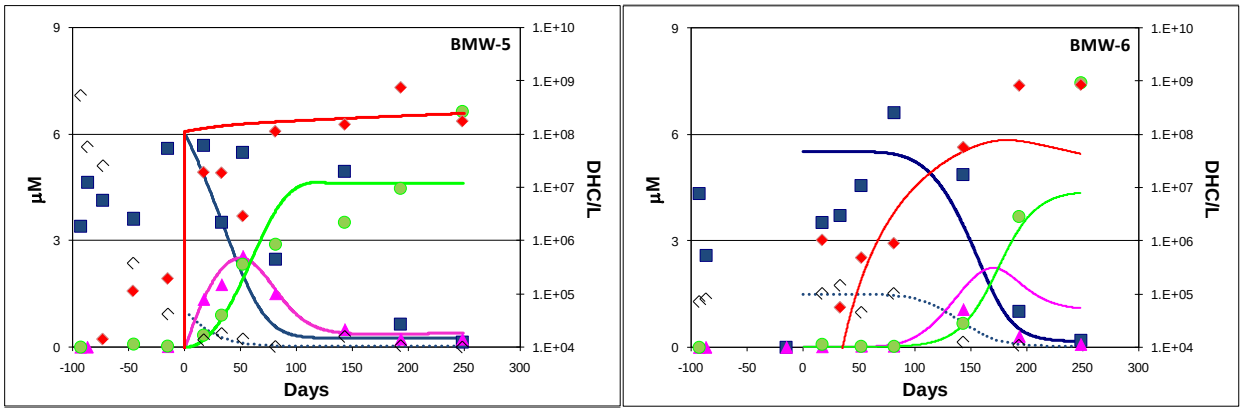


Figure 9. Ethenes and DHC concentrations plotted as a function of time for Loop 3.
Bioaugmentation was performed at 0 days. ◇ - TCE, ■- DCE, ▲-VC, ● - ethene, ◆ - DHC
Solid and dotted lines represent corresponding model simulations.
Simulated DHC concentrations in the bioaugmentation injection well (BMW-5) include the total (mobile and immobile) DHC.

The treatment model also was applied to evaluate the expected performance of two lower cell dosages in Loop 3 of the test plot. During the field demonstration, the second dose of SDC-9 applied to Loop 3 would result in 10^7 DHC/L if evenly distributed through the plume/loop. Model simulations were performed assuming both 10^6 and 10^5 DHC/L. The results of these simulations are shown in Figure 10. They demonstrate that adding a 10-fold lower cell dosage (10^6 DHC/L) would have resulted in only a moderate delay (~3 months) in treatment at the downgradient monitoring well. Adding only 10^5 DHC/L would result in a significant delay in treatment. Thus, the optimum dosage for this treatment loop appears to be between 10^6 and 10^7 DHC/L. Interestingly, however, the simulations also demonstrated that adding 10-fold fewer cells (i.e., 10^6 DHC/L) in this test loop would have resulted in significantly reduced treatment near the injection well, and that treatment effectiveness convergence between the two dosages occurred only with prolonged treatment time (i.e., further downgradient of the injection point). The important implication of this is that the model can be used to predict, based on culture dosage, how far downgradient from the injection points compliance concentrations may be reached. In some cases adding more culture will reduce the length of a plume. For example, at the demonstration site adding 10-fold fewer cells would have resulted in nearly 3 months longer treatment time. If the groundwater moved 30 ft/month, adding the greater cell dosage could shorten the plume by 90 ft. This could be significant if the plume was nearing a sensitive receptor or a compliance point (e.g., a property line).

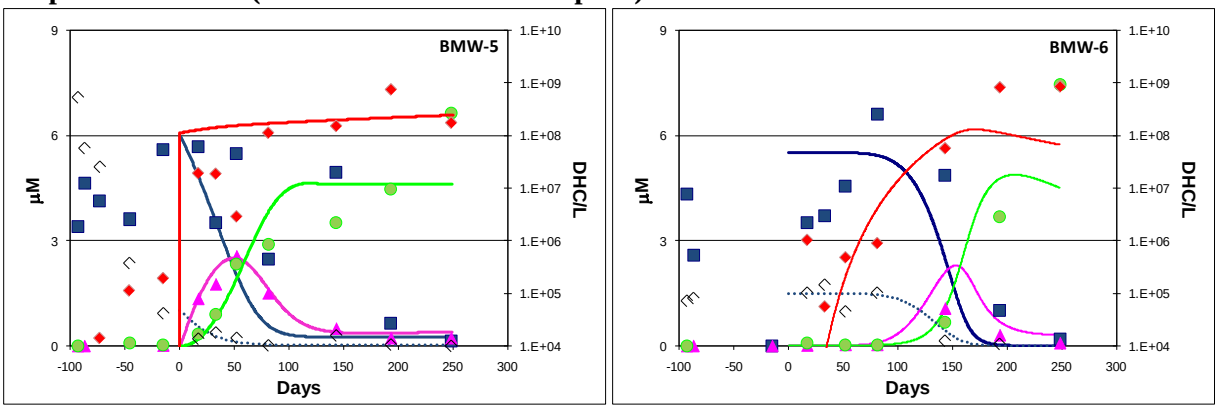
To further evaluate the affect of cell dosage during other bioaugmentation applications, additional model simulations were performed. The simulations evaluated how dosage affects the time required to reach 99% CVOC reduction. For example, one simulation evaluated the affect of cell dosage in a biobarrier application at low and high TCE concentrations and at two different *f* (attachment/detachment factors) values (Figure 11). With high TCE concentration (0.5 millimeter [mM]) and bioaugmentation dosages between ~10^6 and 10^9 DHC/L, there was minimal difference in treatment time between the dosages but a greater effect at a low *f* value (*f*=0.1) than at a high *f* value (*f*=0.55). Conversely, at a low TCE concentration (0.005 mM TCE), there was a significant difference in treatment times between the dosages, especially at the higher *f* value. The *f* value can be affected by soil pore size, distribution and architecture, groundwater velocity (although constant in these simulations at 0.5 ft/day), sheer forces, and/or soil geochemistry that affects detachment and transport of the catalyst. A similar effect was observed for treatment of a dense non-aqueous phase liquid (DNAPL) source area where adding higher cell dosages significantly shortened treatment time. A limited cell dosage affect was observed for simulated treatment of a low concentration TCE source area (data not shown).

Overall, the results of this field demonstration show that many factors including groundwater flow velocity, contaminant concentration, groundwater chemistry, and heterogeneity of the subsurface can affect the amount of culture needed to effectively treat chlorinated solvent-contaminated aquifers. Simply adding organisms based on the volume of groundwater to be treated may or may not lead to successful and timely remediation.

