

FINAL

**PHASE II FIELD FEASIBILITY TEST FOR
IN-SITU BIOREMEDIATION OF CHLORINATED SOLVENTS
VIA VEGETABLE OIL INJECTION AT SITE SS015,
TRAVIS AIR FORCE BASE, CALIFORNIA**

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EXECUTIVE SUMMARY

This report documents the results of a Phase II field feasibility test to evaluate the application of vegetable oil as an organic substrate to enhance the *in situ* anaerobic reductive dechlorination of chlorinated aliphatic hydrocarbons (CAHs, or chlorinated solvents) in groundwater at Site SS015, Travis Air Force Base (AFB), California. Prior to the feasibility test, the distribution of parent compounds tetrachloroethene (PCE) and trichloroethene (TCE) and degradation daughter products *cis*-1,2-dichloroethene (*cis*-1,2-DCE) and vinyl chloride (VC) in groundwater indicated that limited reductive dechlorination of chlorinated ethenes was occurring at the site, but that the process was electron donor (substrate) limited. Vegetable oil was selected as an insoluble organic substrate to overcome the electron donor deficiency and enhance reductive dechlorination of chlorinated solvents in groundwater.

A Phase I field test was conducted from April to December 2000 (Parsons Engineering science, Inc. [Parsons], 2001b). A total of 62 gallons of refined soybean oil and 16 gallons of water were injected into three injection points in June 2000. An expanded Phase II field test was implemented to further stimulate reductive dechlorination of chlorinated solvents at the site. An additional 35 injection points and 9 monitoring points were installed. The Phase II injection was conducted in December 2000, with approximately 165 gallons of vegetable oil injected either as straight oil with a water push, or as an oil-in-water emulsion. Process monitoring was performed in September 2001.

PHASE II RESULTS

Addition of vegetable oil has induced anaerobic and reducing conditions sufficient to support ferric iron reduction, sulfate reduction, and methanogenesis. Relatively low background concentrations of nitrate indicate that nitrate reduction, or denitrification, is not a significant reduction/oxidation (redox) process at the site. Sulfate concentration data suggest that sulfate reduction is the dominant terminal electron accepting process (TEAP) occurring at the site, and that sulfate is competing with chlorinated compounds for use as an electron acceptor in microbially-mediated redox reactions. As sulfate continues to be reduced, this condition may change, with an increasing utilization of organic substrate to support reductive dechlorination of chlorinated compounds.

Following the Phase II injection, substantial increases in dissolved methane concentrations indicate that methanogenesis had been induced. Similar increases in dissolved ethene and ethane concentrations indicate that a significant amount of chlorinated ethenes were completely detoxified to ethene or ethane. While methanogens may be competing with dechlorinating organisms for hydrogen produced by microbial fermentation of vegetable oil, an active population of dechlorinating organisms is present at the site that is capable of complete degradation of PCE to ethene.

Significant reductions in dissolved PCE and TCE concentrations occurred at several locations, particularly within the radius of influence of the injected vegetable oil. Overall, the maximum concentration of TCE decreased from 4,200 micrograms per liter

(µg/L) in April 2000 to 1,800 µg/L in September 2001. Relatively low TCE concentrations within the plume core near the injection points suggests that the Phase I and Phase II vegetable oil injections have reduced aqueous-phase TCE concentrations at the site. In addition to biodegradation, some of the reduction in TCE concentrations at these locations is likely a result of partitioning of TCE from the aqueous phase into the vegetable oil non-aqueous phase liquid (NAPL).

Concentration trends for *cis*-1,2-DCE and VC are less apparent, likely due to the fact that these compounds are produced as a result of degradation of more highly chlorinated ethenes. From April 2000 to September 2001, the maximum concentration of *cis*-1,2-DCE in groundwater decreased from 22,000 µg/L to 5,300 µg/L. Similar to the TCE plume, the *cis*-1,2-DCE plume exhibits lower concentrations near the center of the injection points. From April 2000 to September 2001, the maximum concentration of VC similarly decreased from 17,000 µg/L to 4,800 µg/L.

Elevated concentrations of CAHs in vegetable oil purged from the Phase I injection points indicates that partitioning from groundwater into the oil is occurring. This is expected, because CAHs have a greater affinity for dissolution into an oil phase relative to an aqueous phase. While partitioning of CAHs from the aqueous phase into the oil phase appears to be significant and may account for some of the observed decrease in dissolved contaminant concentrations, it should be noted that the total volume of oil injected (approximately 227 gallons) is several orders of magnitude less than the volume of groundwater present in the Phase I and Phase II treatment zones (on the order of tens of thousands of gallons). Therefore, the actual mass of CAHs that can partition into the vegetable oil is less than that which would remain in the aqueous phase. Once an initial aqueous- and oil-phase equilibrium is reached, CAHs are released from the oil to groundwater at a rate dependent upon dissolution and/or degradation of the vegetable oil, and degradation of contaminants in the dissolved phase. In any event, contaminants are released back to groundwater within a zone of adequate substrate and optimal conditions for reductive dechlorination.

Other supporting evidence of enhanced biodegradation, including changes in concentration and molar ratio of parent and daughter products, indicate that a substantial portion of the decrease in contaminant concentrations is due to reductive dechlorination. The presence of daughter products that were not used in Base operations, particularly *cis*-1,2-DCE, VC, and ethene, provides strong evidence that PCE and TCE are being reductively dechlorinated. Progressive transformation of PCE to ethene is indicated by the molar ratio of parent compounds to daughter products at a specific location.

For example, within the treatment zone, chlorinated ethene concentrations and molar fractions over time for monitoring point PES-MW4 exhibit trends characteristic of reductive dechlorination. Concentrations of all compounds decreased, with the exception of VC and ethene. Most noticeably, concentrations of PCE and TCE have decreased consistently for each sampling event. PCE decreased from 440 µg/L in April 2000 to 5.2 µg/L in September 2001, a decrease of 98.8 percent. Likewise, TCE decreased from 1,500 µg/L in April 2000 to 45 µg/L in September 2001, a decrease of 97 percent. Concentrations of *cis*-1,2-DCE first increased from 690 µg/L in April 2000 to 2,600 µg/L in September 2000, likely due to degradation of TCE. However, as TCE and PCE were depleted after September 2000, the generation of *cis*-1,2-DCE was exceeded by the

degradation of this compound to VC. Concentrations of *cis*-1,2-DCE decreased to 670 µg/L in September 2001, while concentrations of VC increased from less than 100 µg/L to 2,100 µg/L. Evidence that dechlorination is proceeding to completion is indicated by an increase in the concentrations of ethene from less than 1 µg/L in December 2000 to 29 µg/L in September 2001.

Trends in molar fractions for monitoring point PES-MW4 also reflect substantial reductive dechlorination. As PCE and TCE were degraded, the respective molar fractions for these compounds decreased. The molar fraction of *cis*-1,2-DCE initially increased as TCE was dechlorinated to *cis*-1,2-DCE. However, once number of moles of PCE and TCE were depleted relative to *cis*-1,2-DCE, the molar fraction of *cis*-1,2-DCE decreased as the moles of *cis*-1,2-DCE degraded to VC exceeded that of TCE degraded to *cis*-1,2-DCE. At the same time, molar fraction of VC exhibited a dramatic increase from December 2000 to September 2001. As VC also was degraded, ethene was produced and an increase in both concentration and molar fraction of ethene was observed. Clearly, reductive dechlorination has been stimulated at location PES-MW4 by both the Phase I and Phase II injections.

Other monitoring locations also show evidence of reductive dechlorination, although not to the extent observed at PES-MW4. Significant increases in ethene concentrations following the Phase II injection were observed. This strongly suggests that a significant amount of reductive dechlorination at Site SS015 is proceeding to completion.

In summary, trends in chlorinated ethene concentrations and molar fractions indicate that reductive dechlorination has been stimulated at the site by both the Phase I and Phase II injections. An overall decrease in chlorinated ethene concentrations is occurring across the site. Transformation of PCE to TCE and TCE to *cis*-1,2-DCE appear to be the most common and consistent reduction steps, but degradation *cis*-1,2-DCE and VC also were observed. While partitioning of chlorinated ethenes into the vegetable oil NAPL may account for some reduction in aqueous-phase concentrations, molar fraction data indicate that a significant amount of contaminant reduction is due to reductive dechlorination.

RECOMMENDATIONS

Results of the Phase II evaluation indicate that reductive dechlorination of CAHs is occurring at Site SS015 as a result of vegetable oil addition. However, high naturally occurring concentrations of sulfate appear to be a significant competing electron acceptor. To overcome the competing reaction of sulfate reduction, injection of additional vegetable oil will likely be required. Therefore, replacement of the failed Phase II injection points is recommended, and the Phase II injection should be completed.

An additional three rounds of process monitoring at 6-month intervals also is recommended. Several parameters that would be useful for determining the effectiveness of substrate addition, electron donor demand and utilization, and the groundwater redox processes that are occurring at the site are not currently part of the monitoring program. Parsons recommends that TOC, total inorganic carbon, volatile fatty acids, and dissolved hydrogen be added to the monitoring program, at least for one sampling event. Analyses of additional nutrient parameters (total nitrogen and phosphorous) are also warranted.

Finally, Parsons recommends that aquifer (slug) tests be conducted in existing conventional 2-inch-diameter monitoring wells to better characterize hydraulic conductivity at the site. Alternative aquifer testing techniques, such as constant-drawdown test, should be considered to determine post-injection hydraulic conductivity in small-diameter monitoring points within the radius of influence of the vegetable oil. All monitoring points also should be sampled for bromide to better determine tracer breakthrough, groundwater flow direction, and groundwater seepage velocity.

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ACRONYMS AND ABBREVIATIONS

µg/L	micrograms per liter
AFB	Air Force Base
AFCEE/ERT	Technology Transfer Division, Air Force Center for Environmental Excellence
Bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylenes
CaCO ₃	calcium carbonate
CAHs	chlorinated aliphatic hydrocarbons
cm/sec	centimeters per second
COCs	contaminants of concern
CPT	cone penetrometer testing
DCA	dichloroethane
DCB	dichlorobenzene
DCE	dichloroethene
DO	dissolved oxygen
EIOU	East Industrial Operable Unit
ft amsl	feet above mean sea level
ft/day	feet per day
ft/ft	foot per foot
ft/yr	feet per year
gpm	gallons per minute
GSAP	Groundwater Sampling and Analysis Program
ID	inside-diameter
iron (II)	ferrous iron
iron (III)	ferric iron
MEK	methyl ethyl ketone
mg/L	milligrams per liter
mV	millivolts
N	nitrogen
NAPL	non-aqueous phase liquid
NEWIOU	North, East, West Industrial Operable Unit
ORP	oxidation-reduction potential
Parsons	Parsons Engineering Science, Inc.
PCE	tetrachloroethene
ppmv	parts per million, volume per volume
psi	pounds per square inch
PVC	polyvinyl chloride
redox	reduction-oxidation
RI	remedial investigation
ROD	Record of Decision
SSA	Solvent Spill Area
su	standard pH units

TCE	trichloroethene
TEAP	terminal electron accepting process
tetraglyme	tetraethylene glycol dimethyl ether
TOC	total organic carbon
TPH	total petroleum hydrocarbons
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
VC	vinyl chloride
VOCs	volatile organic compounds

SECTION 1

INTRODUCTION

This report presents the results of a Phase II field feasibility test for *in-situ* bioremediation of chlorinated solvents via vegetable oil injection at Site SS015, Travis Air Force Base (AFB), California. This work was performed for the Technology Transfer Division of the Air Force Center for Environmental Excellence (AFCEE/ERT) and Travis AFB by Parsons Engineering Science, Inc. (Parsons).

1.1 OBJECTIVES

This project is part of an enhanced bioremediation initiative being conducted by AFCEE/ERT in conjunction with Parsons. The primary objective of this multi-site initiative is to develop a systematic process for scientifically investigating and documenting the enhanced bioremediation of chlorinated solvents dissolved in groundwater and sorbed to the aquifer matrix by injecting vegetable oil into the subsurface below the water table. A secondary goal is to provide a database from multiple sites to demonstrate that enhanced bioremediation can reduce contaminant concentrations in groundwater to below regulatory standards. An extensive discussion of the processes by which addition of vegetable oil enhances *in situ* reductive dechlorination of chlorinated solvents can be found in the *Draft Field Feasibility Test for In Situ Bioremediation of Chlorinated Solvents via Vegetable Oil Injection* (Parsons, 2001a).

The objective of the Phase II field feasibility test at Site SS015 is to determine if the application of vegetable oil as an organic substrate is a viable approach to enhance the *in situ* anaerobic reductive dechlorination of chlorinated aliphatic hydrocarbons (CAHs, or chlorinated solvents) present in groundwater at the site. Results of the Phase I baseline sampling were used to design a full-scale Phase II expanded test, intended to remediate the suspected source area to regulatory criteria.

1.2 SCOPE OF WORK

Site-specific activities conducted at Travis AFB in support of the Phase II expanded field feasibility test included:

- Installation of 35 vegetable oil injection points and 9 groundwater monitoring points using direct-push technology;
- Background (i.e., pre-injection) sampling of groundwater at the newly installed injection and monitoring points in accordance with the *Technical Protocol for*

Evaluating Natural Attenuation of Chlorinated Solvents in Groundwater (US Environmental Protection Agency [USEPA], 1998);

- Injection of a total of 165 gallons of refined soybean oil; and
- Post-injection sampling of groundwater at selected monitoring points and existing monitoring well MW-216 at 9 months after injection.

This report describes the activities performed for the Phase II field test and results of process monitoring.

