FINAL

COST AND PERFORMANCE REPORT

ENHANCED *IN-SITU* ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS AT LF-08, WHITEMAN AIR FORCE BASE, MISSOURI

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Prepared for:

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1.0 INTRODUCTION

This report summarizes the cost and performance of a demonstration of enhanced *in situ* anaerobic bioremediation of chlorinated solvents at the Landfill 1 (LF-08) Site, Whiteman Force Base (AFB), Missouri. This demonstration was conducted by Parsons Infrastructure & Technology Group, Inc. (Parsons) as a case study for the use of vegetable oil as an organic substrate in support of the Air Force Center for Engineering and the Environment (AFCEE) *Enhanced In Situ Bioremediation Initiative*. The environmental program at Whiteman AFB is managed by AFCEE, which facilitated site selection and implementation of this demonstration. Technology demonstration summary information is listed in Table 1.

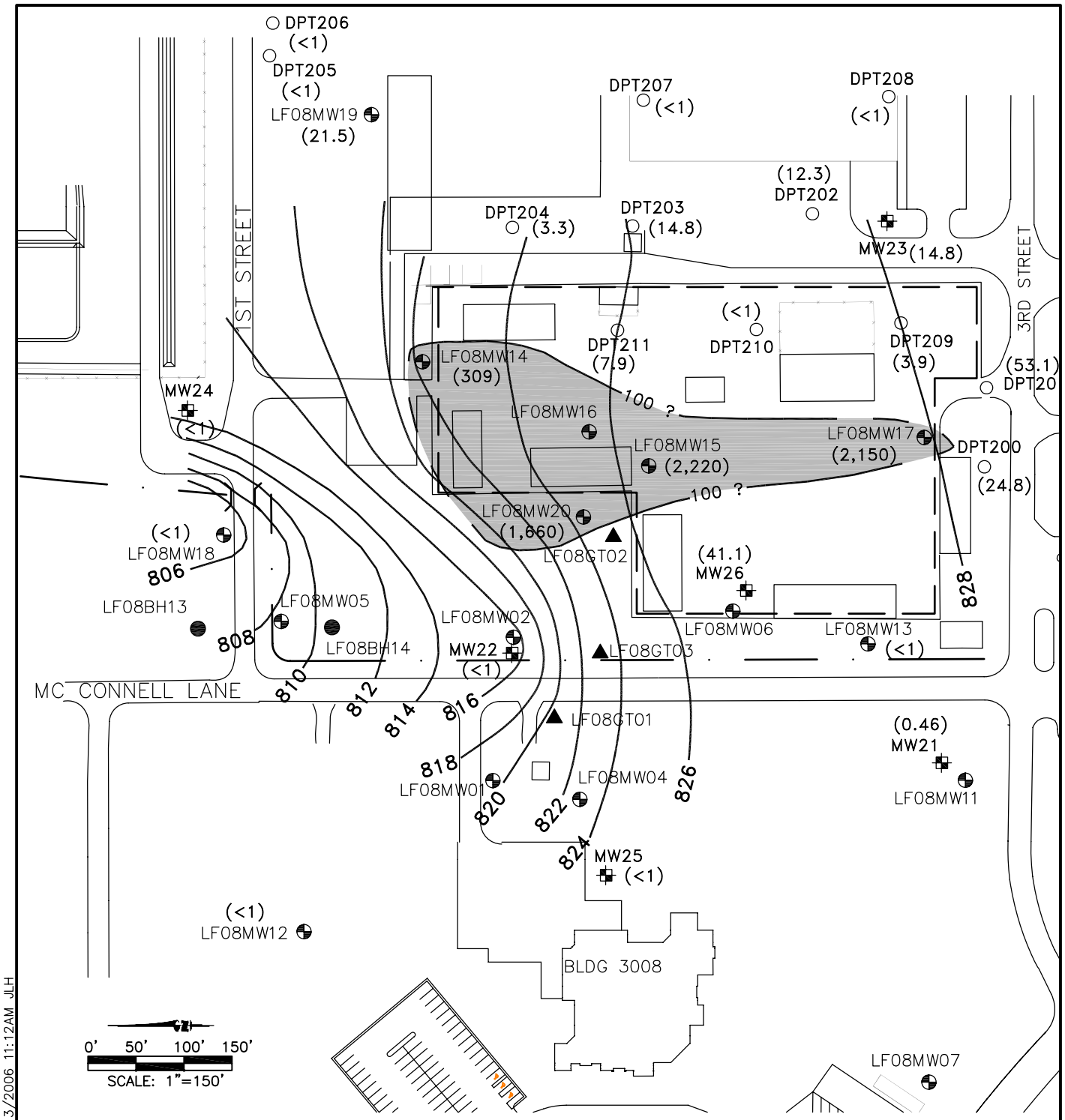
TABLE 1. SUMMARY INFORMATION

Site Name, Location	Site LF-08, Whiteman Air Force Base, Missouri
Treatment Mechanism	Anaerobic Reductive Dechlorination
Technology	Enhanced Anaerobic Bioremediation using Vegetable Oil Substrate
Configuration	Direct Subsurface Injection
Technology Scale	Pilot
Media/Matrix Treated	Groundwater
Contaminants Targeted	Chlorinated Ethenes – trichloroethene (TCE) and *cis*-1,2-dichloroethene (*cis*-1,2-DCE)
Period of Operation	June 2002 to February 2003