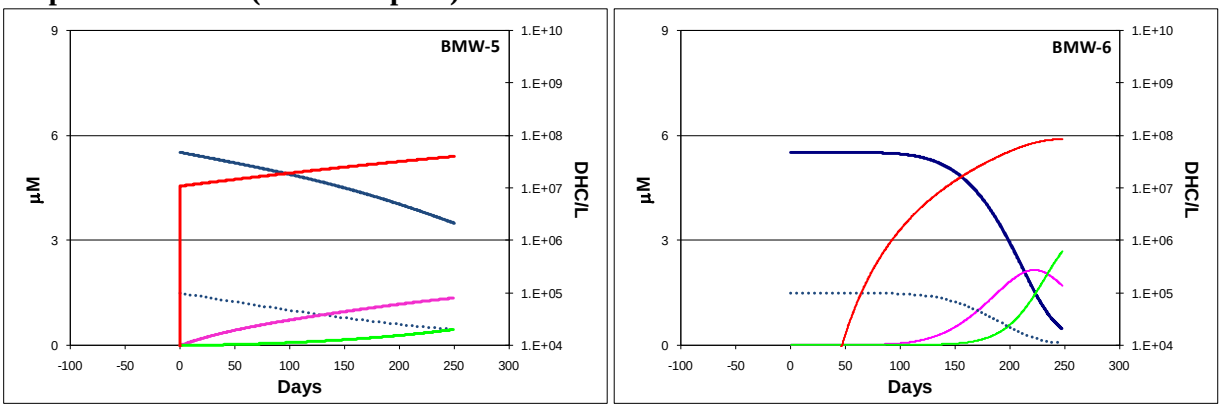
In cases like Loop 3 in this demonstration where contaminant concentrations are fairly high, the formation is suitable for microbial transport, and groundwater recirculation is used to enhance the flow gradient and culture distribution, adding smaller amounts of culture may be warranted provided the organisms can grow in the treated environment. In cases where contaminant

concentrations are lower (e.g., Loop 1), or where bacterial transport conditions are not optimum, a higher bioaugmentation dosage appears warranted. In either case, precisely determining the amount of culture needed for a given site still requires a site-by-site evaluation.

Loop 3: 10^7 DHC/L (measured and simulated plots)



Loop 3: 10^6 DHC/L (simulated plots)



Loop 3: 10^5 DHC/L (simulated plots)

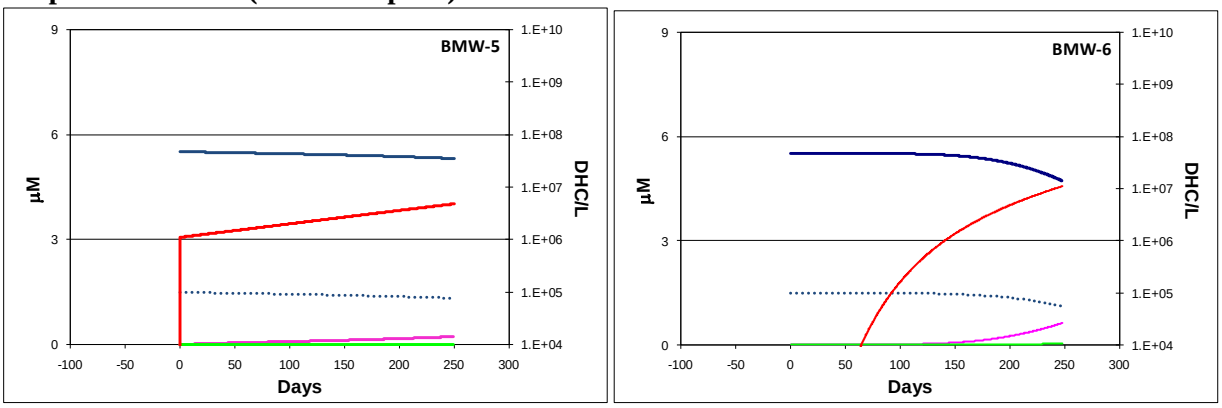


Figure 10. Model simulation of cell dosage effects on treatment of TCE in Loop 3.

Bioaugmenation was performed at 0 days. Measured values: ◇ - TCE, ■- DCE, ▲-VC, ● - ethene, ◆ - DHC
Solid and dotted lines represent corresponding model simulations.
Simulated DHC concentrations in the bioaugmentation injection well (BMW-5) include the total (mobile and immobile) DHC.

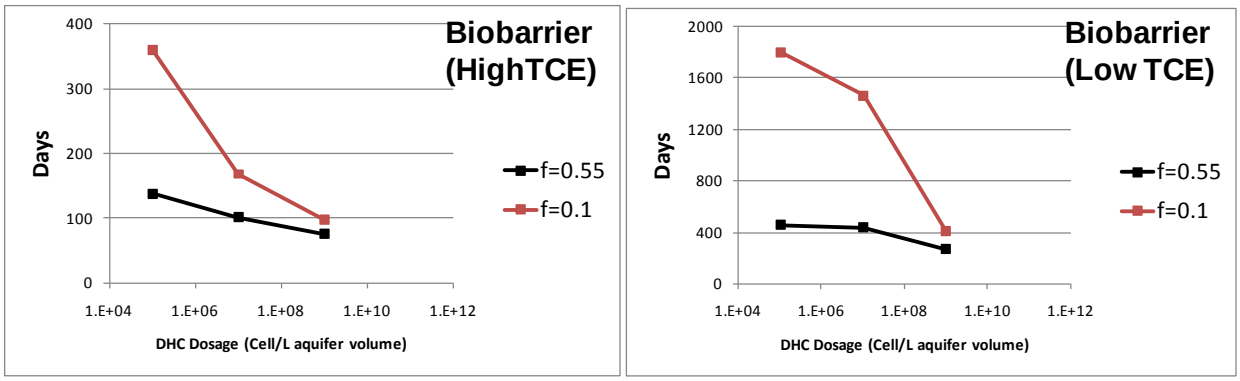


Figure 11. Model simulation of cell dosage effects on treatment of TCE in biobarrier applications.

(Schaefer et al., 2009). Data represent the amount of time required to reach 99% removal of cVOCs. All simulations assumed a groundwater velocity of 0.5 ft/day. High concentration TCE was 0.5 mM, and low concentration TCE was 0.005 mM.

Importantly, the 1-dimensional model developed during this project and used to predict and evaluate growth of DHC and treatment effectiveness (Schaefer et al., 2009) reasonably described the results of the field demonstration. Consequently, the model appears suitable for evaluating the effect of different DHC dosages on treatment times and effectiveness, and it is a useful design tool for planning bioaugmentation applications and more precisely determining the desired culture dosage.

7.2 BIOAUGMENTATION/BIOSTIMULATION COMPARISON

Another performance objective was to compare dechlorination in the three test loops bioaugmented with SDC-9 to dechlorination by indigenous microorganisms through biostimulation in the control loop. Groundwater sampling results indicated that aqueous DHC concentration increases were orders of magnitude higher in the test loops, compared to the control loop. TCE concentrations decreased significantly in the test loops as well as the control loop. TCE decreases were expected in the control loop, as the addition of electron donor in the microcosm studies stimulated degradation of TCE (but not cDCE). Concentrations of a cDCE in the control loop generally increased during the demonstration. VC was not observed in the control loop monitoring wells.

7.3 ELECTRON DONOR DISTRIBUTION

The third performance objective was to effectively distribute electron donor throughout all four demonstration recirculation loops. The effective distribution of electron donor was critical to create anaerobic conditions within the aquifer and to provide a source of carbon and hydrogen for microbial growth and dehalogenation of the target contaminants. VFA data collected during the demonstration indicated that lactate injection and groundwater recirculation rates used during the demonstration provided effective distribution of electron donor throughout all four recirculation loops.