1.3 REPORT ORGANIZATION

This report consists of six sections, including this introduction, and two appendices. Section 2 summarizes historical site characterization and results of the Phase I field test. Section 3 describes the field system installation, substrate addition, and the procedures followed for data collection. Section 4 discusses and evaluates the results of the Phase II vegetable oil injection. Section 5 provides conclusions and recommendations, and Section 6 contains the references used in preparing this document. Appendix A contains analytical results and Appendix B contains field sampling data and forms.

1.4 SITE HISTORY

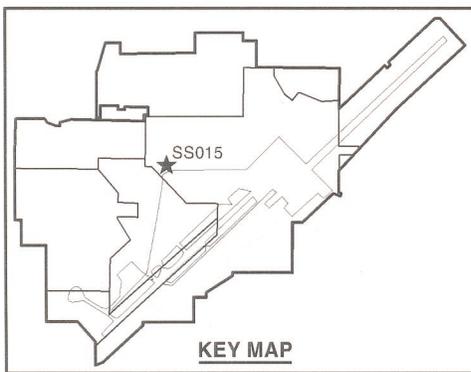
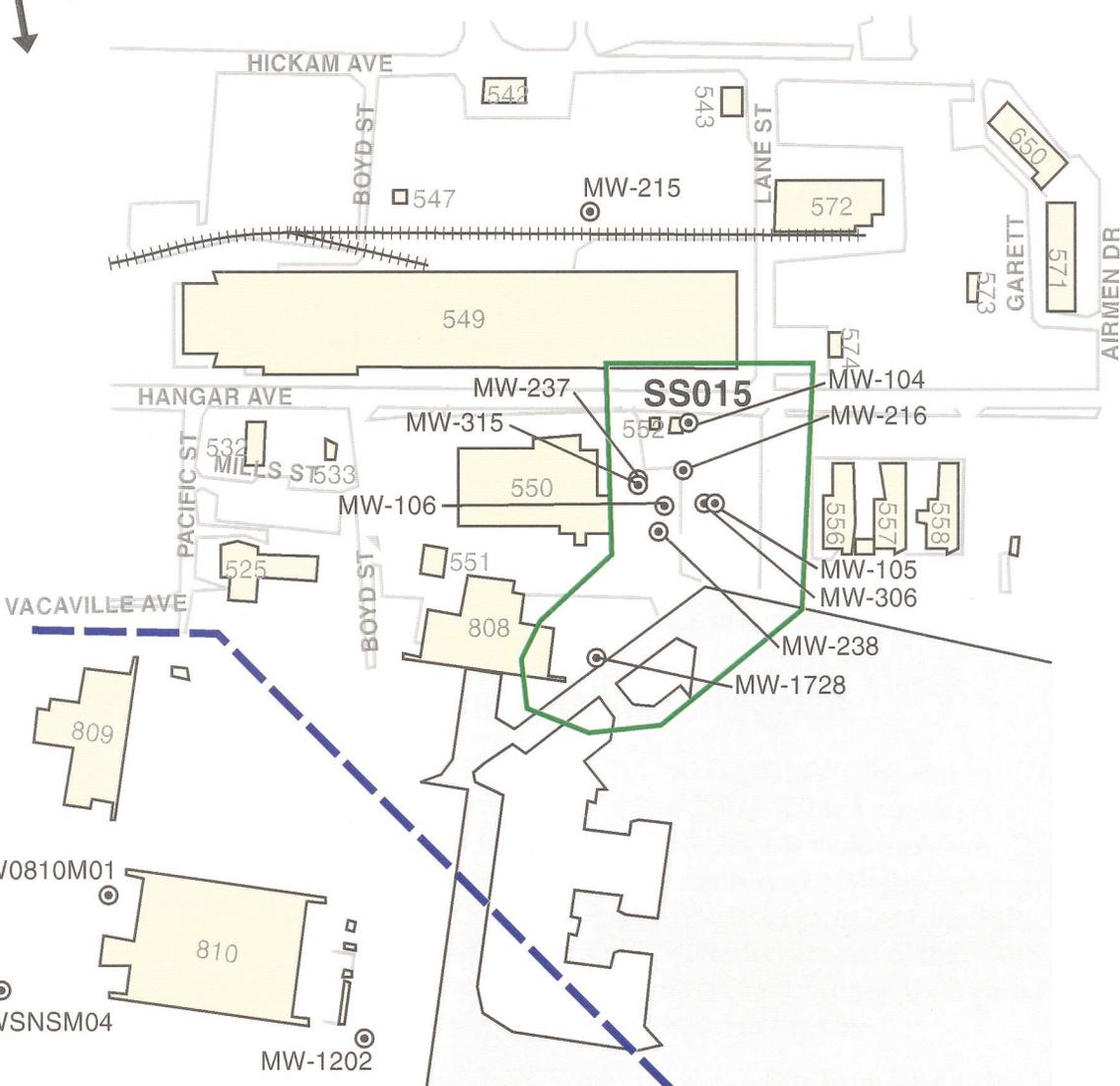
Site SS015 comprises approximately 3.5 acres of the Base and is located in the northwestern part of the East Industrial Operable Unit (EIOU) near the center of Travis AFB. Site SS015 consists of the Solvent Spill Area (SSA) and Facilities 550 and 552. Figure 1.1 shows the layout of Site SS015 and the locations of pre-existing Base monitoring wells.

The SSA covers approximately 1.4 acres east of Facility 550. The area was previously used for stripping paint from aircraft. Use of this area is not well documented prior to 1981; however, stained soil visible in historical aerial photographs suggests that the area was in use prior to 1970. Solvent spills were reported to have occurred in the area east of Facility 550; however, actual dates of spill occurrences are unknown. Approximately 100 to 150 gallons per month of either methyl ethyl ketone (MEK), toluene, or tetraethylene glycol dimethyl ether (tetraglyme) were reported to have leaked from or splashed out of work trays used for collecting stripping wastes during operations at the site (Weston, 1995).

Facility 550, constructed in 1952, is not currently occupied and is scheduled for demolition. It formerly housed a corrosion control shop, a metals processing shop, a fiberglass shop, and nondestructive inspection operations. Past practices at the corrosion control shop included discharging wastes to a floor drain that was connected to a sanitary sewer. Wastes generated included paints, thinners, MEK, acids, and stripping wastes (Weston, 1995).

Facility 552 consists of a fenced, bermed concrete pad constructed in 1964. The pad was most recently used as a temporary hazardous waste collection point. Radomes were chemically stripped of paint near Facility 552 from 1964 to 1980. Stored wastes included

REGIONAL
GROUNDWATER
FLOW DIRECTION



- LEGEND**
- ROADS
 - ++++ RAILROADS
 - SITE BOUNDARY
 - - - - OPERABLE UNIT BOUNDARY
 - ▭ PAVEMENT AREAS
 - ⊙ MONITORING WELL

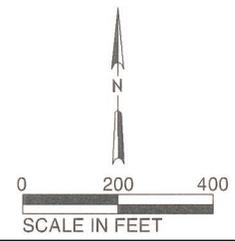


FIGURE 1.1
SITE PLAN AND
MONITORING WELL LOCATIONS
 Site SS015
 Travis AFB, California
PARSONS
PARSONS ENGINEERING SCIENCE, INC.
 Denver, Colorado

(From CH2MHill, 1999a)

paint, chromic acid, and solvents generated during aircraft maintenance operations at Facility 550. There is no documentation of past spills occurring at the facility (Weston, 1995).

As part of the Groundwater Interim Record of Decision (ROD) for the North, East, West Industrial Operable Unit (NEWIOU), Site SS015 was designated for a natural attenuation assessment and groundwater monitoring (Travis AFB, 1997). Chemicals of concern (COCs) identified for Site SS015 include: tetrachloroethene (PCE); trichloroethene (TCE); 1,1-dichloroethene (1,1-DCE) and the DCE isomers *cis*-1,2-DCE and *trans*-1,2-DCE; vinyl chloride (VC); 1,4-dichlorobenzene (1,4-DCB); 1,2-dichloroethane (1,2-DCA); bis(2-ethylhexyl)phthalate; nickel; total petroleum hydrocarbons-gas (TPH-gas); and TPH-diesel. The work under this project focuses primarily on the enhanced bioremediation of chlorinated ethenes (i.e., PCE, TCE, 1,1-DCE, *cis*-1,2-DCE, *trans*-1,2-DCE, and VC).

SECTION 2

SUMMARY OF HISTORICAL SITE CHARACTERIZATION AND PHASE I RESULTS

This section summarizes the results of site characterization conducted by Travis AFB and results of the Phase I field test performed by Parsons.

2.1 HISTORICAL SITE CHARACTERIZATION

Site-specific data were reviewed to evaluate groundwater flow and contaminant transport, primarily to determine locations for placement of injection and groundwater monitoring points. Because chlorinated ethenes comprise the bulk of dissolved chlorinated solvents at Site SS015, they are the focus of this discussion.

The following discussion is based upon review of data from the following primary sources:

- *Draft Summary of the Site SS015 Investigation, Travis Air Force Base, California, October 1999* (CH2M Hill, 1999a);
- Portions of the *July 1999 Draft Travis Air Force Base 1999 Semi-Annual Report – Groundwater Sampling and Analysis Program* (CH2M Hill, 1999b); and
- Portions of the *Travis Air Force Base Remedial Investigation Report, East Industrial Operable Unit* (Weston, 1995).

The reader is referred to these documents for a more detailed review of site-specific data. Additional sources are referenced within the text.

2.1.1 Geology

The bedrock underlying the EIOU consists of Eocene-age marine and nearshore sediments of the (from oldest to youngest) Domengine Sandstone, Nortonville Shale, and Markley Sandstone (Weston, 1995). The Domengine Sandstone is the oldest formation underlying the EIOU. The Nortonville Shale overlies the Domengine Sandstone beneath Site SS015 and the SSA. The Nortonville Shale underlying Travis AFB is a very dark gray, grayish brown, and purplish black shale and siltstone, often thinly laminated with lenses of fine sandstone and containing gypsum nodules or crystals. The Markley Sandstone overlies the Nortonville Shale and is exposed adjacent to the northwestern boundary of the EIOU at Facility 531 on Hangar Avenue. Boring logs from Travis AFB (Weston, 1995) indicate that the weathered Markley Sandstone in the study area is a

brown, light yellow-gray, and brownish gray micaceous, silty, fine- to medium-grained sandstone with clay- or silt-rich laminae.

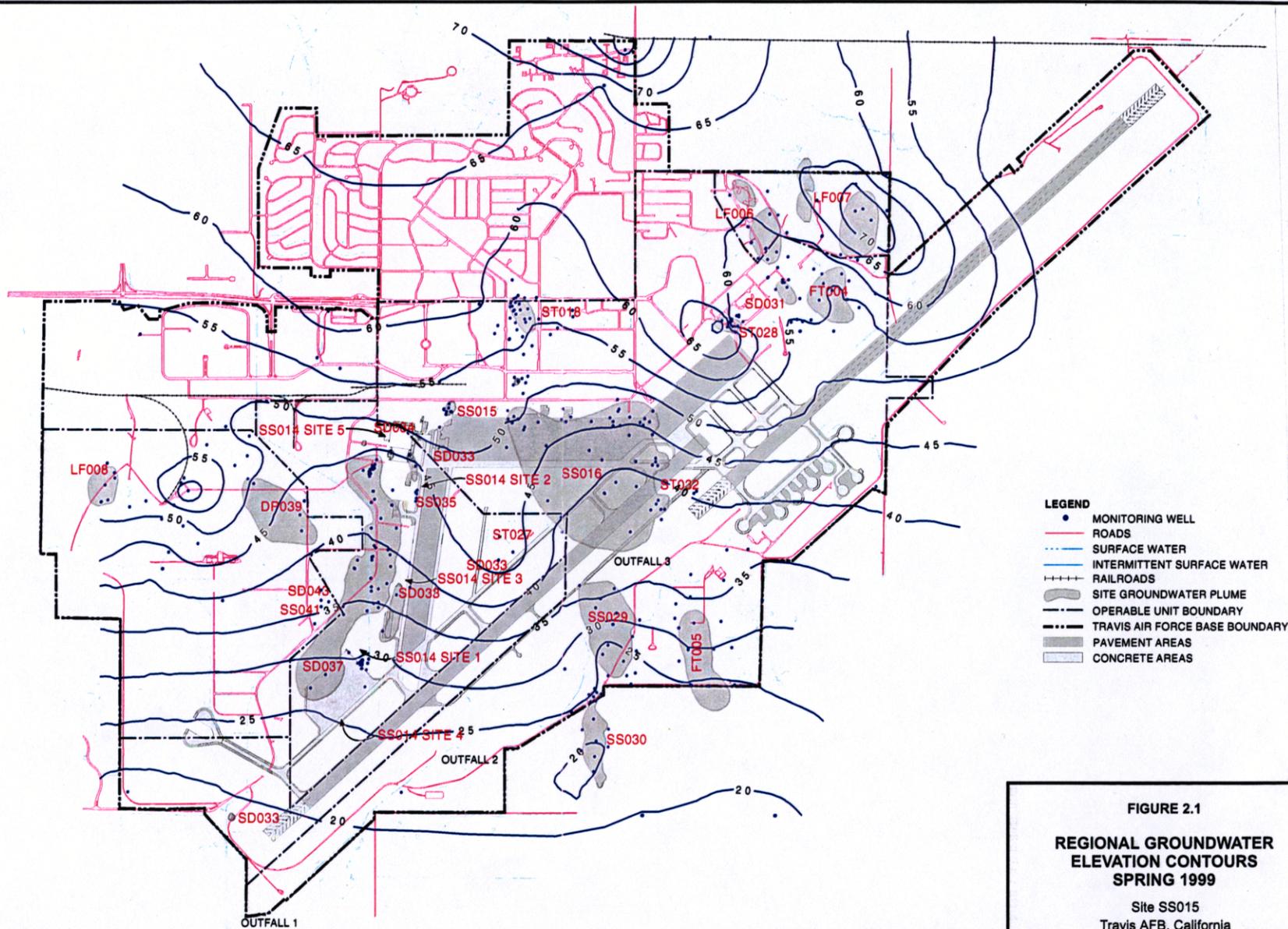
The overburden at Travis AFB was deposited in alluvial fans and stream channels, and as sheets of colluvium. The overburden is not a continuous unit across the EIOU, and is thickest in buried bedrock valleys described in the Remedial Investigation (RI) report (Weston, 1995). The overburden in the EIOU consists of a sand unit that overlies the bedrock, overlain by a silty clay unit. The sand unit was deposited in stream channels and as colluvium, and locally contains lenses of gravelly sand. The silty clay unit was deposited on the alluvial fan surface between the stream channels during floods. Thin channel, levee, and splay sands occur in the silty clay unit. Numerous buried soil horizons are present in the overburden. The overburden is underlain by weathered bedrock that varies in thickness from 0 to 20 feet. The weathered bedrock is frequently indistinguishable from the overburden. Trends in grain size in the overburden reflect trends in permeability, with lenses of gravelly sand in the sand unit, and of fine sand in the silty clay unit, usually being more permeable than the surrounding unit.