2.0 SITE DESCRIPTION

Whiteman AFB encompasses approximately 4,677 acres in Johnson County, Missouri. The Base is located approximately 65 miles southeast of Kansas City, just south of the town of Knob Noster. LF-08 (also known as Landfill 1), is located in the central northwest area of the Base. This landfill is located in a natural depression estimated to cover approximately 25,000 square feet, and was operated during the 1940s as a surface disposal area.

Historical information concerning the operation of LF-08 is limited. Records indicate the landfill materials are comprised of industrial and sanitary waste, including sludge, solvents, paint wastes, lubricating and cutting oils, and dry cleaning filters and filtrates (Booz, Allen & Hamilton, Inc., 1997). The site was originally identified during utility excavation in the deactivated Civil Engineering Compound (CEC), now the Base recycling center (Figure 1).



LEGEND

- EXISTING MONITORING WELL LOCATION
- DPT LOCATION (APPROXIMATE)
- BOREHOLE LOCATION (APPROXIMATE)
- FORMER CEC BOUNDARY
- MONITORING WELL LOCATION
- GEOPROBE LOCATION
- (24.8) TCE CONCENTRATION
- 806 GROUNDWATER ELEVATION CONTOUR LINE (BASED ON OCT/NOV 2000 DATA)
- 100 µg/L TCE CONCENTRATION CONTOUR

NOTES:
DATA COLLECTED BETWEEN SEPTEMBER AND NOVEMBER 2000.

FIGURE 1

HISTORICAL CONCENTRATIONS OF TCE AND GROUNDWATER ELEVATIONS

Whiteman Air Force Base
Johnson County, Missouri

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2.1 Hydrogeology

Baseline site conditions are summarized in Table 2. Unconsolidated sediments beneath LF-08 consist primarily of gray to brown clay or silty clay to a depth of 7 to 27 feet below ground surface (bgs). Underlying the clay/silty clay is orange to brown, clayey gravel, interspersed with thin, laterally discontinuous clayey sand lenses. When present, the clayey gravel ranges in thickness from 0.2 to 6 feet. Bedrock is encountered from 8.5 to 32 feet bgs.