7.4 pH ADJUSTMENT

The fourth performance objective of the demonstration, which was specific to the Fort Dix site, was to increase and maintain groundwater pH levels within an acceptable range required for

biological reductive dechlorination (~5.5–8.0 standard units). Increasing and maintaining pH levels within the recirculation loops was challenging. pH was increased from generally below 5.0 to between 6.0 and 7.1 standard units, except at injection wells where pH levels were often greater than 9.0 standard units due to the injection of sodium carbonate. However, the pH levels sometimes dropped below 5.5 in some of the monitoring wells during periods of the demonstration.

7.5 REMEDIAL EFFECTIVENESS

The final performance objective was to determine remedial effectiveness of bioaugmentation with SDC-9. The results of this project demonstrated that CVOCs in the Fort Dix MAG-1 aquifer can be effectively remediated by using bioaugmentation with the SDC-9 consortium and pH adjustment. TCE concentrations in the test area decreased by 90 to 100%, and cDCE concentrations decreased by 73 to 99% and were trending downward at the termination of the demonstration project. The production of ethene confirmed complete dehalogenation of the target contaminants and demonstrated the effectiveness of the applied bioaugmentation culture. The CVOC and ethene data indicate that conversion of TCE and cDCE to ethene can exceed 95% in the treatment zones.

8.0 COST ASSESSMENT

This section describes the cost performance criteria that were evaluated in completing the economic analysis of the bioaugmentation technology for in situ remediation of chlorinated solvents.

8.1 COST MODEL

In order to evaluate the cost of a potential full-scale bioaugmentation remediation program and compare it against traditional remedial approaches, costs associated with various aspects of the demonstration were tracked throughout the course of the project. Table 3 summarizes the various cost elements and total cost of the demonstration project. The costs have been grouped by categories as recommended in the Federal Remediation Technologies Roundtable Guide to Documenting Cost and Performance for Remediation Projects (FRTR, 1998). Many of the costs shown on this table are a product of the innovative and technology demonstration/validation aspects of this project and would not be applicable to a full-scale site application. Therefore, as described in subsequent sections, these costs have been excluded or appropriately discounted from the subsequent remedial technology cost analysis and comparison.

Costs associated with the bioaugmentation demonstration at Fort Dix were tracked from July 2006 (site selection) until July 2009 (preparation of the final report and cost and performance report). The total cost of the demonstration was $786,700, resulting in treatment (>90% reduction of TCE and cDCE) of approximately 900 cubic yards of contaminated aquifer (note: this estimate assumes that treatment would have occurred in the control loop, had 1 L of SDC-9 culture been added to the loop). This corresponds to a unit cost of approximately $875 per cubic yard of contaminated aquifer. However, as discussed below, actual remedial costs would be much less for non-research/demonstration-oriented projects and/or for sites where significant pH adjustment is not required.

8.1.1 Capital Costs

Capital costs (primarily system design and installation) accounted for $385,400 (or 49%) of the demonstration costs. These costs far exceed what would be expected during a typical remediation project due partially to the following unique cost elements:

- The large number of performance monitoring wells (11) installed within the relatively small (30 ft x 100 ft) demonstration area.
- The installation of extensive data collection processes (such as injection well pressure transducers and the SCADA system) built into the groundwater recirculation and amendment delivery systems.
- The need for design and installation of a buffer injection system that would not be required at most sites. In addition to the system itself (which included eight tanks and four metering pumps), a 40-ft Conex box was required to house the system to prevent freezing during winter months. The Conex box was insulated and included a heating system, ceiling lights, and an electrical panel and outlets. Additionally, each of the four buffer metering pumps had to be tied into the

process controls (programmable logic controller [PLC] and SCADA) system located in the neighboring 20-ft Conex.

Table 3. Demonstration cost components.

Cost Element	Details	Cost
CAPITAL COSTS		
Groundwater Modeling	Labor	$18,000
System Design	Labor	$32,000
Well Installation, Development, & Surveying	Labor	$25,000
	Materials	$3,800
	Subcontracts (driller/surveyor)	$63,000
System Installation	Labor	$42,000
	Equipment & Materials	$176,000
	Subcontracts (PLC/SCADA)	$24,000
Travel		$1,600
	Subtotal	**$385,400**
OPERATION AND MAINTENANCE COSTS		
Groundwater Sampling (2 baseline & 12 performance monitoring events)	Labor	$47,700
	Materials	$5,600
Analytical	In-House Labor	$48,400
	Outside Lab	$3,900
System O&M (including testing & start-up)	Labor	$31,900
	Materials (lactate, buffer, nutrients, consumables)	$21,000
Bioaugmentation	Labor (fermentation & injection)	$5,700
Utilities	Electric	$7,800
Reporting & Data Management	Labor	$68,000
Travel		$2,400
	Subtotal	**$242,400**
OTHER TECHNOLOGY-SPECIFIC COSTS		
Site Selection	Labor & Travel	$36,800
Site Characterization (direct push investigation, piezometer installations, slug tests, pump tests)	Labor (including in-house analytical)	$19,500
	Materials	$2,200
	Subcontractor (driller)	$13,200
Laboratory Microcosm and Column Testing	Labor (including in-house analytical)	$44,100
Tracer Testing	Labor (including in-house analytical)	$13,500
	Materials	$2,000
IPR* Meeting & Reporting	Labor & Travel	$12,000
C&P Report	Labor	$5,500
Guidance Document Sections	Labor	$10,100
	Subtotal	**$158,900**
	TOTAL COSTS	**$786,700**

*in-progress review

8.1.2 O&M Costs

O&M and reporting costs accounted for $242,400 (or 31%) of the demonstrations cost. These costs consisted primarily of groundwater monitoring (including analytical), system operation and maintenance, amendments (lactate, buffer, and nutrients), the SDC-9 culture, and reporting costs. Operation and maintenance cost elements unique to this demonstration included:

- Extensive performance monitoring activities, including 15 groundwater sampling events and over 1200 samples being collected and analyzed over a 15-month period (this does not include tracer testing sampling discussed below).
- Operation and maintenance of the buffer injection system, which included the mixing and injection of 16,600 lb of solid buffer (sodium bicarbonate and sodium carbonate).
- The need to redevelop the four injection wells on two separate occasions because the addition of the buffering agents caused fouling of the wells.
- The need to add an additional 108 L of SDC-9 culture to test Loops 2 and 3 because of a sever pH spike that affected microbial activity. Demonstration results indicated that 1 L of SDC-9 culture, with ~1011 DHC/L, was sufficient for remedial success in the recirculation loop with the greatest level of contamination because of extensive in situ growth of the culture.

8.1.3 Demonstration-Specific Costs

Other demonstration-specific costs (those cost not expected to be incurred during non research/demonstration-oriented remediation projects) accounted for $158,900 (or 20%) of the demonstration cost. These costs included site selection, laboratory and tracer testing, additional demonstration reporting and IPR meeting requirements, preparation of a cost and performance report, and preparation of three chapters for publication in an upcoming Strategic Environmental Research and Development Program (SERDP)/ESTCP-sponsored volume on bioaugmentation for remediation of chlorinated solvents.