2.1.2 Hydrogeology

Travis AFB is located in a groundwater region designated as the Central Valley and Pacific Coast Ranges Groundwater Region (Weston, 1995). Most of Travis AFB is located within a subregional groundwater basin known as the Fairfield-Suisun Hydrologic Basin. The major groundwater-bearing unit in this area is the overburden. Bedrock is considered to be relatively impermeable, except where it is fractured or weathered (Weston, 1995).

The regional groundwater flow patterns are shown on Figure 2.1, which depicts the Base-wide groundwater elevations for Spring 1999. As shown, the regional flow direction near Site SS015 is toward the south and southeast and has a horizontal gradient of approximately 0.003 foot per foot (ft/ft) (CH2M Hill, 1999a). To further assess the groundwater flow direction in the vicinity of Site SS015, the United States Army Corps of Engineers (USACE) installed temporary piezometers in 1999. Figure 2.2 presents the groundwater elevation contours derived from the data from the piezometer/well water elevation survey presented in CH2M Hill (1999a).

Figure 2.2 indicates that locally, groundwater in the vicinity of Site SS015 flows toward the north rather than following the southerly regional flow direction. There appears to be a groundwater trough in the northeastern portion of the site, and the groundwater flow lines converge toward this trough. This suggests that groundwater beneath Site SS015 flows in a generally northerly direction; this finding appears to be corroborated by the distribution of contaminants in groundwater samples (CH2M Hill, 1999a). The local flow direction near Site SS015 probably changes from the northeast toward the east and southeast with increasing distance along the flowpath downgradient from the site. Local groundwater flow at the site may be influenced by the presence of storm water drains.



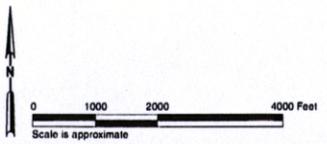
- LEGEND**
- MONITORING WELL
 - ROADS
 - SURFACE WATER
 - - - - - INTERMITTENT SURFACE WATER
 - ++++ RAILROADS
 - SITE GROUNDWATER PLUME
 - - - - - OPERABLE UNIT BOUNDARY
 - TRAVIS AIR FORCE BASE BOUNDARY
 - ▨ PAVEMENT AREAS
 - ▩ CONCRETE AREAS

FIGURE 2.1

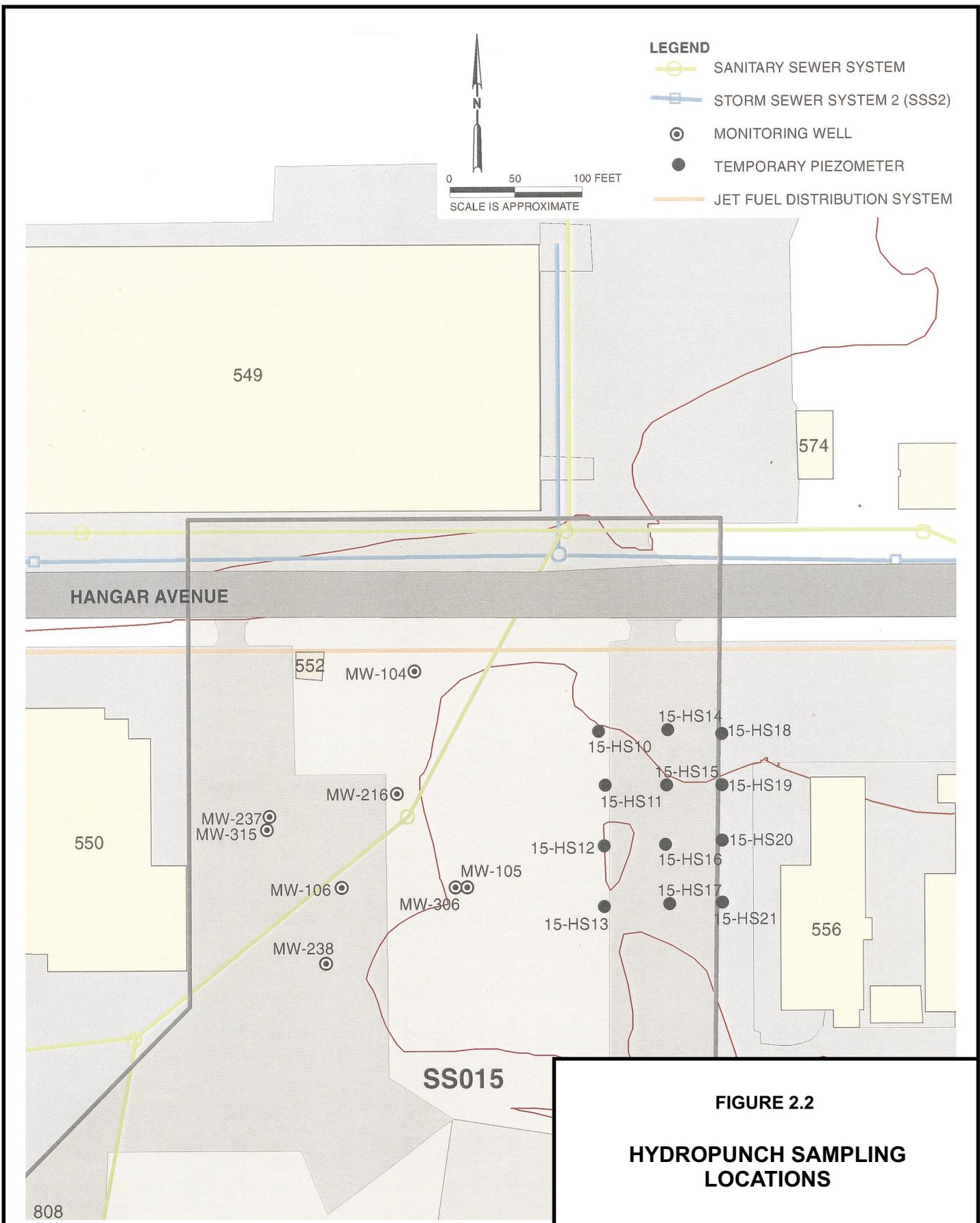
**REGIONAL GROUNDWATER
ELEVATION CONTOURS
SPRING 1999**

Site SS015
Travis AFB, California

PARSONS
PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado



Source: CH2MHILL, 1999a
draw111x17.cdr pasteup nap 1299



LEGEND

-  SANITARY SEWER SYSTEM
-  STORM SEWER SYSTEM 2 (SSS2)
-  MONITORING WELL
-  TEMPORARY PIEZOMETER
-  JET FUEL DISTRIBUTION SYSTEM

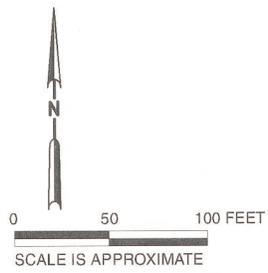


FIGURE 2.2

HYDROPUNCH SAMPLING LOCATIONS

Site SS015
Travis AFB, California

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Denver, Colorado

(From CH2MHill, 1999a)

2.1.3 Historical Contaminant Results for Site SS015

Site SS015 was designated in the NEWIOU Interim ROD for a natural attenuation assessment. However, before this assessment could take place it was necessary to perform a pre-design investigation. Based on the Groundwater Sampling and Analysis Program (GSAP) record, the extent of groundwater contamination at this site had not been completely defined. The pre-design investigation was intended to define the extent of contamination (CH2M Hill, 1999a), and included a soil gas survey, sampling of existing monitoring wells, and HydroPunch[®] groundwater sampling.

2.1.3.1 Groundwater Quality

Five wells (MW-105, MW-215, MW-216, MW-238, and MW-306) have been consistently sampled as part of the GSAP at Site SS015. Table 2.1 summarizes COC concentrations detected in Site SS015 wells sampled in the Spring of 1999. Table 2.2 summarizes the volatile COCs detected since the 1994 RI in samples from MW-216, the well with the highest observed concentrations of chlorinated ethenes. Appendix A of CH2M Hill (1999a) provides a complete summary of chemicals detected at SS015 as part of the GSAP.

Table 2.2 indicates that PCE, TCE, *cis*-1,2-DCE, and VC have been detected regularly in samples from MW-216 over time. Concentrations of PCE and TCE have been increasing gradually, while concentrations of *cis*-1,2-DCE and VC have been gradually decreasing. Other COCs at SS015, including TPH-gas and TPH-diesel, have either not been detected or have been detected at such low concentrations that they have been dropped from the analyses routinely performed at Site SS015 as part of the GSAP (CH2M Hill, 1999a).

Three wells, MW-215, MW-216, and MW-238, were monitored for natural attenuation parameters during 1998 and 1999 (Appendix A of CH2M Hill, 1999a). The results show some evidence for biodegradation, although the data are inconclusive because the sampled wells are not optimally located (e.g., only MW-216 is located within the plume). Factors indicating biodegradation of chlorinated ethenes include: the presence of transformation products of PCE and TCE (i.e., TCE, *cis*-1,2-DCE, and VC) and the historical presence of petroleum hydrocarbons at the site (acting as potential electron donors). However, the increase in concentrations of parent compounds PCE and TCE and the decrease in concentrations of biodegradation daughter products *cis*-1,2-DCE and VC over recent years strongly suggests that intrinsic biodegradation of chlorinated solvents at Site SS015 is electron-donor limited.

2.2 PHASE I RESULTS

A Phase I enhanced bioremediation field test was conducted from April to December 2000 (Parsons, 2001b). The Phase I field test included the installation of a well point network consisting of three injection points and seven groundwater monitoring points in the suspected Site SS015 source area using direct-push technology (Figure 2.3). A total of 62 gallons of refined soybean oil and 16 gallons of water were injected into three injection points in June 2000. Post-injection sampling of groundwater was performed at

TABLE 2.1
SUMMARY OF ANALYTICAL RESULTS FOR GROUNDWATER COCs^{a/}
SPRING 1999
SITE SS015
TRAVIS AFB, CALIFORNIA

Well Location	PCE^{b/} (mg/L)^{c/}	TCE^{b/} (mg/L)	cis-1,2-DCE^{b/} (mg/L)	Vinyl- Chloride (mg/L)	1,2-DCA^{b/} (mg/L)	1,4-DCB^{b/} (mg/L)
MW-105	ND ^{d/}	ND	ND	ND	ND	ND
MW-215	ND	ND	ND	ND	ND	ND
MW-216	62	330	91	1.0	ND	ND
MW-238	ND	ND	ND	ND	ND	ND
MW-306	ND	ND	ND	ND	ND	ND

^{a/} COCs = contaminants of concern (from CH2M Hill, 1999a).

^{b/} PCE = tetrachloroethene; TCE = trichloroethene; DCE = dichloroethene; DCA = dichloroethane; and DCB = dichlorobenzene.

^{c/} µg/L = micrograms per liter.

^{d/} ND = not detected.

TABLE 2.2
CONCENTRATIONS OF VOLATILE COCs^{a/}
DETECTED IN WELL MW-216
SITE SS015
TRAVIS AFB, CALIFORNIA

Chemical	EIOU RI	EIOU RI	1996 GSAP	1996 GSAP	1998 GSAP	1998 GSAP	1999 GSAP
	(Round 7)	(Round 8)	(3rd Quarter)	(3rd Quarter)	(1st Semi-Annual)	(2nd Semi-Annual)	(1st Semi-Annual)
	Jan-94	May-94	Sep-96	Sep-97	Mar-98	Sep-98	Mar-99
	(mg/L)^{b/}	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
PCE ^{c/}	11J ^{d/}	2.7J	11.3	11	37	17	62
TCE ^{c/}	27	35J	33.9	35	150	79	330
cis-1,2-DCE ^{c/}	370	210J	207	41	48	70	91
Vinyl Chloride	48	31J	15.4	3	2	4	1
1,2-DCA ^{c/}	ND ^{e/}	ND	ND	ND	ND	ND	ND
1,4-DCB ^{c/}	ND	ND	ND	ND	ND	ND	ND

^{a/} COCs = chemicals of concern (from CH2M Hill, 1999a).

^{b/} µg/L = micrograms per liter.

^{c/} PCE = tetrachloroethene; TCE = trichloroethene; DCE = dichloroethene; DCA = dichloroethane; and DCB = dichlorobenzene.

^{d/} J flag indicates estimated concentration.

^{e/} ND = not detected.