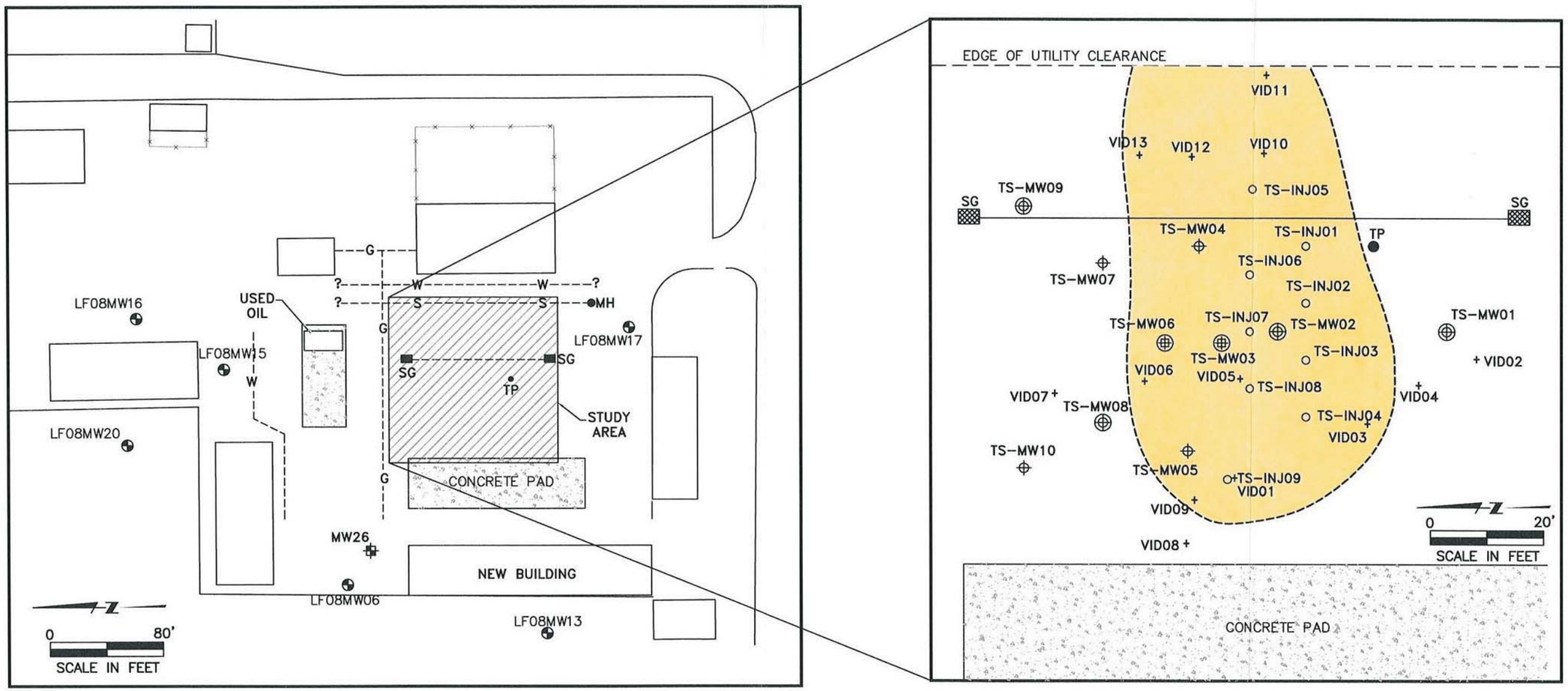
TABLE 2. HYDROGEOLOGIC AND CONTAMINANT CHARACTERISTICS

Site Attribute	Description
Aquifer Matrix	Dense Clay to Clayey Gravel
Depth to Groundwater	6 to 10 feet below ground surface
Thickness of Aquifer	8.5 to 32 feet
Hydraulic Conductivity	0.02 to 0.15 feet per day (ft/day)
Effective Porosity	15 percent (estimated)
Hydraulic Gradient	0.016 feet per foot (ft/ft)
Groundwater Velocity	0.8 to 5.8 feet per year (ft/yr)
Maximum Groundwater Pre-Injection Contaminant Concentrations [a/]	TCE = 2,140 micrograms per liter (µg/L) *cis*-1,2-DCE = 33 µg/L Methylene chloride = 139 µg/L
DNAPL Presence	Not Encountered
Fraction Organic Carbon	Not Available

[a/] Pre-injection concentrations at TS-MW-01 or TS-MW-07 (see Table 3).

The clayey-gravel horizon of the unconsolidated sediments is a relatively loose, saturated material consisting of predominantly clay and silt intermixed with varying amounts of angular gravel and coarse sand. This horizon varies in thickness and depth, with the thickest unit encountered in the southern portion of LF-08, and pinching out in the northeastern and northwestern central portions of the site. The clayey gravel horizon is the primary shallow water-bearing zone within the unconsolidated sediments. Moisture content and plasticity in the unconsolidated sediments beneath the site vary widely from dry with low plasticity to wet with medium to high plasticity. Intermittent mottling, iron and manganese nodules, and black stringers of organic rich material are encountered in the clay/silty clay.

Groundwater occurs under unconfined conditions in the clayey gravel horizon at a seasonally variable depth of approximately 6 to 10 feet bgs (Figure 2). The groundwater potentiometric surface slopes toward the northwest with an average gradient of approximately 0.016 foot per foot (ft/ft) based on water level measurements taken in July 2002 (Parsons, 2002). The hydraulic conductivity in the study area was calculated to range from 0.02 feet per day (ft/day) to 0.15 ft/day. Assuming an effective porosity of 15 percent, groundwater flow in the clayey gravel horizon at the site averages between approximately 0.0021 to 0.016 ft/day, or about 0.8 to 5.8 feet per year (ft/yr).



LEGEND

- ○ INJECTION POINTS
- ⊕ MONITORING POINTS
- + SCAPS/LIF TEST LOCATION (APPROXIMATE)
- TP• TELEPHONE POLE
- SG ▩ STORM SEWER GRATE
- MH ● MANHOLE
- ---W--- UNDERGROUND WATER PIPE (APPROXIMATE)
- ---S--- UNDERGROUND SEWER PIPE (APPROXIMATE)
- ---G--- UNDERGROUND GAS PIPE (APPROXIMATE)
- EXTENT OF INJECTED OIL OBSERVED IN VIDEO PROBES AND SOIL SAMPLES, JULY 2002

FIGURE 2

INJECTION AND MONITORING LOCATIONS

Whiteman Air Force Base
Johnson County, Missouri

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Draw\738863 Monitoring Locations.cdr ma 10/13/06

2.2 Pre-Injection Nature and Extent of Contamination

Groundwater sampling results collected prior to vegetable oil injection indicate that four contaminants were detected at concentrations greater than respective method detection limits (Table 3). Trichloroethene (TCE) was detected at a maximum concentration of 2,140 micrograms per liter (µg/L) at location TS-MW-01 (Figure 2). Dechlorination products of TCE that were detected in groundwater during baseline sampling include the dichloroethene (DCE) isomers *cis*-1,2-DCE (up to 36.9 µg/L) and *trans*-1,2-DCE (up to 2.5 µg/L). Methylene chloride was also detected at monitoring wells TS-MW-01 and TS-MW-07 at concentrations of 30.8 µg/L and 139 µg/L, respectively, and at concentrations less than 2.0 µg/L at all other locations.