8.2 COST DRIVERS

The expected cost drivers for installation and operation of a bioaugmentation groundwater recirculation system for the remediation of chlorinated ethenes and those that will determine the cost/selection of this technology over other options include the following:

- Depth of the CVOC plume below ground surface
- Width of the CVOC plume
- Thickness of the CVOC plume
- Aquifer lithology and hydrogeology
- Regulations/acceptance of groundwater extraction and re-injection
- Regulatory considerations concerning secondary groundwater contaminants
- Length of time for cleanup (e.g., necessity for accelerated cleanup)
- Concentrations of CVOCs and alternate electron acceptor (e.g., NO_3, SO_4^{-2} and O_2)
- Presence of co-contaminants, such as chloroform or chlorinated ethanes
- O&M costs and issues (particularly injection well fouling).

A thorough cost analysis of various in situ treatment approaches, including active-pumping systems, passive systems, and active-passive designs is provided in a recent book chapter by Krug and Cox (2008). These approaches are compared technically and economically with each

other and with *ex situ* treatment under a variety of contamination scenarios. The reader is referred to this chapter and others in this volume by Stroo and Ward (2008) for descriptions and economic comparisons of different in situ technologies.

The plume characteristics and those of the local aquifer will play an important role in the cost and applicability of a bioaugmentation for groundwater CVOC remediation. For shallow groundwater plumes (<50 ft bgs) passive in situ options, such as installation of a permeable reactive barrier (PRB) consisting of either injection well or direct-push applied slow-release substrates, are likely to be the most cost effective options. These systems require little O&M after installation and are not subject to the biofouling issues that impact active pumping designs. However, passive approaches may be less suitable at sites where significant pH adjustment is required, or where secondary reaction concerns (e.g., metals mobilization, sulfate reduction) exist. Passive approaches utilizing direct-push technologies can also be limited to sites where the target treatment zones are greater than 50 to 100 ft bgs, due to depth restrictions associated with this injection technology. Additionally, effective distribution of bioaugmentation cultures within the subsurface can be considerably slower with passive in situ treatment options.

For deeper plumes (e.g., >50 ft bgs) or those that are very thick, passive approaches are often not technically feasible (e.g., for direct-push injection of passive substrates >100 ft bgs) and/or are cost-prohibitive (e.g., injecting passive substrates at closely spaced intervals to >50 ft bgs). Active treatment systems may be technically and economically more attractive under these conditions. Active treatment approaches may also be better suited for layered lithologic units or sites where significant pH adjustment is required (such as the MAG-1 Area), as groundwater recirculation improves mixing and distribution of injected amendments within the subsurface. Longer treatment time frames, high contaminant concentrations, and secondary reaction concerns may also present conditions favorable for utilizing an active approach, since electron donor addition and mixing rates can be adjusted more easily then with passive approaches (which often utilize less frequent injection of electron donors at high concentrations). However, active approaches may be limited where re-injection of contaminated water (e.g., extracted groundwater with electron donor added) is either prohibited due to water usage/rights concerns or subject to regulatory injection permits.

Factors such as required cleanup time, contaminant concentrations, and presence of select co-contaminants can also affect costs and technology selection. However, perhaps the most significant long-term O&M cost and obstacle for any active in situ pumping systems is well fouling control. During this active treatment project, as well as others that have recently been completed (e.g., Hatzinger and Lippincott, 2009; Hatzinger et al., 2008), control of injection well fouling is a key component of system design and operation. This issue remains a critical technical and economic constraint to active pumping designs for CVOC treatment. Injecting an anti-biofouling agent on a regular basis during this field demonstration could have potentially impacted the results by killing some of the injected SDC-9 culture. Therefore, biofouling mitigation was limited to redevelopment of the injection wells during the demonstration.

Another cost associated with this technology and a major focus of this demonstration is the amount of microorganisms required to effectively treat a site. The amount of microorganisms needed depends upon contaminant concentrations, site hydrogeochemical conditions,

competition by indigenous microorganisms, the relative concentration of DHC in the bioaugmentation culture, in situ growth, transport, and decay of the bioaugmented culture, and various other site-specific factors, including access and shipping costs. In addition, the cost of the bioaugmentation culture is based on vendor selection as commercially available cultures vary in price and DHC concentration and activity. Overall, the results of this demonstration show that several factors affect the amount of DHC-containing bacterial culture needed to facilitate successful in situ bioremediation of chlorinated solvents. Most notably, the amount of culture needed is dependent largely on the contaminant concentration and soil properties that affect the attachment and detachment of the added DHC cells. ***Consequently, the impact of DHC dosage on bioaugmentation performance likely will need to be evaluated on a site-by-site basis, and the model developed during this project (Schaefer et al., 2009) can assist in predicting the affect of different cell dosages on in situ performance of the cultures. Efforts are underway to incorporate the model in to widely-used groundwater models so that it is readily accessible to remediation practitioners.***

8.3 COST ANALYSIS

Bioaugmentation for in situ treatment of groundwater contaminated with chlorinated ethenes can be used to replace traditional groundwater extraction with aboveground treatment and discharge or re-injection approaches (pump-and-treat [P&T]). Bioaugmentation is most often used in situations where biostimulation alone is not a viable alternative because DHC are not present in the aquifer. However, bioaugmentation can also be utilized in situations where biostimulation alone is a viable alternative (because DHC are already present the aquifer), but accelerated cleanup times are preferred or required.

As discussed above, bioaugmentation remedial approaches can be either active, where distribution of amendments and bioaugmented culture is achieved using groundwater recirculation, or passive, where distribution is accomplished via ambient groundwater flow. Active groundwater treatment approaches often involve pairs or groups of injection and extraction wells to recirculate groundwater and effectively distribute injected amendments and culture within the subsurface. Passive treatment approaches generally involve injection of amendments and culture via closely-spaced injection wells or direct-push technology. A carbon source is typically added prior to bioaugmentation or with the bioaugmentation culture in order to promote and maintain the highly reducing, anaerobic conditions and supply carbon needed for in situ growth of DHC and degradation of target contaminants. A slow-release carbon source, such as emulsified vegetable oil (EVO) is often utilized with passive treatment approaches to reduce injection frequency.

Cost analyses comparing active bioaugmentation to active biostimulation and P&T, and passive bioaugmentation to passive biostimulation are presented in the following subsections.

8.3.1 Active Bioaugmentation, Active Biostimulation, and Pump-and-Treat Comparison

For the purpose of this cost analysis, an active bioaugmentation treatment system (similar to that used in this demonstration) is compared to an active biostimulation system and to a traditional P&T system. The cost analysis is presented for a typical site, assuming full-scale application.

8.3.1.1 Site Description

Following is the basic site description used for the cost analysis:

- Depth to groundwater is approximately 30 ft bgs.
- Depth to base of impacted zone is approximately 50 ft bgs.
- Contaminant source area has either been removed or is no longer a continuing source of contamination to the plume.
- Plume dimensions are 160 ft at the point of treatment or capture and 250 ft long (total treatment volume = 29,629 cubic yards).
- Total CVOC concentrations in treatment area range from ~100 to 3000 µg/L. Lithology consists of fine to medium silty sands from 30-50 ft bgs, underlain by a clay confining unit.
- The average hydraulic conductivity value is 1.0×10^{-3} cm/s in silty sand unit.
- DHC are present at low concentrations ($<1.0 \times 10^{3}$ cells/L).
- Average electron acceptor concentrations are:
  - Dissolved oxygen: 1.5 mg/L
  - Nitrate (as N): 2.5 mg/L
  - Sulfate: 50 mg/L
- It has a neutral pH of ~ 6.5-7.0 standard units.