HANGER AVENUE

LEGEND

- PES-INJ3 ● GROUNDWATER INJECTION POINT
- PES-SG3 ● SOIL GAS MONITORING POINT
- PES-MW1 ○ GROUNDWATER MONITORING POINT
- MW6 ● GROUNDWATER MONITORING WELL
- x—x— CHAIN LINK FENCE

MW104 ●

GRASS

ASPHALT

PES-MW5 ○

PES-SG5 ●

PES-SG4 ●

PES-MW3 ○

PES-MW6 ○

PES-SG3 ●

PES-INJ1 ●

PES-MW7 ○

PES-INJ3 ●

PES-MW4 ○

PES-INJ2 ●

PES-SG2 ●

PES-MW1 ○

PES-MW2 ○

PES-SG1 ●

MW216 ●

ASPHALT

SEWER LINE

MANHOLE

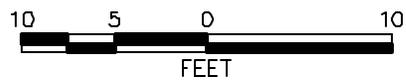


FIGURE 2.3

PHASE I FIELD TEST
SITE LAYOUT

Site SS015
Travis Air Force Base, California

PARSONS
PARSONS ENGINEERING SCIENCE, INC.

Denver, Colorado

the newly installed points and existing monitoring well MW-216 at 3 and 6 months after the Phase I injection (September and December 2000).

Due to the low permeability of soils at Site SS015, vegetable oil was injected at pressures sufficient to fracture the formation. Radius of influence testing indicates that oil was distributed primarily along relatively permeable silt and sand seams at depths of 15 to 19 feet below ground surface. Secondary distribution of oil is inferred to have occurred along vertical fractures. The extent of oil distribution was not uniform, ranging from approximately 1 to 5 feet from the injection points.

The addition of vegetable oil induced anaerobic conditions across the study area. Dissolved oxygen (DO) concentrations decreased uniformly from greater than 6 milligrams per liter (mg/L) to less than 1.5 mg/L after injection. Oxidation-reduction potential (ORP) also decreased after injection. ORP values prior to injection ranged from 52 millivolts (mV) to 264 mV. Following the Phase I injection, ORP in the treatment zone ranged from -293 mV to 34 mV in December 2000. This range in ORP indicates that the groundwater environment is sufficiently reducing to support ferric iron reduction, sulfate reduction, and methanogenesis, and is more conducive to reductive dechlorination of CAHs.

Relatively low background concentrations of nitrate and low concentrations of ferrous iron indicate that nitrate reduction and iron reduction are not significant redox processes at the site. A significant reduction in sulfate concentrations was observed in December 2000, although sulfate concentrations still ranged from 1,100 mg/L to 3,100 mg/L. Sulfate concentration data indicate that sulfate reduction is the dominant terminal electron accepting process (TEAP) occurring at the site, and that sulfate is a significant competing electron acceptor to reductive dechlorination of chlorinated compounds. Inconsistent trends and small increases in methane concentration over time suggests that methanogenesis did not occur at a significant rate during the Phase I study.

Overall, the maximum concentration of TCE decreased from 4,200 micrograms per liter ($\mu\text{g/L}$) in April 2000 to 2,500 $\mu\text{g/L}$ in December 2000. Significant reductions in TCE concentrations occurred at four of the nine locations monitored. Two of these locations are within the radius of influence (area of distribution) of the injected vegetable oil, and reductions in TCE concentrations at these locations are likely a result of both partitioning of TCE from the aqueous phase into the vegetable oil non-aqueous phase liquid (NAPL) and biodegradation. TCE concentrations increased slightly at four locations, which may be a result of natural temporal variations in contaminant concentration, or lateral spreading of contaminants due to a temporary mounding of the potentiometric surface induced by the oil/water injection.

From April to December 2000, the maximum concentration of *cis*-1,2-DCE also decreased from 22,000 $\mu\text{g/L}$ to 4,000 $\mu\text{g/L}$. The relative increase or decrease in *cis*-1,2-DCE levels at monitoring locations was similar to that of TCE. Similarly, the maximum concentration of VC decreased from 17,000 $\mu\text{g/L}$ in April 2000 to 2,800 $\mu\text{g/L}$ in December 2000.

To help evaluate partitioning of chlorinated ethenes from water into the oil, concentrations of chlorinated ethenes in oil samples collected from two of the injection

points were measured in December 2000. Maximum concentrations of PCE (900 µg/L), TCE (4,200 µg/L), and *cis*-1,2-DCE (8,900 µg/L) in the vegetable oil were measured. These concentrations were generally three times the aqueous phase concentration at injection point PES-INJ1, and up to two orders of magnitude greater than the aqueous phase concentration at injection point PES-INJ3. This indicates a substantial partitioning of CAHs into the vegetable oil NAPL, and likely accounts for a significant percentage of any concentration reduction in aqueous-phase concentrations within the immediate zone of vegetable oil influence.

Phase I chlorinated ethene data indicate an overall reduction of maximum contaminant concentrations. Based on contaminant trend analysis alone, it is difficult to determine whether, or to what extent, this reduction was due to biodegradation, partitioning of solvents into vegetable oil, temporal lateral spreading of contaminants due to injection, or to natural variations in contaminant concentration. However, other evidence of enhanced biodegradation, including changes in groundwater geochemistry and molar ratios of parent and daughter products, indicate that at least a portion of the reduction in contaminant concentrations was due to reductive dechlorination.

For example, with the exception of VC, chlorinated ethene concentrations at injection point PES-INJ3 decreased from April to December 2000. Some of the reduction in contaminant concentration may be attributable to partitioning from the aqueous phase to the oil NAPL. However, changes in molar fractions at injection point PES-INJ3 exhibit the trends expected if reductive dechlorination is occurring, particularly an increase in VC. The molar fractions of parent compounds PCE and TCE decreased, while the molar fractions of daughter products *cis*-1,2-DCE and VC increased. The lack of ethene suggests that either the reduction of VC to ethene is limited, or that ethene is unstable or also degraded. Downgradient of the injection points, concentrations and molar fractions of TCE for other monitoring points generally tended to decrease and molar fractions of *cis*-1,2-DCE tended to increase, suggesting that reductive dechlorination of TCE to *cis*-1,2-DCE occurred. Changes in molar fractions of PCE, VC, and ethene at these locations are less consistent.

In summary, trends in chlorinated ethene concentrations and molar fractions indicates that reductive dechlorination was stimulated by the Phase I injection at the site. Transformation of TCE to *cis*-1,2-DCE appeared to be the most common and consistent reduction step. The decrease in chlorinated ethene concentrations was not uniform across the site. This suggests either non-uniform distribution of vegetable oil or the presence of significant competing electron acceptors. It appears that a significant percentage of the vegetable oil may be utilized to overcome the naturally high concentrations of sulfate at the site (i.e., microbes utilize the vegetable oil to preferentially reduce sulfate rather than CAHs). Based on little change in dissolved methane concentrations, it does not appear that methanogenesis utilized a substantial amount of substrate relative to sulfate reduction or reductive dechlorination.

SECTION 3

PHASE II FIELD TEST IMPLEMENTATION

Based on the results of the Phase I baseline sampling event, a larger scale system (Phase II) was installed in September 2000. Phase II baseline sampling was performed concurrently with the Phase I process monitoring event in September 2000. The Phase II injection event was conducted after the final Phase I process monitoring event in December 2000.

Site-specific activities performed for the Phase II field feasibility test for enhanced bioremediation included:

- Installation of 35 vegetable oil injection points (PES-INJ4 through PES-INJ38) and 9 groundwater sampling points (PES-MW8 through PES-MW-16) by the USACE using a cone penetrometer testing (CPT) rig;
- Baseline (i.e., pre-injection) sampling of groundwater for newly installed Phase II monitoring points (PES-MW8 through PES-MW-16) and selected injection points (PES-INJ18 and PES-INJ24);
- Plumbing of the pilot system to the injection points and injection of the vegetable oil;
- Completion of Phase II monitoring and injection point protective casings; and
- Post-injection sampling of groundwater at select Phase I and Phase II monitoring points and soil vapor monitoring points at 9 months after the Phase II injection (September 2001).

The materials and methodologies used to accomplish the activities for Phase II are described in this section. For materials and methodologies used to accomplish Phase I activities, refer to the Draft Phase I results report (Parsons, 2001a).

3.1 PHASE II SYSTEM INSTALLATION

Phase II field activities performed from August 2000 to September 2001 are summarized in Table 3.1. The following sections provide a description of these activities.

TABLE 3.1
SUMMARY OF PHASE II SITE ACTIVITIES - EXPANDED FIELD TEST
SITE SS015
TRAVIS AFB, CALIFORNIA

Location	Monitoring/ Injection Point Installation	Aquifer (Slug) Test Analysis	Water Level Measurement	Oil Analyses	Soil Gas Analyses ^{b/}	Groundwater Analyses							
				VOCs ^{b/} SW8260B		VOCs (SW8260B)	Methane, Ethane, Ethene (AM-18)	Nitrate + Nitrite (E300.1)	Chloride (E300.1)	Bromide (E320.1)	Metals ^{c/} (SW6010)	Well Head Analyses ^{d/}	Mobile Lab Analyses ^{e/}
Soil Gas Monitoring Points													
PES-SG-1					1								
PES-SG-2					1								
PES-SG-3					1								
PES-SG-4					1								
PES-SG-5					1								
Existing Monitoring Well													
MW-216			X			1	1	1	1			1	1
Groundwater Monitoring Points													
PES-MW-1			X			1	1	1	1			1	1
PES-MW-2			X			1	1	1	1			1	1
PES-MW-3			X			1	1	1	1			1	1
PES-MW-4			X			1	1	1	1			1	1
PES-MW-5			X			1	1	1	1			1	1
PES-MW-6			X			1	1	1	1	1	1	1	1
PES-MW-7			X			1	1	1	1	1	1	1	1
PES-MW-8	X		X			1	1	1	1			1	1
PES-MW-9	X		X			1	1	1	1			1	1
PES-MW-10	X		X			1	1	1	1			1	1
PES-MW-11	X		X			1	1	1	1			1	1
PES-MW-12	X		X			1	1	1	1			1	1
PES-MW-13	X		X			1	1	1	1			1	1
PES-MW-14	X		X			1	1	1	1			1	1
PES-MW-15	X		X			1	1	1	1			1	1
PES-MW-16	X		X			1	1	1	1			1	1
Injection Points													
PES-INJ-1		X	X	1		1		1	1			1	1
PES-INJ-2		X	X										
PES-INJ-3			X	1		1		1	1		1	1	1
PES-INJ-4	X												
PES-INJ-5	X	X											
PES-INJ-6	X												
PES-INJ-7	X												
PES-INJ-8	X												
PES-INJ-9	X	X											
PES-INJ-10	X												
PES-INJ-11	X												
PES-INJ-12	X												
PES-INJ-13	X												
PES-INJ-14	X												
PES-INJ-15	X												
PES-INJ-16	X												
PES-INJ-17	X												
PES-INJ-18	X					1	1	1	1			1	1
PES-INJ-19	X	X											
PES-INJ-20	X												
PES-INJ-21	X												
PES-INJ-22	X												
PES-INJ-23	X												
PES-INJ-24	X					1	1	1	1			1	1
PES-INJ-25	X												
PES-INJ-26	X												
PES-INJ-27	X												
PES-INJ-28	X												
PES-INJ-29	X												
PES-INJ-30	X												
PES-INJ-31	X												
PES-INJ-32	X												
PES-INJ-33	X												
PES-INJ-34	X												
PES-INJ-35	X												
PES-INJ-36	X												
PES-INJ-37	X												
PES-INJ-38	X	X											
SUBTOTALS	44	6	20	2	5	21	19	21	21	2	3	21	21
QA/QC Samples													
Duplicates						1	1	1	1				1
Trip Blanks						1							
Matrix Spikes						1							
MS Duplicates						1							
TOTAL:				2	5	25	20	22	22	2	3	21	22

^{a/} Soil gas analyses include oxygen, carbon dioxide, and methane by direct reading meter.
^{b/} VOCs include aromatic and chlorinated aliphatic hydrocarbons.
^{c/} Metals analyses include arsenic, manganese, and selenium.
^{d/} Well head analyses include dissolved oxygen, oxidation-reduction potential, pH, temperature, and conductivity.
^{e/} Mobile lab analyses include carbon dioxide, alkalinity, ferrous iron, sulfate, hydrogen sulfide, and manganese.

3.1.1 Injection Point and Groundwater Sampling Locations

Locations for the 35 injection points and 9 groundwater monitoring points are shown on Figure 3.1. These locations were determined from a review of available site data and results of the Phase I test (Section 2), with the injection points located to provide oil distribution in the portion of the plume with the highest contaminant concentrations.

3.1.2 Injection and Groundwater Monitoring Point Installation

Newly installed Phase II monitoring and injection points were constructed of 0.75-inch inside-diameter (ID) polyvinyl chloride (PVC) casing placed with the USACE CPT rig. Phase II injection and monitoring points were installed in August 2000 and construction details are summarized in Table 3.2. Injection and monitoring point screens were constructed of 10 feet of flush-threaded, Schedule 40 PVC with an ID of 0.75 inch and with 0.01-inch factory-slotted openings. Injection screens were placed at least 2 to 3 feet below the water table to avoid short circuiting of injected vegetable oil to the vadose zone. Monitoring point screens were placed at similar depths as the injection screens. All injection and monitoring points had factory installed pre-packed bentonite well seals. Each injection and groundwater monitoring point was completed slightly below grade. Flush-mounted protective casings were used to protect the monitoring points.