2.2 Pre-Injection Groundwater Geochemical Conditions

Groundwater geochemical data collected prior to substrate injection indicate that natural conditions on this site are moderately to strongly aerobic. Groundwater geochemical data are summarized in Table 4. Concentrations of dissolved oxygen (DO) ranged from 1.8 milligrams per liter (mg/L) to 8.9 mg/L, while oxidation reduction potential (ORP) ranged from -53 millivolts (mV) to +146 mV. These geochemical conditions are generally not conducive to anaerobic degradation processes. Chlorinated solvent compounds are not readily degraded under the natural geochemical conditions encountered at LF-08.

Analysis of total organic carbon (TOC) during the baseline sampling event indicates that native groundwater beneath the LF-08 demonstration site was low in soluble organic carbon prior to substrate injection. In all cases, concentrations of TOC detected during baseline sampling were less than 5.0 mg/L. These concentrations are well below the minimum levels thought to be necessary to support biologically mediated reductive dechlorination (AFCEE *et al*., 2004). The objective of the demonstration was to overcome this lack of soluble organic carbon and to induce strongly anaerobic conditions conducive to the reductive dechlorination of chlorinated solvents in groundwater.

3.0 TECHNOLOGY DESCRIPTION

Enhanced *in situ* anaerobic bioremediation is an effective method of degrading chlorinated aliphatic hydrocarbons (CAHs, commonly referred to as chlorinated solvents) dissolved in groundwater. One advantage of this technology is that it can lead to complete destruction of chlorinated solvents *in situ* with little impact on site infrastructure or a need for secondary treatment trains. In addition, enhanced anaerobic bioremediation can generally be implemented at a cost that is low relative to other engineered remedial options.

The addition of an organic substrate to an aquifer stimulates microbial growth, resulting in the formation of an anaerobic environment that may greatly enhance rates of anaerobic degradation of CAHs. To date, a variety of organic substrates have been applied to the subsurface to promote anaerobic degradation of CAHs to innocuous end products. Examples of easily fermentable organic substrates include carbohydrates and sugars, vegetable oils, and low-molecular-weight fatty acids. Vegetable oil was selected as the organic substrate for the demonstration at LF-08 because it is a cost-effective, slow-release source of organic carbon.

TABLE 3
SUMMARY OF VOLATILE ORGANIC COMPOUNDS DETECTED IN GROUNDWATER

Sample Location	Sample Date	TCE[a/] (µg/L)[b/]	cis-1,2-DCE[a/] (µg/L)	trans-1,2-DCE (µg/L)	Vinyl Chloride (µg/L)	Methylene Chloride (µg/L)
Groundwater Monitoring Wells						
TS-MW-01	6/21/2002	**2,140**	**33.2**	< 6.0	< 1.1	**30.8**
	10/1/2002	**2,010**	**31.0**	**2.0**	<11	<2.0
	2/12/2003	**2,350**	**25.7**	< 6.0	<11	<20
TS-MW-02	6/24/2002	**368**	**12.2**	**0.64**	< 1.1	**1.2 F** [c/]
	10/1/2002	**252**	**16.5**	< 6.0	<11	<20
	2/11/2003	**414**	**34.5**	< 6.0	<11	<20
TS-MW-03	6/24/2002	**278**	**10.8**	**0.50 F**	< 1.1	**1.1 F**
	10/1/2002	**583**	**22.1**	**2.6**	<11	<2.0
	2/11/2003	**511**	**15.4**	< 6.0	<11	<20
TS-MW-04	6/24/2002	**393**	**9.4**	**0.52 F**	< 1.1	**1.2 F**
	10/1/2002	**1,300**	**20.8**	**1.3**	<11	<2.0
	2/11/2003	**1,630**	**18.8**	< 6.0	<11	<20
TS-MW-05	6/24/2002	**1,080**	**21.8**	**1.1**	< 1.1	**0.98 F**
	10/1/2002	**2,120**	**29.1**	**1.7**	<11	<2.0
	2/12/2003	**1,350**	**36.1**	< 6.0	<11	<20
TS-MW-06	6/24/2002	**499**	**18.8**	**1.0**	< 1.1	**0.92 F**
	10/1/2002	**1,130**	**19.0**	**1.4**	<11	<2.0
	2/11/2003	**1,430**	**28.3**	< 6.0	<11	<20
TS-MW-07	6/24/2002	**1,730**	**22.4 F**	< 30	< 55	**139**
	10/1/2002	**2,080**	**32.2**	**2.5**	<11	<2.0
	2/12/2003	**1,720**	**29.9**	< 6.0	<11	<20
TS-MW-08	6/24/2002	**1,610**	**32.3**	**1.9**	< 1.1	**1.0**
	10/1/2002	**2,850**	**33.3**	**2.3**	<11	<2.0
	2/11/2003	**2,300**	**27.8**	< 6.0	<11	<20
TS-MW-09	6/24/2002	**532**	**7.3**	**0.53 F**	< 1.1	**0.98 F**
	10/1/2002	**939**	**8.7**	**0.66**	<11	<2.0
	2/12/2003	**955**	**8.3 F**	< 6.0	<11	<20
TS-MW-10	6/24/2002	**1,610**	**28.1**	**1.6**	< 1.1	**0.96 F**
	10/1/2002	**2,920**	**36.9**	**2.5**	<11	<2.0
	2/12/2003	**2,500**	**23.3**	< 6.0	<11	<20
LF08MW15	6/26/2002	**1,760**	**15.4**	**1.6**	< 1.1	< 2.0
	10/1/2002	**1,490**	**15.0 F**	**1.4**	<11	<2.0
	2/12/2003	**1,550**	**10.9 F**	< 6.0	<11	<20