8.3.1.2 Assumptions: Active Bioaugmentation and Active Biostimulation

Following are the assumptions used for analyzing costs associated with treatment utilizing bioaugmentation with groundwater recirculation:

- Nine extraction wells:
  - Three rows, 100 ft apart and perpendicular to groundwater flow
  - Three wells per row at 40-ft centers
  - Each 4-inch well to be completed at a depth of 50 ft bgs, with screen interval from 30 to 50 ft bgs. Well screens to be continuously-wrapped and constructed of stainless steel. Well casing to be constructed of polyvinyl chloride (PVC).
- Twelve injection wells:
  - Three rows 100 ft apart and perpendicular to groundwater flow
  - Four wells per row at 40-ft centers
  - Each 4-inch well to be completed at a depth of 50 ft bgs, with screen interval from 30 to 50 ft bgs. Well screens to be continuously-wrapped and constructed of stainless steel. Well casing to be constructed of PVC.

- Six monitoring wells:
    - Each 2-inch well to be completed at a depth of 50 ft bgs, with screen interval from 35 to 45 ft bgs. Well screens and casing to be constructed of PVC.
- The average pumping rate per well is between 3 and 5 gpm
- Electron donor agent will be sodium lactate
- Recirculation system to consist of the following major components:
    - Nine submersible groundwater extraction pumps and controls
    - Filtration system
    - 1000-gallon equilibration tank
    - Transfer/re-injection pump
    - Biofouling mitigation system (chlorine dioxide)
    - PLC/SCADA unit with flow and level control for each extraction well.
- System controls and amendment delivery system to be housed in Conex box or small temporary structure
- Lactate and nutrient injections to be performed manually once per month
- Groundwater sampling of 6 wells quarterly for the first 5 years and annually thereafter.

8.3.1.2.1 Active Bioaugmentation

- System to be operated continuously for 6 months, followed by 12 months of active/passive operation
- One bioaugmentation event with 680 L of SDC-9, obtaining an average aquifer DHC concentration of 1.0×10^7 cells/L
- Site closure at 15 years.

8.3.1.2.2 Active Biostimulation

- System to be operated continuously for 6 months, followed by 30 months of active/passive operation
- No bioaugmentation performed
- Site closure at 16 years.

8.3.1.3 Pump-and-Treat Assumptions

Following are the assumptions used for analyzing costs associated with treatment utilizing P&T:

- Six extraction wells:
    - One row perpendicular to groundwater flow
    - Wells at 30-ft centers

- Each 4-inch well to be completed at a depth of 50 ft bgs, with screen interval from 30 to 50 ft bgs. Well screens to be continuously wrapped and constructed of stainless steel. Well casing to be constructed of PVC.

- Six monitoring wells
  - Each 2-inch well to be completed at a depth of 50 ft bgs, with screen interval from 35 to 45 ft bgs. Well screens and casing to be constructed of PVC.
- The average pumping rate per well is between 8 and 12 gpm
- P&T system to consist of the following major components:
  - Six submersible groundwater extraction pumps and controls
  - Filtration system
  - Two 1000-gallon equilibration tanks
  - Three Transfer pumps
  - Air Stripper
  - Two liquid-phase granular-activated carbon vessels (1000 lb each)
  - PLC/SCADA unit with flow and level control for each extraction well.
- Permanent structure to be constructed to house system
- Carbon change-outs to be performed every 6 months
- Discharge to sanitary sewer
- System to be operated continuously for 30 years
- Groundwater sampling of six wells quarterly for the first 5 years and annually thereafter
- Monthly effluent sampling/reporting
- Site closure at 30 years.

8.3.1.4 Active Bioaugmentation Cost Analysis

Table 4 shows the estimated capital costs, O&M costs and long-term monitoring costs for implementation of bioaugmentation with active groundwater recirculation under the base case. The net present value (NPV) of 2.7% (White House Office of Management and Budget, 2009) for O&M and monitoring costs was utilized in the cost estimates. The capital costs and NPV of the other O&M and monitoring costs provides the respective life-cycle costs adjusted to take into account the time value of money.

The costing has been developed for the base case conditions using assumptions described previously and is based on operating the groundwater recirculation system continuously for 6 months, followed by 12 months of active/passive operation (groundwater recirculation approximately 50% of the time), and adding electron donor manually once per month. The estimated 18 months of operation in the estimate is conservative, considering remedial objectives were largely achieved during the demonstration with less than 1 year of system operation. The estimate for this alternative also assumes that site closure can be attained within 15 years.

The capital cost including design, installation of wells, installation of the downhole and above grade equipment and controls, and system start-up and testing is approximately $683,500 and the NPV of the O&M totals an additional $422,714 of costs over 18 months of operation. The O&M costs include the costs for labor for system O&M, costs for equipment repair and replacement, and cost for electron donor. O&M costs also include $51,000 for 680 L of SDC-9 culture (cell density = 1.0 x 1011 cells/L) at the General Services Administration (GSA)-approved price of $75.00 per liter. The NPV of the long-term monitoring costs is estimated to be $492,552 resulting in a total life-cycle cost for this alternative of $1,598,765 (Table 4).

Table 4. Cost components for in situ bioaugmentation with groundwater recirculation.

	Year Cost is Incurred										NPV of Costs*
	1	2	3	4	5	6	7	8	9	10-16	
Capital Costs											
System Design	$95,000	-	-	-	-	-	-	-	-	-	$95,000
Well Installation	234,000	-	-	-	-	-	-	-	-	-	234,000
System Installation	344,500	-	-	-	-	-	-	-	-	-	344,500
Start-up and Testing	10,000	-	-	-	-	-	-	-	-	-	10,000
Subcost ($)	**683,500**	-	-	-	-	-	-	-	-	-	**683,500**
O&M Costs											
System O&M	301,000	125,000	-	-	-	-	-	-	-	-	422,714
Subcost ($)	**301,000**	**125,000**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**422,714**
Long-Term Monitoring Costs											
Sampling/Analysis/ Reporting (quarterly through 5 years, then annually)	71,000	71,000	71,000	71,000	71,000	20,000	20,000	20,000	20,000	Years 10-16 costs same as year 9	492,552
Subcost ($)	**71,000**	**71,000**	**71,000**	**71,000**	**71,000**	**20,000**	**20,000**	**20,000**	**20,000**	**Same**	**492,552**
Total Cost ($)	**1,055,500**	**196,000**	**71,000**	**71,000**	**71,000**	**20,000**	**20,000**	**20,000**	**20,000**	**Repeat 9**	**1,598,765**

Notes: NPV – net present value
* – NPV calculated based on a 2.7% discount rate

8.3.1.5 Active Biostimulation Cost Analysis

Table 5 shows the estimated capital costs, O&M costs, and long-term monitoring costs for implementation of biostimulation only with active groundwater recirculation under the base case. The NPV of the O&M and monitoring costs is also included.

Table 5. Cost components for in situ biostimulation with groundwater recirculation.