3.2 MEASUREMENT OF BASELINE GEOCHEMICAL CONDITIONS AND CONTAMINANT PROFILES

After installation of the injection and groundwater monitoring points, groundwater samples were collected in September 2000 to characterize initial (pre-Phase II injection) site-specific geochemical and contaminant conditions. Groundwater samples collected from the groundwater monitoring and select injection point locations were analyzed for ORP, DO, pH, specific conductivity, temperature, ferrous iron, manganese, hydrogen sulfide, sulfate, alkalinity, carbon dioxide, bromide, nitrate, nitrite, chloride, methane, ethane, ethene, and volatile organic compounds (VOCs) (Table 3.3). In addition, three samples were analyzed for arsenic, selenium, and manganese. Laboratory analytical results are contained in Appendix A, and field groundwater sampling forms are contained in Appendix B.1.

3.3 AQUIFER TESTING

Aquifer testing (slug tests) were conducted before oil injection on selected injection and monitoring points (Table 3.1) to estimate the hydraulic conductivity of unconsolidated deposits at the site, and to estimate the impact of oil injection. Aquifer test calculations are included in Appendix B.2.

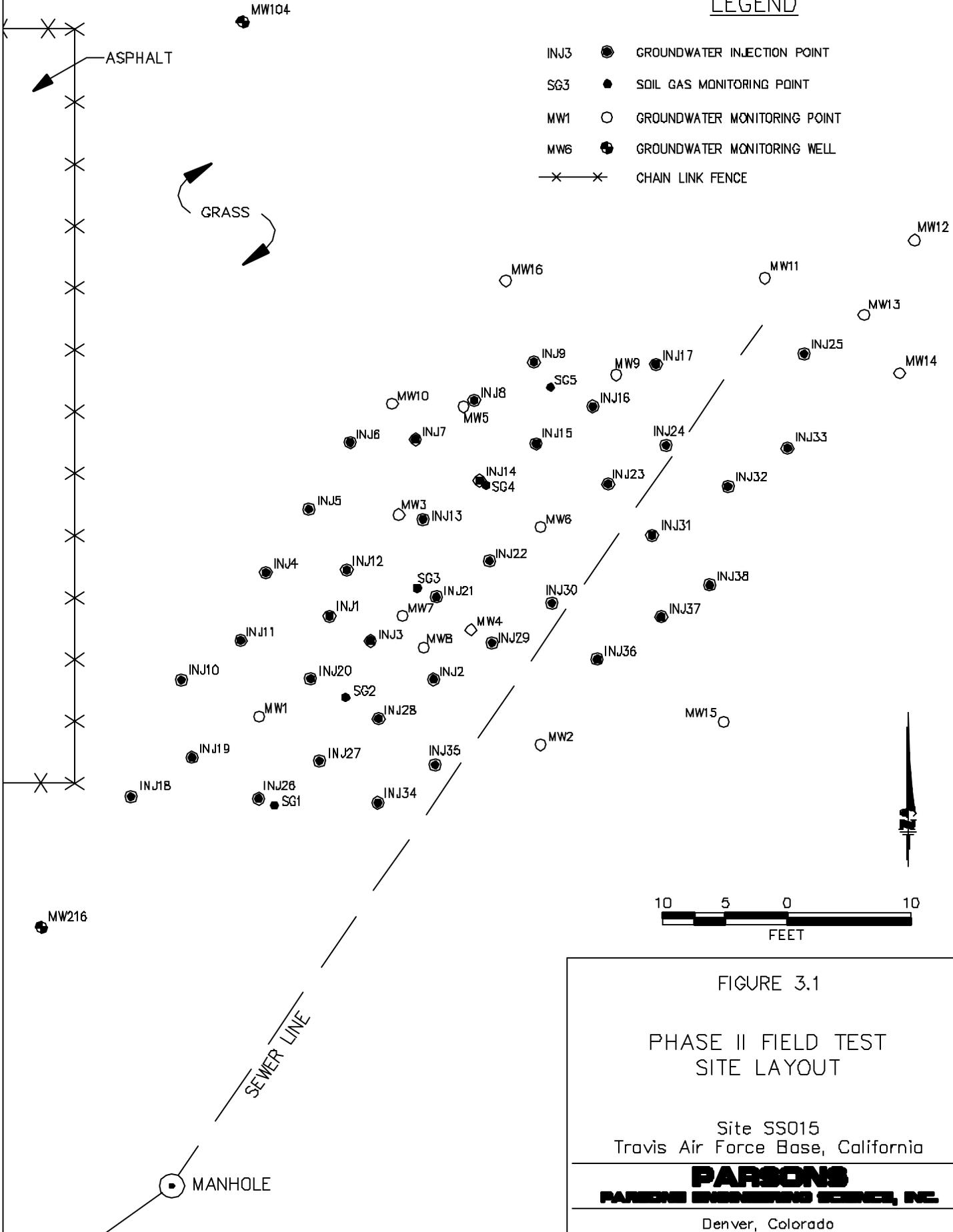
3.4 SUBSTRATE ADDITION

After the background geochemical and contaminant sampling and aquifer testing were completed, a total of 165 gallons of partially hydrogenated soybean oil was injected on December 15 and 16, 2000. Four injection scenarios were planned to be tested on injection points PES-INJ4 through PS-INJ38. The strategy for the oil injection was to

HANGER AVENUE

LEGEND

- INJ3 ● GROUNDWATER INJECTION POINT
- SG3 ● SOIL GAS MONITORING POINT
- MW1 ○ GROUNDWATER MONITORING POINT
- MW6 ● GROUNDWATER MONITORING WELL
- X—X— CHAIN LINK FENCE



S:\ES\Remed\736116\05000\report\Phase 2 CAD\01dn0407.dwg, 12/11/01 at 10:27

FIGURE 3.1

PHASE II FIELD TEST SITE LAYOUT

Site SS015
Travis Air Force Base, California

PARSONS
PARSONS ENGINEERING SCIENCE, INC.

Denver, Colorado

TABLE 3.2
SUMMARY OF WELL/POINT CONSTRUCTION
SITE SS015
TRAVIS AFB, CALIFORNIA

Well/Borehole Identification	Completion Date	Well Diameter (Inches)	Screened Interval (feet bgs) ^{a/}	Ground Surface Elevation (feet msl) ^{b/}	Elevation Datum (feet msl)	Survey Northing (State Plane)	Survey Easting (State Plane)
Existing Monitoring Wells							
MW-104	NA ^{c/}	NA	20.0 - 30.0	NA	60.42	NA	NA
MW-216	7/28/97	2.0	7.0 - 22.0	59.77	61.80	1858710.11	6577028.88
Phase I Monitoring Points							
PES-MW1	4/24/00	1.0	11.5 - 21.5	59.87	59.71	1858727.14	6577046.40
PES-MW2	4/26/00	1.0	3.2 - 18.2	60.49	60.31	1858724.83	6577069.06
PES-MW3	4/25/00	1.0	6.3 - 16.3	60.01	59.80	1858743.41	6577057.73
PES-MW4	4/25/00	1.0	7.2 - 17.2	60.10	59.97	1858734.14	6577063.49
PES-MW5	4/25/00	1.0	9.0 - 19.0	60.00	59.85	1858752.12	6577062.92
PES-MW6	4/27/00	1.0	10.0 - 20.0	60.14	59.90	1858742.36	6577069.11
PES-MW7	4/27/00	1.0	6.2 - 21.2	60.12	59.90	1858735.16	6577058.05
Phase II Monitoring Points							
PES-MW8	8/29/00	0.75	15.0 - 20.0	NM ^{d/}	NM	NM	NM
PES-MW9	8/29/00	0.75	17.6 - 22.6	NM	NM	NM	NM
PES-MW10	9/7/00	0.75	8.3 - 18.3	NM	NM	NM	NM
PES-MW11	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-MW12	9/9/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-MW13	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-MW14	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-MW15	9/9/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-MW16	9/9/00	0.75	12.0 - 22.0	NM	NM	NM	NM
Phase I Injection Points							
PES-INJ1	4/25/00	1.0	11.0 - 21.0	59.93	59.90	1858735.19	6577052.06
PES-INJ2	4/25/00	1.0	11.0 - 21.0	60.18	60.11	1858730.14	6577060.53
PES-INJ3	4/25/00	1.0	11.0 - 21.0	60.08	59.99	1858733.23	6577055.41
Phase II Injection Points							
PES-INJ4	8/29/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ5	8/29/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ6	8/29/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ7	8/29/00	0.75	10.5 - 20.5	NM	NM	NM	NM
PES-INJ8	9/7/00	0.75	11.8 - 21.8	NM	NM	NM	NM
PES-INJ9	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ10	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ11	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ12	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ13	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ14	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ15	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ16	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ17	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ18	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ19	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ20	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ21	9/7/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ22	9/9/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ23	9/8/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ24	9/8/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ25	9/8/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ26	9/8/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ27	9/8/00	0.75	12.0 - 22.0	NM	NM	NM	NM

TABLE 3.2 (Continued)
SUMMARY OF WELL/POINT CONSTRUCTION
SITE SS015
TRAVIS AFB, CALIFORNIA

Well/Borehole Identification	Completion Date	Well Diameter (Inches)	Screened Interval (feet bgs) ^{a/}	Ground Surface Elevation (feet msl) ^{b/}	Elevation Datum (feet msl)	Survey Northing (State Plane)	Survey Easting (State Plane)
PES-INJ28	9/8/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ29	9/8/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ30	9/8/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ31	9/8/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ32	9/8/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ33	9/8/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ34	9/8/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ35	9/9/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ36	9/9/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ37	9/9/00	0.75	12.0 - 22.0	NM	NM	NM	NM
PES-INJ38	9/9/00	0.75	12.0 - 22.0	NM	NM	NM	NM
Soil Vapor Monitoring Points							
PES-SG1	4/27/00	0.5	5.5 - 6.5	NM	NA	NM	NM
PES-SG2	4/27/00	0.5	6.0 - 7.0	NM	NA	NM	NM
PES-SG3	4/27/00	0.5	5.0 - 6.0	NM	NA	NM	NM
PES-SG4	4/27/00	0.5	6.0 - 7.0	NM	NA	NM	NM
PES-SG5	4/27/00	0.5	5.0 - 6.0	NM	NA	NM	NM

^{a/} feet bgs indicates depth in feet below ground surface.

^{b/} feet msl indicates elevation in feet above mean sea level.

^{c/} NA indicates data not available.

^{d/} NM indicates point not measured.

TABLE 3.3
ANALYTICAL PROTOCOLS FOR
GROUNDWATER, SOIL GAS, AND OIL SAMPLES
SITE SS015
TRAVIS AFB, CALIFORNIA

MATRIX Analyte	METHOD	FIELD (F) OR ANALYTICAL LABORATORY (L)
WATER		
Redox Potential	Direct-reading meter	F
Oxygen	Direct-reading meter	F
pH	Direct-reading meter	F
Conductivity	Direct-reading meter	F
Temperature	Direct-reading meter	F
Ferrous Iron (Fe ⁺²)	Colorimetric, Hach Method 8146	F
Manganese	Colorimetric, Hach Method 8034	F
Hydrogen Sulfide	Colorimetric, Hach Method 8131	F
Sulfate	Colorimetric, Hach Method 8051	F
Alkalinity (Carbonate [CO ₃ ⁻²] and Bicarbonate [HCO ₃ ⁻¹])	Titrimetric, Hach Method 8221	F
Carbon Dioxide	Titrimetric, Hach Method 1436-01	F
Sulfate	E300.1	L
Nitrate + Nitrite [as Nitrogen (N)]	E300.1	L
Chloride	E300.1	L
Bromide	E320.1	L
Metals ^{a/}	SW6010	L
Methane, Ethane, Ethene	AM-18 ^{b/}	L
Total Organic Carbon	Walkley-Black	L
VOCs ^{c/}	SW8260B	L
SOIL GAS		
Oxygen	Direct-reading meter	F
Carbon Dioxide	Direct-reading meter	F
Methane	Direct-reading meter	F
VEGETABLE OIL		
VOCs	SW8260B	L

^{a/} Metals = arsenic, selenium, and manganese.

^{b/} AM-18 = Microseeps, Inc. laboratory standard operating procedure.

^{c/} VOCs = volatile organic compounds (chlorinated ethenes).

compare the following injection scenarios in order to determine the optimum method for maximum extent and uniform delivery of the vegetable oil into the subsurface:

Test Scenario #1: A straight oil injection followed by a water push.

Test Scenario #2: Injection of an oil-in-water emulsion with Polysorbate 80 as an emulsifier.

Test Scenario #3: Injection of an oil-in-water emulsion with lecithin as an emulsifier, followed by a water push.

Test Scenario #4: Injection of a relatively dilute oil-in-water emulsion with lecithin as an emulsifier.

However, problems were encountered with the factory installed pre-packed bentonite well seals used for the Phase II injection points. A combination of the relatively thin bentonite seal (1 foot in thickness) and a lack of cement grout above the seal led to failure of many annular seals during injection. Because of the low permeability of the formation, relatively high injection pressures (up to 25 pounds per square inch [psi]) were required at this site. Without an overlying rigid cement grout, the relatively soft bentonite seals are thought to have been deformed and breached by the injection fluids. Therefore, only the first two injection scenarios were accomplished during the field effort.

The injection system consisted of two Ingersol-Rand ARO air-operated diaphragm pumps that were plumbed in a configuration that used four flow meters, pressure gauges, and valves to control the volume, pressure, and flow rate of the injected fluids (see report cover photograph). The configuration also used a ½-inch diameter static in-line mixer to emulsify an oil and water mixture for the second injection scenario. The system was configured to inject into two injection points simultaneously through 1-inch high pressure hoses, while being able to separately control the volume and pressure of injection into each of the two injection points.

A summary of the injection volumes, rates, and pressures is presented in Table 3.4. Each of the two completed injection scenarios is described in further detail below. A fluorescent dye (Chromatint Fluorescent) was added to all oil injected at the site in order to facilitate future radius of influence testing. Bromide was also added to the water used for Test Scenario #1 to trace the flow of the aqueous phase portion of the water push.