[a/] TCE = trichloroethene, DCE = dichloroethene.

[b/] µg/L = micrograms per liter.

[d/] F-flag indicates the analyte was detected at a concentration above the method detection limit but below the reporting limit. The value listed is estimated.

TABLE 4
SUMMARY OF GROUNDWATER GEOCHEMICAL DATA

Sample Location	Sample Date	pH (su)[a/]	Dissolved Oxygen (mg/L)[b/]	Redox Potential (mV)[c/]	Nitrite+ Nitrate (mg/L)	Total Organic Carbon (mg/L)	Manganese (mg/L)	Ferrous Iron (mg/L)	Sulfate (mg/L)	Alkalinity (mg/L)	Carbon Dioxide (mg/L)	Methane (µg/L)[d/]	Ethane (µg/L)	Ethene (µg/L)
TS-MW-01	6/21/2002	6.96	1.81	-53	20	< 5.0	0.5	0.34	120	240	35	1.8	0.14	0.39
	10/1/2002	7.67	1.85	96	15	< 5.0	4.4	<0.1	120	240	35	1.5	0.13	0.63
	2/12/2003	6.73	0.30	179	13	< 5.0	0.31	<0.1	120	220	40	4.9	0.088	0.15
TS-MW-02	6/24/2002	6.61	8.92	146	21	< 5.0	< 0.04	0.08	100	220	32	0.24	0.017	0.14
	10/1/2002	5.77	3.71	-56	0.34	410	3.1	4.6	4.9	200	160	1,000	1.8	1.8
	2/11/2003	5.76	0.27	-56	14	110	2.3	2.3	5.1	260	115	7,700	0.52	2.0
TS-MW-03	6/24/2002	7.92	8.81	100	20	< 5.0	0.3	0.06	90	300	25	0.80	0.083	0.20
	10/1/2002	6.45	2.03	-113	ND[e/]	290	2.0	2.9	5.2	340	130	1,200	0.25	1.6
	2/11/2003	6.09	0.28	-69	6.5	140	1.5	2.4	53	260	165	2,500	1.1	2.5
TS-MW-04	6/24/2002	NA[f/]	NA	NA	17	< 5.0	< 0.04	< 0.007	83	240	32	0.16	0.006	0.015
	10/1/2002	7.92	5.02	-7	19.5	6.6	0.25	<0.1	99	300	25	1,800	0.009	0.20
	2/11/2003	6.69	1.01	117	14	< 5.0	0.16	<0.1	95	240	30	3,500	0.052	0.37
TS-MW-05	6/24/2002	NA	NA	NA	19	< 5.0	< 0.04	< 0.007	93	240	22	0.98	0.22	0.55
	10/1/2002	7.58	3.91	62	23	< 5.0	0.11	<0.1	92	280	30	1,300	0.14	1.8
	2/12/2003	6.76	0.91	113	12	5.1	0.10	<0.1	89	220	32	3,400	0.15	1.4
TS-MW-06	6/24/2002	7.10	7.44	108	22	< 5.0	0.20	0.13	110	260	38	0.87	0.09	0.22
	10/1/2002	6.94	4.46	-50	2.8	< 5.0	0.14	0.60	77	340	75	12	0.18	1.3
	2/11/2003	6.38	0.10	65	1.8	5.7	0.10	<0.1	55	280	60	1,000	0.31	1.2
TS-MW-07	6/24/2002	6.80	3.82	104	23	< 5.0	0.10	0.03	120	220	20	0.91	0.031	0.15
	10/1/2002	7.64	3.72	23	5.6	< 5.0	0.10	<0.1	71	300	40	1,900	0.19	1.2
	2/12/2003	6.81	0.54	-9	3.6	< 5.0	0.18	0.20	58	280	35	4,100	0.16	1.3
TS-MW-08	6/24/2002	7.02	6.07	66	22	< 5.0	0.30	0.06	110	240	30	0.66	0.15	0.39
	10/1/2002	7.67	3.35	65	15	< 5.0	0.08	<0.1	88	300	25	980	0.15	0.78
	2/11/2003	6.61	1.64	54	7.5	< 5.0	0.07	<0.1	90	220	30	4,700	0.10	0.60
TS-MW-09	6/24/2002	7.17	8.07	98	20	< 5.0	0.20	< 0.007	120	220	15	1.0	0.059	0.17
	10/1/2002	7.58	2.05	37	16	< 5.0	0.08	<0.1	110	280	44	760	0.098	0.45
	2/12/2003	6.84	0.31	120	8.4	< 5.0	0.08	<0.1	110	200	25	1,500	0.020	0.20
TS-MW-10	6/24/2002	7.00	6.47	83	22	< 5.0	0.30	< 0.007	100	240	20	1.0	0.054	0.16
	10/1/2002	7.59	3.13	72	15	< 5.0	0.08	<0.1	100	280	52	1,200	0.17	1.1
	2/12/2003	6.78	0.74	107	17	5.3	0.09	<0.1	85	220	45	880	0.088	0.70
LF08MW15	6/26/2002	6.31	0.65	151	21	< 5.0	0.30	NA	86	240	50	4.8	0.58	2.1
	10/1/2002	7.36	0.10	38	22	< 5.0	0.02	0.8	86	260	35	730	0.014	0.08
	2/12/2003	6.77	0.15	124	24	< 5.0	<0.01	<0.1	89	220	35	1,100	0.012	0.03