	Year Cost is Incurred										NPV of Costs*
	1	2	3	4	5	6	7	8	9	10-15	
Capital Costs											
System Design	95,000	-	-	-	-	-	-	-	-	-	95,000
Well Installation	234,000	-	-	-	-	-	-	-	-	-	234,000
System Installation	344,500	-	-	-	-	-	-	-	-	-	344,500
Start-up and Testing	10,000	-	-	-	-	-	-	-	-	-	10,000
Subcost ($)	**683,500**	-	-	-	-	-	-	-	-	-	**683,500**
O&M Costs											
System O&M	250,000	250,000	125,000	-	-	-	-	-	-	-	611,941
Subcost ($)	**250,000**	**250,000**	**125,000**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**611,941**
Long Term Monitoring Costs											
Sampling / Analysis / Reporting (Quarterly through 5 years then Annually)	71,000	71,000	71,000	71,000	71,000	20,000	20,000	20,000	20,000	Years 10-15 costs same as year 9	505,963
Subcost ($)	**71,000**	**71,000**	**71,000**	**71,000**	**71,000**	**20,000**	**20,000**	**20,000**	**20,000**	**Same**	**505,963**
Total Cost ($)	**1,004,500**	**321,000**	**196,000**	**71,000**	**71,000**	**20,000**	**20,000**	**20,000**	**20,000**	**Repeat 9**	**1,801,404**

Notes: NPV – net present value
* – NPV calculated based on a 2.7% discount rate

The costing has been developed for the base case conditions using assumptions described previously and is based on operating the groundwater recirculation system continuously for 6 months, followed by 24 months of active/passive operation, and adding electron donor manually once per month. The costing assumes an additional 12 months of active/passive operation (over the 18 months used in the bioaugmentation cost estimate) to obtain the same DHC cell density and degradation kinetics observed in the bioaugmentation case study. The estimate for this alternative also assumes that site closure can be attained within 16 years.

The capital cost including design, installation of wells, installation of the downhole and above grade equipment and controls, and system start-up and testing is approximately $683,500 and the NPV of the O&M totals an additional $611,941 of costs over 30 months of operation. The O&M costs include the costs for labor for system O&M, costs for equipment repair and replacement, and cost for electron donor. The NPV of the long-term monitoring costs is estimated to be $505,963, resulting in a total life-cycle cost for this alternative of $1,801,404 (Table 5).

8.3.1.6 Pump-and-Treat Cost Analysis

Table 6 shows the estimated capital costs, O&M costs, and long-term monitoring costs for implementation of the P&T under the base case. The NPV of the O&M and monitoring costs is also included. The costing has been developed for the base case conditions using assumptions described previously and is based on operating the groundwater recirculation system and performing long-term monitoring for 30 years.

Table 6. Cost components for pump-and-treat.

	Year Cost is Incurred									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**7-30**	**10, 15, 20, 25, 30**	**NPV of Costs***
Capital Costs										
System Design	$105,000	-	-	-	-	-	-	-		$105,000
Well Installation	103,500	-	-	-	-	-	-	-		103,500
System Installation	468,000	-	-	-	-	-	-	-		468,000
Start-up and Testing	10,000	-	-	-	-	-	-	-		10,000
Subcost ($)	**686,500**	-	-	-	-	-	-	-		**686,500**
O&M Costs										
System O&M	$204,000	204,000	204,000	204,000	229,000	204,000	204,000	Repeat $204,000 annually through year 30	Add $25,000 for non-routine O&M and well rehab in each year listed above	4,369,539
Subcost ($)	**204,000**	**204,000**	**204,000**	**204,000**	**229,000**	**204,000**	**204,000**			**4,369,539**
Long Term Monitoring Costs										
Sampling / Analysis / Reporting (Quarterly through 5 years then Annually)	$72,000	72,000	72,000	72,000	72,000	22,500	22,500	Years 8-30 costs same as year 7		$705,821
Subcost ($)	**72,000**	**72,000**	**72,000**	**72,000**	**72,000**	**22,500**	**22,500**	**Same**	**Same**	**705,821**
Total Cost ($)	**962,500**	**276,000**	**276,000**	**276,000**	**301,000**	**226,500**	**226,500**			**5,761,860**

Notes: NPV – net present value
* – NPV calculated based on a 2.7% discount rate

The capital cost including design, installation of wells, installation of the downhole and above grade equipment and controls, and system start-up and testing is approximately $686,500, and the NPV of the O&M totals an additional $4,369,539 of costs over 30 years of operation. The O&M costs include the costs for labor for system O&M, costs for equipment repair and replacement, and carbon change-outs. The NPV of the long-term monitoring costs is estimated to be $705,821, resulting in a total life-cycle cost for this alternative of $5,761,860 (Table 6).

8.3.1.7 Active Treatment Cost Comparison

The comparison of the cost analysis for the three remedial scenarios provided above indicates that bioaugmentation with active groundwater recirculation is the least costly and fastest remedial approach for the base case. Even with the estimated $51,000 additional cost of the bioaugmentation culture, bioaugmentation provides an estimated cost savings of approximately $203,000 over the biostimulation-only approach. The higher cost of the biostimulation-only approach is due to the need to operate the groundwater recirculation system and add amendments for an additional 12-month period. This additional treatment time would be required because of the reduced biodegradation kinetics associated with this approach.

The bioaugmentation approach provides a cost saving of approximately $4,163,000 over that of the pump-and-treat approach (approximately one-third of the cost). In addition to the cost savings, the bioaugmentation approach provides treatment of the entire contaminated zone within 3 years, while the P&T approach only provides capture of contaminants at the downgradient

edge of the plume over a 30-year period. Therefore, the bioaugmentation option provides both faster and more complete remediation of the target zone.

The capital costs associated with all three technologies are almost identical (Tables 4 through 6). However, because the P&T system requires 30 years of continuous operation, the O&M costs and long-term monitoring costs are significantly higher than that of the bioaugmentation option (which requires only 3 years of operation). Additionally, the P&T option requires 30 years of long-term monitoring (including monitoring of system effluent for compliance with discharge permits) compared to 15 years of monitoring for the bioaugmentation option. It should be noted that even if the bioaugmentation option required 30 years of long-term monitoring, the additional NPV of these costs would total less than $270,000, which would still make the cost of the bioaugmentation approach considerably less than the P&T approach.

8.3.2 Passive Bioaugmentation and Passive Biostimulation Comparison

For the purpose of this cost analysis, a passive bioaugmentation treatment approach is compared to a passive biostimulation approach at three different scales; ¼ acre, 1 acre, and 3 acres. Two SDC-9 dosages (obtaining average aquifer DHC concentrations of 1.0×10^6 and 1.0×10^7 cells/L) for the bioaugmentation approach and two biostimulation injection strategies are also compared at each scale. The cost analysis is presented for a typical site, assuming full-scale application.

8.3.2.1 Site Description

Following is the basic site description used for the cost analysis:

- Depth to groundwater is approximately 15 feet bgs
- Depth to base of impacted zone is approximately 25 feet bgs
- Contaminant source area has either been removed or is no longer a continuing source of contamination to the plume
- Treatment areas: ¼ acre, 1 acre, and 3 acres (total treatment volumes = 4033, 16,133, and 48,400 cubic yards, respectively)
- Total CVOC concentrations in treatment area range from ~100 to 3000 µg/L ("DCE stall" observed)
- Lithology consists of fine to medium silty sands from 15-25 ft bgs, underlain by a clay confining unit
- Average hydraulic conductivity value of 1.0×10^{-3} cm/s in silty sand unit
- DHC are present at low concentrations ($<1.0 \times 10^3$ cells/L)
- Average electron acceptor concentrations:
    - DO: 1.5 mg/L
    - Nitrate (as N): 2.5 mg/L
    - Sulfate: 50 mg/L

- Neutral pH: ~ 6.5-7.0 standard units.