Test Scenario #1

A straight injection of approximately 15 to 28 gallons of partially hydrogenated soybean oil per injection point followed by a water flush of approximately 5 to 60 gallons per point was successfully performed at six Phase II injection points (Table 3.4 and Figure 3.2). A total of 120 gallons of oil and 170 gallons of water were used for this injection scenario. The test plan was designed to inject sufficient water to yield a residual oil saturation of 30 percent. However, failure of annular seals during the water push stage often resulted in a greater oil saturation. Overall, the average oil saturation was 41 percent.

TABLE 3.4
SUMMARY OF PHASE I AND PHASE II VEGETABLE OIL INJECTION
SITE SS-015
TRAVIS AFB, CALIFORNIA

Well	Oil/Water Mixture		Emulsifier (agent)	Water Push (gallons)	Total Volume (gallons)	Final Percent Oil	Radius of Influence ^{d/} (feet)	Oil Injection Pressure (psi) ^{b/}	Oil Injection Flow Rate (gpm) ^{e/}	Water Push Pressure (psi)	Water Push Flow Rate (gpm)	Comments
	Oil (gallons)	Water (gallons)										
<i>Phase I Pilot Test (June 2000) - Straight oil Injection with Water Push</i>												
PES-INJ-1	18.2	0	NA ^{d/}	3.5	22	83.9	1.0	10 to 25	<0.1 to 0.11	15	0.15	
PES-INJ-2	23.0	0	NA	4.5	28	83.6	1.1	15 to 25	0.15	15	0.30	
PES-INJ-3	21.1	0	NA	8.0	29	72.5	1.1	15 to 25	<0.1 to 0.32	15	0.90	
TOTAL:	62.3	0		16.0	78	79.6						
<i>Phase II Test Scenario #1 (December 2001) - Straight Oil Injection with Water Push</i>												
PES-INJ-4	18	0	NA	5	23	78.3	1.0	23 to 25	1.0	5	1.0	Well seal failed during water push
PES-INJ-5	15	0	NA	10	25	60.0	1.0	4 to 18	0.7	1	1.0	Well seal failed during water push
PES-INJ-12	20	0	NA	40	60	33.3	1.6	14 to 20	0.6	10 to 18	0.3 to 0.5	Breakthrough at wells INJ3 and INJ5
PES-INJ-13	28	0	NA	60	88	31.8	1.9	18 to 25	0.3	14 to 18	0.6	High back-pressure
PES-INJ-21	20	0	NA	15	35	57.1	1.2	15 to 25	0.2 to 1.0	10 to 15	1.3	Well seal failed during water push
PES-INJ-22	19	0	NA	40	59	32.2	1.6	15 to 25	0.1 to 0.5	16 to 18	1.6	
PES-INJ-29	0	0	NA	0	0	NA	0.0	<15	NA	NA	NA	Well seal failed
PES-INJ-30	0	0	NA	0	0	NA	0.0	<15	NA	NA	NA	Well seal failed
TOTAL:	120	0		170	290	41.4						
<i>Phase II Test Scenario #2 (December 2001) - Oil-in-Water Emulsion with Polysorbate Emulsifier</i>												
PES-INJ-9	6	14	Polysorbate ^{e/}	0	20	30.0	0.9	3	0.5	NA	NA	
PES-INJ-10	4	10	Polysorbate	0	14	30.0	0.8	10 to 16	NA	NA	NA	Emulsion flowing out well PES-INJ34
PES-INJ-11	2.5	5.7	Polysorbate	0	8	30.0	0.6	2 to 5	<1	NA	NA	Well seal failed
PES-INJ-18	18	42	Polysorbate	0	60	30.0	1.6	2 to 5	2 to 3	NA	NA	
PES-INJ-19	12	28	Polysorbate	0	40	30.0	1.3	2 to 5	2 to 3	NA	NA	
PES-INJ-20	0.3	0.7	Polysorbate	0	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-26	0.7	1.5	Polysorbate	0	2	30.0	0.3	<10	NA	NA	NA	Well seal failed
PES-INJ-27	0.5	1.1	Polysorbate	0	2	30.0	0.3	10 to 15	NA	NA	NA	Well seal failed
PES-INJ-28	0.4	0.8	Polysorbate	0	1	30.0	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-34	0.3	0.7	Polysorbate	0	1	30.0	0.2	10 to 16	NA	NA	NA	Well seal failed
PES-INJ-35	0.3	0.7	Polysorbate	0	1	30.0	0.2	<10	NA	NA	NA	Well seal failed
TOTAL:	45	105		0	150	30.0						

TABLE 3.4 (Continued)
SUMMARY OF PHASE I AND PHASE II VEGETABLE OIL INJECTION
SITE SS-015
TRAVIS AFB, CALIFORNIA

Well	Oil/Water Mixture		Emulsifier (agent)	Water Push (gallons)	Total Volume (gallons)	Final Percent Oil	Radius of Influence ^{a/} (feet)	Oil Injection Pressure (psi) ^{b/}	Oil Injection Flow Rate (gpm) ^{c/}	Water Push Pressure (psi)	Water Push Flow Rate (gpm)	Comments
	Oil (gallons)	Water (gallons)										
<i>Phase II Test Scenario #3 (December 2001) - Oil-in-Water Emulsion with Lecithin Emulsifier and Water Push (Not Implemented)</i>												
PES-INJ-6	0	0	Lecithin ^{f/}	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-7	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-8	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-14	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-15	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-16	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-17	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-23	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-24	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
TOTAL:	0	0		9	9	NA						
<i>Phase II Test Scenario #4 (December 2001) - Oil-in-Water Emulsion with Lecithin Emulsifier (Not Implemented)</i>												
PES-INJ-25	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-31	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-32	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-33	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-36	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-37	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
PES-INJ-38	0	0	Lecithin	1	1	NA	0.2	<10	NA	NA	NA	Well seal failed
TOTAL:	0	0		7	7	NA						

^{a/} Assumes an effective porosity of 10 percent.

^{b/} psi = pounds per square inch.

^{c/} gpm = gallons per minute.

^{d/} NA = not applicable.

^{e/} Polysorbate 80 was mixed at a volume of 0.5 percent of the total volume of the emulsion.

^{f/} Lecithin was pre-mixed in the oil at a ratio of 1 part lecithin to 9 parts oil.

HANGER AVENUE

LEGEND

- INJ3 ● GROUNDWATER INJECTION POINT (1" DIAMETER)
- SG3 ● SOIL GAS MONITORING POINT
- MW1 ○ GROUNDWATER MONITORING POINT (1" DIAMETER)
- MW6 ● GROUNDWATER MONITORING WELL (4" DIAMETER)
- X—X— CHAIN LINK FENCE
- 18 VOLUME OF OIL INJECTED (IN GALLONS)

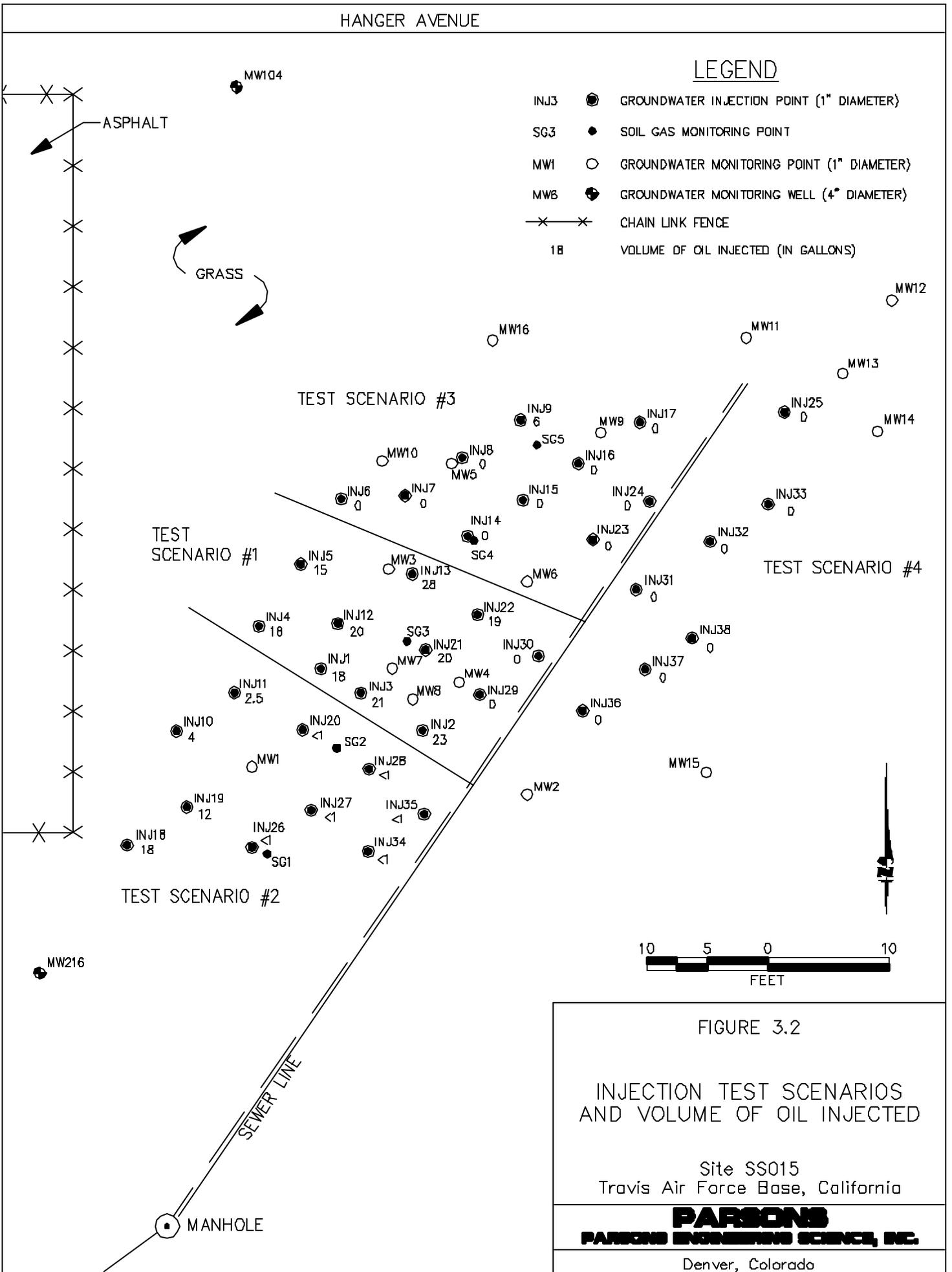


FIGURE 3.2

INJECTION TEST SCENARIOS AND VOLUME OF OIL INJECTED

Site SS015
Travis Air Force Base, California

PARSONS
PARSONS ENGINEERING SCIENCE, INC.

Denver, Colorado

Oil injection was performed simultaneously at two injection points using an injection manifold with the configuration described above. The flow rate for oil injection into each point ranged from 0.1 to 1.0 gallon per minute (gpm) at surface pressures ranging up to 25 psi. The flow rate for the water flush into each point ranged from 0.3 to 1.6 gpm at surface pressures ranging up to 18 psi. Injection pressures higher than the overburden pressure (approximately 11 to 21 psi) were required in some cases to induce fracturing of the soil and obtain measurable flow rates for injection. The flow rate varied depending upon back-pressure from aquifer resistance and the ability of the oil to be introduced into the aquifer matrix. Water for all injection scenarios was obtained from an onsite source (monitoring well MW-216).

Test Scenario #2

Injection of an oil-in-water emulsion with food-grade Polysorbate 80 as an emulsifier was performed at 11 Phase II injection points (Table 3.4 and Figure 3.2). However, a significant volume of emulsion (more than 3 gallons) was only injected in five of the injection points due to failure of annular seals. The emulsion consisted of 3 parts oil to 7 parts water, with Polysorbate 80 added at a concentration of 0.4 percent of the total oil and water volume. This yielded a residual oil saturation of 30 percent, similar to that designed for Test Scenario #1.

Mixing of the oil and water to form the emulsion was performed using the two diaphragm air pumps (one for water, one for oil) connected to an static in-line mixer. Volumes of oil and water were monitored using in-line flow meters to ensure that the proper proportions of oil and water were used to form the emulsion. The emulsion was injected simultaneously into two wells at a time using an injection manifold. The emulsion flow rate ranged from 0.5 to 3 gpm at injection pressures ranging from 3 to 16 psi.

3.5 PROCESS MONITORING

In order to monitor system performance over time, Parsons sampled select Phase I and Phase II groundwater monitoring points, injection points, well MW-216, and the five soil gas monitoring points for the parameters listed in Table 3.3 at 9 months (September 2001) after the Phase II oil injection. A summary of the Phase II process monitoring activities is shown in Table 3.5.