[a/] su = standard pH units.
[b/] mg/L = milligrams per liter.
[c/] mV = millivolts.
[d/] µg/L = micrograms per liter.
[e/] ND = not detected.
[e/] NA = not analyzed (wells sometimes purged dry).

Addition of an organic substrate depletes the aquifer of DO and lowers the ORP, which results in stimulation of biogeochemical conditions that are conducive to anaerobic degradation processes. After DO is consumed, anaerobic microorganisms use available native electron acceptors in the following order of preference: nitrate, manganese and ferric iron hydroxides or oxyhydroxides, sulfate, and finally carbon dioxide (methanogenesis). Evaluation of the distribution of these electron acceptors can provide evidence of where and how biodegradation of chlorinated aliphatic hydrocarbons (CAHs, or chlorinated solvents) may be occurring.

Under anaerobic conditions, biodegradation of chlorinated solvents usually proceeds through the process of reductive dechlorination. During reductive dechlorination, the chlorinated hydrocarbon is used as an electron acceptor, and a chloride atom is removed and replaced with a hydrogen atom. Biologically mediated reductive dechlorination generally occurs sequentially. For example, with chlorinated ethenes dechlorination progresses from tetrachloroethene (PCE) to TCE to isomers of DCE to vinyl chloride (VC) to ethene. Ethene may be further reduced to ethane. This is the process targeted for stimulation by addition of the vegetable oil substrate at LF-08.

Other anaerobic biodegradation processes that may occur include biogeochemical reduction, where a CAH molecule is mineralized through direct contact with a reduced compound such as iron monosulfide (*e.g.*, Butler and Hayes, 1999); and anaerobic oxidation, a biologically-mediated reaction in which less chlorinated CAHs, such as *cis*-1,2-DCE and VC, are directly oxidized (*i.e.*, used as an electron donor) to carbon dioxide, hydrogen, and chloride (Bradley and Chappelle, 1997; Bradley *et al.*, 1998a and 1998b). While these two processes may potentially occur, they were not targeted or evaluated as part of this demonstration.

Vegetable oil is an inexpensive, food-grade carbon source. The separate phase nature and low solubility of vegetable oil allows for its slow dissolution into groundwater, although it may be readily consumed by microbial activity (Parsons, 2004). One objective of this demonstration was to determine whether a single, low-cost injection of vegetable oil in the form of an oil-in-water emulsion could provide sufficient substrate to enhance reductive dechlorination for a period of a year or more.

CAHs also have varying affinities for partitioning from the aqueous, sorbed, and/or free phase (*i.e.*, dense non-aqueous phase liquid, or DNAPL) into vegetable oil (Pfeiffer *et al*., 2005). This temporarily sequesters the CAHs in the vegetable oil, reducing the mass available for dissolution into and transport with groundwater. This may effectively reduce the mass flux of CAHs out of the source area. Ultimately, the partitioned contaminant mass is released back into the aqueous phase as the oil is degraded, into an anaerobic environment optimal for reductive dechlorination to occur. While some partitioning of CAHs in the vegetable oil substrate likely occurred during the demonstration at LF-08, the application was primarily intended to stimulate anaerobic reductive dechlorination of CAHs in the dissolved phase.