8.3.2.2 Assumptions

Following are the assumptions used for analyzing costs associated with treatment utilizing passive bioaugmentation and biostimulation:

- Effective injection radius of influence = 10 ft
- Direct-push points used for injection of EVO, nutrients, and SDC-9 culture (with the bioaugmentation approach):
  - Three 3-foot injection intervals per point
  - Simultaneous injection at six to eight points at a time
  - Average injection rate = 3 gpm per point.
- Three monitoring wells for the ¼-acre scenario, four monitoring wells for the 1-acre scenario, and six monitoring wells for the 3-acre scenario
  - Each 2-inch well to be completed at a depth of 25 ft bgs, with screen interval from 15 to 25 ft bgs. Well screens and casing to be constructed of PVC.
- Groundwater sampling of all wells quarterly for the first 5 years, and annually thereafter.

8.3.2.2.1 Passive Bioaugmentation

- One initial injection of EVO and nutrients required to establish reducing conditions
  - 15% of treatment pore volume injected.
- A second injection consisting of SDC-9 culture and additional nutrients:
  - 3% of treatment zone pore volume injected ("seeding" with SDC-9 culture).
- Site closure at 15 years with the higher DHC dosage, and 16 years with the lower dosage.

Case #1

- One direct-push bioaugmentation event with SDC-9, obtaining average aquifer DHC concentrations of 1.0×10^7.

Case #2

- One direct-push bioaugmentation event with SDC-9, obtaining average aquifer DHC concentrations of 1.0×10^6.

8.3.2.2.2 Passive Biostimulation

- No bioaugmentation performed

- Site closure at 18 years.

Case #1

- Two direct-push injections of EVO and nutrients:
  - 15% of treatment zone pore volume injected
  - Second injection required at beginning of year 3.

Case #2

- One direct-push injections of EVO and nutrients:
  - 15% of treatment zone pore volume injected
  - 50% more EVO and nutrients injected to extend active treatment to 4 years.

8.3.2.3 Passive Bioaugmentation Cost Analysis

Table 7 shows the estimated capital costs, injection costs, and long-term monitoring costs for implementation of passive bioaugmentation utilizing direct-push injections under the three scenarios discussed above. It was assumed that capital costs and injection costs were incurred during the first year of the project. The NPV of 2.7% (White House Office of Management and Budget, 2009) for monitoring costs was utilized in the cost estimates. The costing has been developed for the base case conditions using assumptions described previously and is based on one round of amendment injections (EVO and nutrients) and one round of bioaugmentation injections.

The capital costs include design, work plan preparation, groundwater modeling, and installation of monitoring wells. Capital costs are the same for both DHC dosage cases under each of the three treatment scenarios (e.g., ¼ acre, 1 acre, and 3 acres), respectively. The injection costs include the costs for injection labor, the direct-push injection subcontractor, rental equipment, and EVO, nutrients and the SDC-9 culture. The difference in injection costs between the two DHC dosage cases is the cost associated with the SDC-9 bioaugmentation culture (at the GSA-approved price of $75.00 per liter). The NPV of the long-term monitoring costs was estimated based on a 15-year life cycle for the higher DHC dosage case and a 16-year life cycle for the lower DHC dosage case (Table 7). Faster degradation kinetics, and thus faster site closure, were assumed with the higher DHC dosage because the contaminant concentration is the same in each scenario.

8.3.2.4 Passive Biostimulation Cost Analysis

Table 7 shows the estimated capital costs, injection costs, and long-term monitoring costs for implementation of passive biostimulation utilizing direct-push injections under the three scenarios discussed above. It was assumed that capital costs were incurred during the first year of the project. Costing for two injection scenarios (two rounds of amendment injections and one round of amendment injections at higher concentrations) have been developed for the base case conditions using assumptions described previously. Injection costs were incurred during the first year of the project for the single-injection scenario, and during years 1 and 3 during the two-

Table 7. Summary of passive bioremediation cost comparison.

Treatment Area	¼ Acre				1 Acre				3 Acres			
	Bioaug. DHC=10E7	Bioaug. DHC=10E6	Biostim. 2 Injections	Biostim. 1 Injection	Bioaug. DHC=10E7	Bioaug. DHC=10E6	Biostim. 2 Injections	Biostim. 1 Injection	Bioaug. DHC=10E7	Bioaug. DHC=10E6	Biostim. 2 Injections	Biostim. 1 Injection
Capital Costs ($)	111,500	111,500	111,500	111,500	128,100	128,100	128,100	128,100	154,200	154,200	154,200	154,200
Injection Costs ($)	104,400	97,900	164,200	97,500	303,400	278,300	474,400	280,500	804,700	729,400	1,230,000	725,000
Long-Term Monitoring Costs ($)	392,600	403,300	424,000	424,000	457,800	470,300	494,400	494,400	579,100	594,900	625,100	625,100
Total Cost ($)	608,200	612,700	699,700	633,000	889,300	876,700	1,096,900	903,000	1,538,000	1,478,500	2,009,300	1,504,300

injection scenario. The NPV of 2.7% (White House Office of Management & Budget, 2009) for monitoring costs and the second injection was utilized in the cost estimates.

The capital costs include design, work plan preparation, groundwater modeling, and installation of monitoring wells. Capital costs are the same for both injection cases under each of the three treatment scenarios (e.g., ¼ acre, 1 acre, and 3 acres), respectively. The injection costs include the costs for injection labor, the direct-push injection subcontractor, rental equipment, and EVO and nutrients. The difference in injection costs between the two injection scenarios is the cost associated with a second direct-push injection (at the beginning of year 3) and additional amendments. The NPV of the long-term monitoring costs was estimated based on a 18-year life cycle for both injection cases (Table 7). The same degradation kinetics were assumed with both cases.

8.3.2.5 Passive Treatment Cost Comparison

The comparison of the cost analysis for the three passive remedial scenarios provided above indicates that bioaugmentation is the fastest remedial approach for the three base cases (Table 7). However, the most cost-effective bioaugmentation approach (i.e., which DHC dosage to use) depends on the scale of the project. The higher DHC dosage approach provides a lower cost alternative to the lower DHC dosage approach (and both biostimulation approaches) for the ¼-acre treatment scenario. However, the lower DHC dosage approach provides a lower cost alternative to the higher DHC dosage approach for the larger 1-acre and 3-acre treatment scenarios. This is largely due to the fact that the cost associated with the addition bioaugmentation culture for the larger treatment areas outweigh the cost of 1 year of additional long-term monitoring for the larger scale projects discussed above. Therefore, treatment times should be weighed against the costs associated with the different dosages when evaluating treatment approaches.