TABLE 3.5
SUMMARY OF PHASE II PROCESS MONITORING ACTIVITIES
DECEMBER 2001
SITE SS015
TRAVIS AFB, CALIFORNIA

Location	Aquifer (Slug) Test Analysis	Water Level Measurement	Oil Analyses	Soil Gas Analyses ^{a/}	Groundwater Analyses									
			VOCs ^{b/} SW8260B		VOCs (SW8260B)	Methane, Ethane, Ethene (AM-18)	Total Organic Carbon (Walkley-Black)	Nitrate + Nitrite (E300.1)	Sulfate (E300.1)	Chloride (E300.1)	Bromide (E320.1)	Metals ^{c/} (SW6010)	Well Head Analyses ^{d/}	Mobile Lab Analyses ^{e/}
Soil Gas Monitoring Points														
PES-SG-1				1										
PES-SG-2				1										
PES-SG-3				1										
PES-SG-4				1										
PES-SG-5				1										
Existing Monitoring Well														
MW-216		X			1	1	1	1	1	1	1	1	1	1
Groundwater Monitoring Points														
PES-MW-1		X			1	1	1	1	1	1	1	1	1	1
PES-MW-2		X			1	1	1	1	1	1	1	1	1	1
PES-MW-3		X			1	1	1	1	1	1	1	1	1	1
PES-MW-4		X			1	1	1	1	1	1	1	1	1	1
PES-MW-5		X			1	1	1	1	1	1	1	1	1	1
PES-MW-6		X			1	1	1	1	1	1	1	1	1	1
PES-MW-7		X		1	1	1	1	1	1	1	1	1	1	1
PES-MW-8		X			1	1	1	1	1	1	1	1	1	1
PES-MW-9		X			1	1	1	1	1	1	1	1	1	1
PES-MW-10		X												
PES-MW-11		X			1	1	1	1	1	1	1	1	1	1
PES-MW-12		X												
PES-MW-13		X												
PES-MW-14		X												
PES-MW-15		X												
PES-MW-16		X												
Injection Points														
PES-INJ-1		X	1		1									
PES-INJ-2		X												
PES-INJ-3		X			1	1								
SUBTOTALS	0	20	1	6	13	11	12	11	11	11	11	2	11	11
QA/QC														
Duplicates					1	1	1	1	1	1	1	1		1
Trip Blanks					1									
Matrix Spike					1									
MS Duplicate					1									
TOTAL:			1	6	17	12	13	12	12	12	12	3	11	12

^{a/} Soil gas analyses include oxygen, carbon dioxide, and methane by direct reading meter.

^{b/} VOCs include aromatic and chlorinated aliphatic hydrocarbons.

^{c/} Metals analyses include arsenic, manganese, and selenium.

^{d/} Well head analyses include dissolved oxygen, oxidation-reduction potential, pH, temperature, and conductivity.

^{e/} Mobile lab analyses include carbon dioxide, alkalinity, ferrous iron, hydrogen sulfide, and manganese.

SECTION 4

PHASE II RESULTS

Because CAH compounds are used as electron acceptors, there must be an appropriate source of carbon for microbial growth in order for reductive dechlorination to occur. Potential carbon sources include vegetable oil, fuel hydrocarbons, low-molecular-weight compounds (e.g., lactate, acetate, or methanol) present in natural organic matter, or less-chlorinated compounds such as VC or DCE. Vegetable oil has been selected to remediate the chlorinated solvent plume at SS015 by overcoming the perceived electron donor limitation.

The separate-phase-nature of vegetable oil allows for slow dissolution into groundwater, thus making it a slow release carbon source. Vegetable oil is an inexpensive, innocuous, edible (i.e., food-grade) carbon source that is not regulated as an environmental contaminant by the USEPA. Because vegetable oil is a NAPL, the potential exists that a single, low cost injection could provide sufficient carbon to drive reductive dechlorination for many years.

Vegetable oil was injected at Site SS015 in December 2000 (Phase II) to create the redox and electron donor conditions necessary to promote the microbial reductive dechlorination of the chlorinated solvents found at the site. A secondary benefit is partitioning of the dissolved contaminants into the vegetable oil NAPL. This is beneficial because aqueous-phase chlorinated solvent concentrations are lowered until steady state conditions are reached. This results in an initial attenuation of the dissolved phase plume. Contaminants are then released from the oil to groundwater at a rate dependent upon dissolution and/or degradation of the vegetable oil, and degradation of contaminants in the dissolved phase. In any event, contaminants are released back to groundwater within a zone of adequate substrate and optimal conditions for reductive dechlorination. An extensive discussion of the processes by which vegetable oil enhances *in situ* reductive dechlorination of CAHs can be found in the *Draft Field Feasibility Test for In Situ Bioremediation of Chlorinated Solvents via Vegetable Oil Injection* (Parsons 2001b).

4.1 GROUNDWATER FLOW

Groundwater levels were measured prior to the Phase I vegetable oil injection (May 2000), prior to the Phase II injection (December 2000), and during process monitoring events (September 2000 and September 2001) (Table 4.1). Depth to groundwater ranged from approximately 8 to 12 feet below ground surface (bgs), with groundwater elevations varying by up to 2 feet over the monitoring period. Groundwater elevations were highest in May 2000 prior to the Phase I injection, and are shown on Figure 4.1. Groundwater

TABLE 4.1
SUMMARY OF GROUNDWATER ELEVATIONS
SITE SS015 PHASE II
TRAVIS AFB, CALIFORNIA

Well/Borehole Identification	Date	Elevation Datum (Feet amsl) ^{a/}	Depth to Water (Feet btoc) ^{b/}	Depth to Oil (Feet btoc)	Groundwater Elevation ^{c/} (Feet amsl)
Monitoring Wells					
MW-104	31-May-00	60.42	8.77	--	51.65
	21-Sep-00	60.42	NM ^{d/}	--	NM
	11-Dec-00	60.42	NM	--	NM
	12-Sep-01	60.42	9.86	--	50.56
MW-216	31-May-00	61.80	9.99	--	51.81
	21-Sep-00	61.80	11.33	--	50.47
	11-Dec-00	61.80	10.91	--	50.89
	12-Sep-01	61.80	11.42	--	50.38
Monitoring Points					
PES-MW1	31-May-00	59.71	7.91	--	51.80
	21-Sep-00	59.71	9.12	--	50.59
	11-Dec-00	59.71	9.10	--	50.61
	12-Sep-01	59.71	9.34	--	50.37
PES-MW2	31-May-00	60.31	8.52	--	51.79
	21-Sep-00	60.31	9.69	--	50.62
	11-Dec-00	60.31	9.85	--	50.46
	12-Sep-01	60.31	9.90	--	50.41
PES-MW3	31-May-00	59.80	8.07	--	51.73
	21-Sep-00	59.80	9.14	--	50.66
	11-Dec-00	59.80	9.15	--	50.65
	12-Sep-01	59.80	9.41	--	50.39
PES-MW4	31-May-00	59.97	8.16	--	51.81
	21-Sep-00	59.97	9.31	--	50.66
	11-Dec-00	59.97	9.44	--	50.53
	12-Sep-01	59.97	10.75	9.51	49.22
PES-MW5	31-May-00	59.85	8.18	--	51.67
	21-Sep-00	59.85	9.13	--	50.72
	11-Dec-00	59.85	NM	--	NM
	12-Sep-01	59.85	9.47	--	50.38

TABLE 4.1 (Continued)
SUMMARY OF GROUNDWATER ELEVATIONS
SITE SS015 PHASE II
TRAVIS AFB, CALIFORNIA

Well/Borehole Identification	Date	Elevation Datum (Feet amsl) ^{a/}	Depth to Water (Feet btoc) ^{b/}	Depth to Oil (Feet btoc)	Groundwater Elevation ^{c/} (Feet amsl)
PES-MW6	31-May-00	59.90	8.18	--	51.72
	21-Sep-00	59.90	9.22	--	50.68
	11-Dec-00	59.90	9.12	--	50.78
	12-Sep-01	59.90	9.47	--	50.43
PES-MW7	31-May-00	59.90	8.15	--	51.75
	21-Sep-00	59.90	9.06	--	50.84
	11-Dec-00	59.90	9.48	--	50.42
	12-Sep-01	59.90	9.70	9.45	50.20
PES-MW8	21-Sep-00	NM	9.55	--	NM
	12-Sep-01	NM	10.45	--	NM
PES-MW9	21-Sep-00	NM	NM	--	NM
	12-Sep-01	NM	9.59	--	NM
PES-MW10	21-Sep-00	NM	9.14	--	NM
	12-Sep-01	NM	10.21	--	NM
PES-MW11	21-Sep-00	NM	9.44	--	NM
	12-Sep-01	NM	9.57	--	NM
PES-MW12	21-Sep-00	NM	9.65	--	NM
	12-Sep-01	NM	9.61	--	NM
PES-MW13	21-Sep-00	NM	9.72	--	NM
	12-Sep-01	NM	9.77	--	NM
PES-MW14	21-Sep-00	NM	NM	--	NM
	12-Sep-01	NM	9.77	--	NM
PES-MW15	21-Sep-00	NM	10.16	--	NM
	12-Sep-01	NM	10.17	--	NM
PES-MW16	21-Sep-00	NM	9.35	--	NM
	12-Sep-01	NM	10.04	--	NM
Injection Points					
PES-INJ1	31-May-00	59.90	7.97	--	51.93
	11-Dec-00	59.90	12.65	8.11	51.42

TABLE 4.1 (Continued)
SUMMARY OF GROUNDWATER ELEVATIONS
SITE SS015 PHASE II
TRAVIS AFB, CALIFORNIA

Well/Borehole Identification	Date	Elevation Datum (Feet amsl) ^{a/}	Depth to Water (Feet btoc) ^{b/}	Depth to Oil (Feet btoc)	Groundwater Elevation ^{c/} (Feet amsl)
PES-INJ2	31-May-00	60.11	8.25	--	51.86
	11-Dec-00	60.11	16.12	8.67	50.85
PES-INJ3	31-May-00	59.99	7.90	--	52.09
	21-Sep-00	59.99	NM	8.02	--
	11-Dec-00	59.99	11.01	9.25	50.60
PES-INJ18	21-Sep-00	NM	9.00	--	--
PES-INJ24	21-Sep-00	NM	9.36	--	--
PES-INJ25	21-Sep-00	NM	9.61	--	--

^{a/} Feet amsl indicates elevation in feet above mean sea level.

^{b/} Feet btoc indicates depth in feet below top of casing.

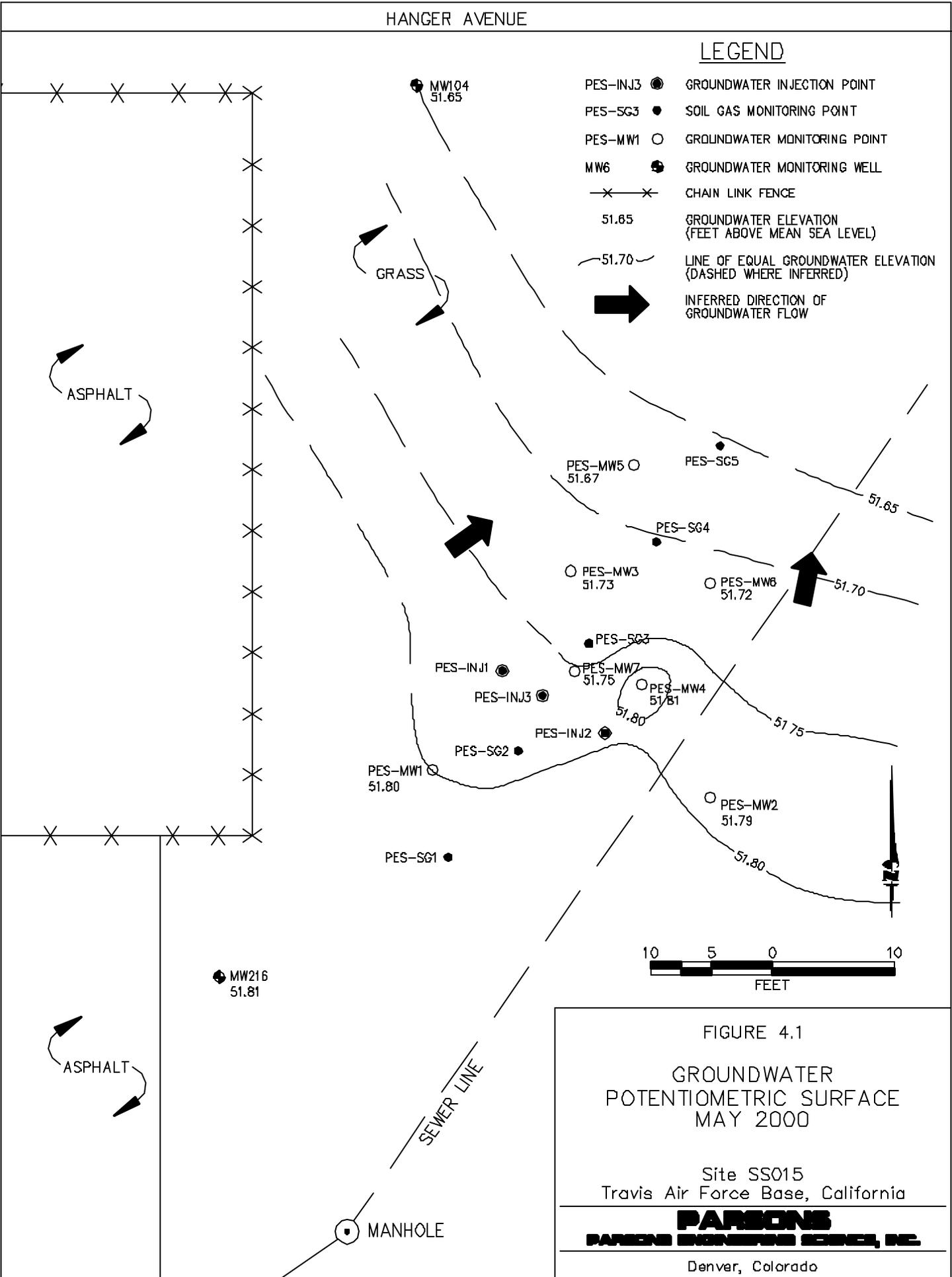
^{c/} Water elevations corrected for presence of oil using a specific gravity of 0.92.

^{d/} NM = datum not measured.