4.0 TECHNOLOGY IMPLEMENTATION

The enhanced bioremediation demonstration at LF-08 was implemented by injecting organic substrate (*i.e.*, emulsified vegetable oil) into the subsurface to create anaerobic *in situ* treatment zone for degradation of CAHs in groundwater. Two monitoring events were conducted after substrate injection to monitor the performance of the demonstration. Site-specific field activities in support the study included the following:

- Installation of 9 temporary direct-push injection points and 10 groundwater monitoring wells at the locations shown on Figure 1;

- Initial condition (*i.e.*, pre-injection) sampling of groundwater in June 2002 at the 10 newly-installed wells and an existing groundwater monitoring well;

- Injection in June 2002 of approximately 4,300 pounds (576 gallons) of food-grade vegetable oil (refined soybean oil) emulsified with approximately 1,570 gallons of a mix of native groundwater and potable water; and

- Performance monitoring by sampling groundwater at 10 newly-installed monitoring wells and an existing monitoring well at 4 months (October 2002) and 8 months (February 2003) following injection.

5.0 TECHNOLOGY PERFORMANCE

5.1 Substrate Distribution

After baseline sampling and aquifer testing were completed, approximately 2,146 gallons of a an oil-in-water emulsion was injected into nine direct injection locations (Figure 2). Each injection location consisted of driving 1-inch diameter hollow-steel-direct-push rods equipped with an expendable point to approximately 28 feet using a Geoprobe® rig. After the expendable point and rods were driven to the total depth of the injection location, the expendable point was dislodged and the rods were withdrawn to a depth of approximately 20 feet bgs. The vegetable oil-in-water emulsion was then injected at pressure directly into the subsurface. A field-mixed emulsion was prepared that consisted of approximately 25 percent partially hydrogenated soybean oil and lecithin and 75 percent native groundwater/base potable water. Chromatint fluorescent dye was added to the vegetable oil for determining the physical distribution of the injected vegetable oil.

The maximum injection rate of the emulsion was approximately 4.7 gallons per minute (gpm), at a maximum injection pressure of approximately 40 pounds per square inch (psi). After injection of the emulsion, up to 100 gallons of native groundwater was injected as a water push into each injection point. After injection was complete at each injection point the borehole was abandoned with pre-hydrated sodium-bentonite grout. The ground surface was repaired with asphalt cold patch.

Radius of influence (ROI) testing was conducted in late July, approximately 30 days after vegetable oil injection activities were completed. ROI testing was performed by the United States Army Corps of Engineers (USACE) with a cone penetrometer technology (CPT) rig equipped with a laser-induced fluorescence (LIF) probe and downhole photography (DHP) capability. A total of 18 push-points were advanced to estimate the areal extent of vegetable oil in the subsurface and to estimate the effective ROI of the injected vegetable oil emulsion. Soil cores were collected from four soil borings to provide visual confirmation of the LIF and DHP results. The LIF, DHP, and four soil boring locations associated with ROI testing at LF-08 are shown on Figure 1.

Testing indicated that the ROI of the vegetable oil emulsion ranged from approximately 10 to 15 feet in the upgradient direction to approximately 20 to 26 feet in the downgradient direction. The vegetable oil zone of influence occupies an area of approximately 2,600 square feet.

However, most oil emulsion was distributed along thin horizons of relatively higher permeability. Assuming an average impacted vertical thickness of approximately 2.4 feet, the volume of the shallow groundwater zone directly impacted by physical distribution of the vegetable oil emulsion was approximately 6,240 cubic feet.

5.2 Geochemistry

Measurements of TOC in groundwater after the injection were variable. For well locations within the treatment zone (TS-MW-02 through TS-MW-07), the concentrations of TOC ranged from less than a detection limit of 5.0 mg/L up to 410 mg/L at location TS-MW-02 (Table 4). Based on these data and observations from ROI testing, the distribution of the vegetable oil substrate not uniform, with the substrate likely to be distributed along thin horizons of higher permeability.

During the 8 months of monitoring following injection, concentrations of DO decreased from the baseline conditions of greater than 5.0 mg/L to below 1.0 mg/L at most sampling locations (Table 4). This indicates that conditions were induced that are suitable for anaerobic degradation processes to occur. Measurements of ORP prior to injection ranged from -53 mV to +151 mV. After injection, ORP for monitoring locations within the treatment zone (TS-MW-02 through TS-MW-07) ranged from -113 mV up to +113 mV. While ORP levels were reduced at many locations, the variability in ORP reflects the non-uniform distribution of substrate.

Overall, manganese and iron concentrations increased within the ROI of the substrate injection. Concentrations of sulfate decreased substantially at monitoring well locations with elevated levels of TOC (TS-MW-02 and TS-MW-03). In addition, concentrations of methane increased by approximately two to three orders of magnitude to greater than or equal to 1.0 mg/L at all well locations, with the exception of the background well TS-MW-01.

These changes in geochemical conditions indicate that iron reduction, manganese reduction, sulfate reduction, and methanogenesis were all stimulated to some extent within the treatment zone by the addition of the vegetable oil substrate to the subsurface. However, the non-uniform distribution of substrate and the variability in groundwater geochemistry indicates that conditions optimal for anaerobic reductive dechlorination to occur were only achieved in limited portions of the treatment zone.