For the ¼-acre treatment scenario, the higher DHC dosage approach provides a cost savings of approximately $4500 over the lower dosage approach, $91,500 over the 2-injection biostimulation approach, and $24,800 over the 1-injection biostimulation approach. For the 1-acre treatment scenario, the lower DHC dosage approach provides a cost savings of approximately $12,600 over the higher dosage approach, $220,200 over the 2-injection biostimulation approach, and $26,300 over the 1-injection biostimulation approach. Finally, for the 3-acre treatment scenario, the lower DHC dosage approach provides a cost savings of approximately $59,500 over the higher dosage approach, $530,800 over the 2-injection biostimulation approach, and $25,800 over the 1-injection biostimulation approach. Based on these estimates, a biostimulation-only approach utilizing one injection could potentially be more cost effective at treatment scales greater than 3 acres. It should be noted that the biostimulation-only approach assumes that DHC are present at the site and capable of being stimulated in situ to a cell density high enough (approximately 10^7 cells/liter) for effective dechlorination of target CVOCs. Additionally, the single injection biostimulation approach assumes that the injected amendments last and don't migrate from the treatment zone before remediation is complete. The need for a second biostimulation injection would make the cost of biostimulation significantly higher than that of either of the bioaugmentation approaches.

It should be noted that the conclusions discussed above were derived from the base case scenarios and should not be extrapolated to all sites without first performing adequate pre-design activities and cost comparisons. Treatability testing, pilot testing, and groundwater modeling should be used to determine the optimal approach for each site. The approach should take into account remedial goals (such as treatment duration) and cost effectiveness. The cost drivers discussed in Section 8.2 also need to be considered. ***Consequently, the impact of DHC dosage on bioaugmentation performance likely will need to be evaluated on a site-by-site basis, and the model developed during this project (Schaefer et al., 2009) can assist in predicting the affect of different cell dosages on*** in situ ***performance and expected treatment times.***

8.3.2.5.1 The Cost of Not Bioaugmenting

To estimate a typical cost for bioaugmentation, we analyzed 40 bioaugmentation applications performed by Shaw Environmental, Inc. with the SDC-9 culture at DoD sites throughout the United States. The treated sites varied widely in the dimension and thickness of the treated area, contaminant concentration, hydrogeology, and remedial goals. The average volume of aquifer treated was 28,667 m^3. The average volume of culture applied was 115 L. Using Shaw's 2009 GSA-approved price for SDC-9 of $75/L, the average cost for bioaugmentation culture at these sites was $8625 or $0.30/$m^3$ of treated aquifer. Assuming an average commercial culture cost of $150 to $300 per liter, the average cost of culture for these projects on a commercial site would have been $17,250 to $34,500, or an equivalent of $0.60 to $1.20/$m^3$ of treated aquifer.

The cost of bioaugmentation should be compared to the potential cost of not bioaugmenting. It is often assumed that bioaugmentation is costly and that the time saved by bioaugmentation may not be significant in the absence of a regulatory driver forcing the early cleanup of the site. That is, a typical response is, "If we don't bioaugment the site, we just have to monitor for a little longer." It is worthwhile then to evaluate the cost of the additional monitoring relative to the cost of bioaugmentation and an expected more rapid site closure. Factoring in the cost of re-injecting electron donor, permit renewals, system O&M, meetings with regulators, and other typical consulting costs, the real cost of additional years of treatment and monitoring are likely to be much greater than the cost of bioaugmentation.

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9.0 IMPLEMENTATION ISSUES

The primary end users of this technology are expected to be DoD site managers and contractors, environmental engineers and consultants, as well as other stakeholders. The general concerns of these end users include technology applicability under local site conditions, technology performance, technology scale-up, and technology cost. The expected cost drivers for installation and operation of a bioaugmentation groundwater recirculation system for the remediation of chlorinated ethenes, and those that will determine the cost and selection of this technology over other options are provided in Section 8. Scale-up of this technology has been performed at several hundred sites and follows standard design practices, with required equipment generally being commercially available off-the-shelf. DHC-containing bacterial cultures are readily available from Shaw (609-895-5350) and several other vendors.

The results of this project demonstrated that CVOCs in a low pH aquifer can be effectively remediated by using active groundwater recirculation, bioaugmentation with the SDC-9 consortium, and pH adjustment. Results of this field demonstration have provided a detailed evaluation of the use of a groundwater recirculation design for the distribution of groundwater amendments (including a TCE-degrading microbial culture), use of buffering agents to control in situ pH, and an application model to allow practitioners to plan bioaugmentation applications and predict their performance. As such, critical design and implementation issues regarding microbial dosage requirements, remedial time frames, and system optimization have been addressed and are being made available to environmental professionals and stakeholders.

The two major challenges encountered during the demonstration were pH adjustment of the aquifer and injection well fouling. Increasing and maintaining pH levels within the recirculation loops was challenging. When pH levels were maintained above 5.5 standard units and the bioaugmentation injections were performed at wells with a neutral pH (i.e., monitoring wells downgradient of the amendment injection wells), compete dechlorination of TCE to ethene was observed. An estimated 4150 lb of buffer was injected into each of the four injection wells during the demonstration.

As with many in situ treatment approaches, both biological and non-biological, fouling and plugging of the injection well screens can be a significant concern. During this demonstration, well fouling appeared to be occurring from an accumulation of carbonate and insoluble complexes (most likely iron sulfides and iron carbonates) within the well screen, sandpack, and the immediate surrounding formation. While the buffer used for pH adjustment was in solution during injection, the cumulative effect of continuous injections, high pH at the injection wells, and interactions with metals likely led to this precipitation. Precipitated metals were observed during well redevelopment and on system piping, components, and filter cartridges during the demonstration.

The accumulation of biomass did not appear to be a major cause of well fouling. However, for sites with more neutral pH levels, biofouling of active recirculation systems can become a significant O&M issue.

The most effective and economical solution for biofouling control with active systems involves multiple approaches, including selection of electron donor, dosing regimen of electron donor, biocide application, water filtration, and system pumping operation. Based on experience from this demonstration and others, the best operational approach to control fouling and minimize O&M costs associated with this issue includes the following:

- Active-passive rather than continuous operation
- Infrequent, high concentration dosing of electron donor during active phase
- Selection of an acidic electron donor to assist in biofouling control. Citric acid is optimal as it serves as an acid and a metal chelating agent
- Daily application of chlorine dioxide or other fouling control chemicals
- Installation of a filtration system to remove biomass from between the extraction wells and the injection wells.

These approaches were proven to be effective in a recent demonstration for bioremediation of perchlorate at the former Whitaker-Bermite facility in California (Hatzinger and Lippincott, 2009). Biofouling was significantly controlled in the groundwater extraction-reinjection system throughout the 6-month demonstration period by implementing the approaches described above.

While the results of this demonstration showed that (for the range of DHC dosages tested) bioaugmentation performance in the test plot used in this study was not substantially impacted by DHC dosage, these results should not be readily extrapolated to diverse field scale bioaugmentation scenarios. Groundwater flow velocity, contaminant concentration and longevity, and heterogeneity of subsurface conditions can impact the relative importance of DHC dosage on bioaugmentation effectiveness. In addition, as observed during performance of model simulations, a DHC attachment-detachment factor plays a significant role in determining the relative importance of DHC dosage on bioaugmentation kinetics (Schaefer et al., 2009). Thus, the impact of DHC dosage on bioaugmentation performance likely will need to be evaluated on a site-by-site basis, but the model developed during this project can assist in predicting the effect of different cell dosages on in situ performance of the cultures.

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APPENDIX A

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