5.3 Changes in CAH Concentrations

Groundwater analytical data collected during the two performance monitoring events are presented in Table 3. During the 8 months of monitoring, concentrations of TCE increased at every monitoring well location, including background location TS-MW-01. During the same period, concentrations of *cis*-1,2-DCE remained relatively stable or increased slightly from baseline conditions, indicating that TCE was not being dechlorinated to *cis*-1,2-DCE during the 8 months of performance monitoring. In addition, VC was not detected at any of the monitoring locations during the demonstration, indicating that *cis*-1,2-DCE was not being dechlorinated to VC. It is interesting to note that concentrations of ethene (a reductive dechlorination end product) increased by approximately one order of magnitude at wells located within the injection area (Table 4). This suggests that dechlorination may have occurred to a limited extent at these locations. However, the absence of a decrease in TCE and an increase in *cis*-1,2-DCE or VC concentrations contradicts this inference.

The reason for the observed increase in concentrations of TCE may be due in part to the injection of the vegetable oil substrate. Vegetable oil may act as a surfactant and strip contaminant mass from the aquifer matrix; short-term increases in contaminant concentrations are not unusual following substrate injections. The production of metabolic acids and an increase in soluble organic carbon may also enhance the desorption of TCE from the aquifer matrix. It is also possible that the increase in concentrations of TCE are at least partially due to some mechanism other than the injected substrate, because TCE also increased at background well TS-MW-01 which was not impacted by the injected substrate.

The duration of performance monitoring data is not sufficient to determine the long-term performance of the demonstration to stimulate dechlorination of TCE at the LF-08 site. Enhanced *in situ* anaerobic bioremediation applications often take 6 to 24 months for an anaerobic microbial population to acclimate and develop in response to the injected substrate. This is particularly applicable to sites with low permeability sediments or low rates of groundwater flow, as is the case at the LF-08 site.

6.0 TECHNOLOGY COSTS

The capital/startup and operating costs for the LF-08 demonstration are presented in Table 5. The capitol cost associated with the LF-08 pilot test installation was approximately $75,700. Capitol costs include approximately $14,100 for a work plan and mobilization; approximately $5,700 for well installation using a Geoprobe® direct-push rig; and approximately $2,000 for the vegetable oil substrate. The oil-in-water emulsion was prepared in the field during injection. The capitol cost also includes approximately $15,400 to prepare a construction completion report immediately after the pilot test system was installed and the substrate was injected.

The total operating cost to date for the FF-87 demonstration is $41,600, which only includes costs associated with sample collection and analysis for two monitoring events. Annual reporting costs are not included because a project completion report was not prepared for this site. Enhanced *in situ* bioremediation applications are typically monitored over a period of 2 to 4 years. Therefore, total long-term operating costs are generally higher than for this demonstration.

7.0 SUMMARY OBSERVATIONS

The injection of vegetable oil has created anaerobic conditions in the treatment zone at the LF-08 demonstration site. Concentrations of DO decreased to below 1.0 mg/L and ORP became more reducing at many sampling locations. Other geochemical parameters indicate that iron reduction, manganese reduction, sulfate reduction, and methanogenesis were all stimulated to some extent within the reaction zone by the addition of the vegetable oil substrate to the subsurface. However, the non-uniform distribution of substrate and the variability in groundwater geochemistry indicates that conditions optimal for anaerobic reductive dechlorination to occur were only achieved in limited portions of the treatment zone.

TABLE 5. TECHNOLOGY DEMONSTRATION COSTS

Element Cost	
Capital Cost	
Work Plan, Planning, and Preparation	$14,100
Travel and Subsistence	$8,600
Site Labor	$15,800
Equipment and Appurtenances -Injection/monitoring well installation -Injection equipment and supplies -Substrate (vegetable oil, delivered) -Monitoring equipment and supplies -IDW disposal	 $5,700 $2,200 $2,000 $2,700 $1,000
Baseline Laboratory Analyses	$6,200
Surveying	$2,000
Project Completion Report	$15,400
Total Capital Costs	**$75,700**
Operating Costs (Performance Monitoring)[a/]	
Mobilization/Demobilization/Per Diem	$2,200
Direct Labor (Performance Monitoring)	$9,000
Sampling Equipment and Supplies	$2,500
Laboratory Analysis	$5,600
Project Management/ Procurement	$1,500
Operating Costs per Event ($41,600 for 2 events over 8 months**)**	**$20,800**

[a/] Process monitoring was conducted by the Base contractor, monitoring costs are estimated.

Reductions in TCE or increases in the dechlorination products *cis*-1,2-DCE or VC were not observed. The 8-month monitoring program associated with this demonstration is likely inadequate in duration to determine the long-term effectiveness of the demonstration. Enhanced *in situ* anaerobic bioremediation pilot tests are typically monitored on a semi-annual frequency for approximately 2 to 3 years. Therefore, the current process monitoring data set may not be adequate to determine the effectiveness of this demonstration.

8.0 CONTACT INFORMATION

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