HANGER AVENUE

LEGEND

- PES-INJ3 ● GROUNDWATER INJECTION POINT
- PES-SG3 ● SOIL GAS MONITORING POINT
- PES-MW1 ○ GROUNDWATER MONITORING POINT
- MW6 ● GROUNDWATER MONITORING WELL
- x—x— CHAIN LINK FENCE
- 51.85 GROUNDWATER ELEVATION (FEET ABOVE MEAN SEA LEVEL)
- 51.70— LINE OF EQUAL GROUNDWATER ELEVATION (DASHED WHERE INFERRED)
- ➔ INFERRED DIRECTION OF GROUNDWATER FLOW



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FIGURE 4.1
GROUNDWATER POTENTIOMETRIC SURFACE
MAY 2000

Site SS015
Travis Air Force Base, California

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Denver, Colorado

flow in the test area prior to the Phase I injection was towards the northeast, similar to that observed in June 1999 (Figure 2.3).

Groundwater flow direction after the Phase I injection in September 2000 (Figure 4.2) was variable, with higher elevations in the injection area. This suggests that mounding of the potentiometric surface induced by oil/water injection was slow to dissipate, and that after injection a radial flow direction developed in the injection area. By December 2000 (Figure 4.3), groundwater elevations returned to near baseline conditions with an overall flow direction towards the east and northeast, but with lower groundwater elevations in the injection area and highly variable local flow directions, indicating that the Phase I vegetable oil injection had an impact on groundwater flow within the test area.

Post-injection groundwater elevations in September 2001 (Figure 4.4) ranged from 50.20 to 50.43 feet above mean sea level (ft amsl), with the exception of an anomalously low groundwater elevation at monitoring point PES-MW4 (49.22 ft amsl, corrected for the presence of oil). Groundwater elevations in September 2001 indicate a very flat groundwater gradient, insufficient to determine the direction(s) of groundwater flow with any confidence. Oil was observed in monitoring points PES-MW4 and PES-MW7, indicating that the Phase II injection influenced these locations. The presence of oil may also be the cause of the anomalous groundwater elevation (although corrected for the presence of oil) at point PES-MW4.

Aquifer test data collected at the site in April and December 2000 are shown in Table 4.2. Hydraulic conductivities measured at the site were very low, ranging from $9.9\text{E-}08$ centimeter per second (cm/sec) to $1.65\text{E-}05$ cm/sec, or from 0.0003 feet per day (ft/day) to 0.047 ft/day. These values are generally within a range of hydraulic conductivity values for silt and clay reported by Domenico and Schwartz (1990) ($1\text{E-}05$ cm/sec to $4.7\text{E-}07$ cm/sec). However, calculated values less than the lower bound reported by Domenico and Schwartz (1990) for clay ($4.7\text{E-}07$ cm/sec) are suspect, as such values do not reflect the soil conditions observed at the site. Furthermore, borehole logs for existing monitoring wells and soil borings at the site (CH2M Hill, 1999a) indicate thin layers of silt and silty sand at depths ranging from 10 to 20 feet bgs that should result in higher average hydraulic conductivities. Therefore, values for hydraulic conductivity derived from the December 2000 tests (average of $1.12\text{E-}05$ cm/sec or 0.032 ft/day for injection point PES-INJ5, and an average of $1.44\text{E-}05$ cm/sec or 0.041 ft/day for injection point PES-INJ9) are probably more representative of the site. Further aquifer testing is required to determine average site-wide hydraulic conductivities with confidence.

Given an average hydraulic conductivity of 0.037 ft/day, an assumed effective porosity of 10 percent, and a hydraulic gradient of 0.005 ft/ft calculated from April 2000 data, the average groundwater seepage velocity at the site is approximately 0.68 feet per year (ft/yr). The low average hydraulic conductivity at the site and relatively low hydraulic gradient suggest that the effects of organic substrate addition may take several years to be seen at downgradient monitoring points. However, the presence of preferential pathways such as thin layers of silt and sand with higher hydraulic conductivity may help to distribute dissolved organic substrate more rapidly.

HANGER AVENUE

LEGEND

- PES-INJ3 ● GROUNDWATER INJECTION POINT
- PES-SG3 ● SOIL GAS MONITORING POINT
- PES-MW1 ○ GROUNDWATER MONITORING POINT
- MW6 ● GROUNDWATER MONITORING WELL
- x-x- CHAIN LINK FENCE
- 50.72 GROUNDWATER ELEVATION (FEET ABOVE MEAN SEA LEVEL)
- 51.70- LINE OF EQUAL GROUNDWATER ELEVATION (DASHED WHERE INFERRED)
- ➔ INFERRED DIRECTION OF GROUNDWATER FLOW

MW104

GRASS

ASPHALT

50.50

50.55

50.60

50.65

50.70

PES-MW1
50.59

PES-SG1 ●

MW216
50.47

SEWER LINE

MANHOLE

PES-MW5 ○
50.72

PES-SG5 ●

PES-SG4 ●

PES-MW3 ○
50.66

PES-MW6 ○
50.68

PES-INJ1 ●

PES-SG3 ●

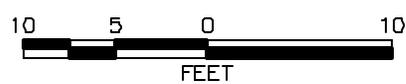
PES-MW7 ○
50.84

PES-MW4 ○
50.65

PES-INJ3 ●

PES-SG2 ●

PES-MW2 ○
50.62



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FIGURE 4.2

GROUNDWATER
POTENTIOMETRIC SURFACE
SEPTEMBER 2000

Site SS015
Travis Air Force Base, California

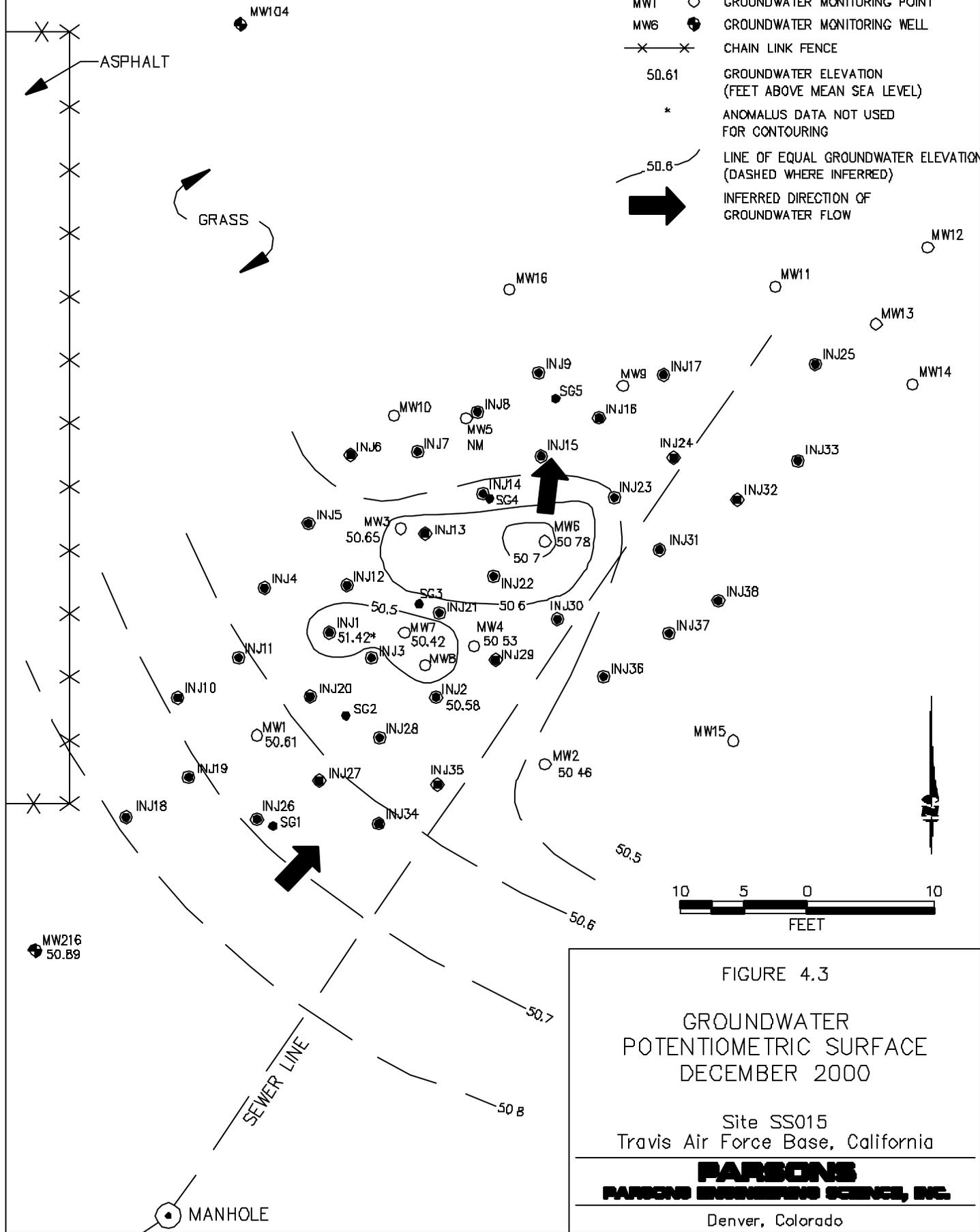
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Denver, Colorado

HANGER AVENUE

LEGEND

- INJ3 ● GROUNDWATER INJECTION POINT
- SG3 ● SOIL GAS MONITORING POINT
- MW1 ○ GROUNDWATER MONITORING POINT
- MW6 ● GROUNDWATER MONITORING WELL
- X-X- CHAIN LINK FENCE
- 50.61 GROUNDWATER ELEVATION (FEET ABOVE MEAN SEA LEVEL)
- * ANOMALOUS DATA NOT USED FOR CONTOURING
- 50.6 LINE OF EQUAL GROUNDWATER ELEVATION (DASHED WHERE INFERRED)
- ➔ INFERRED DIRECTION OF GROUNDWATER FLOW



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FIGURE 4.3

GROUNDWATER POTENTIOMETRIC SURFACE DECEMBER 2000

Site SS015
Travis Air Force Base, California

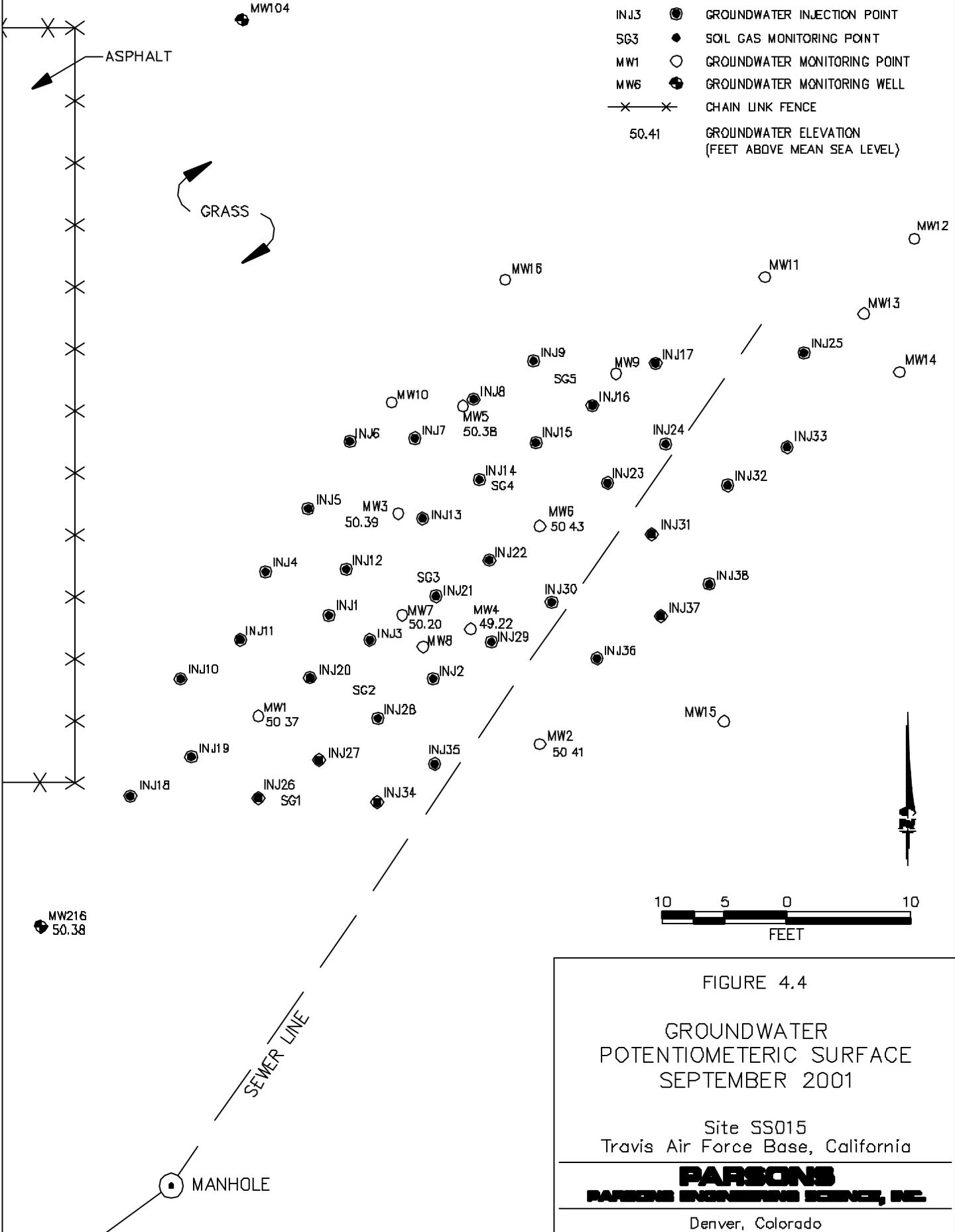
PARSONS
PARSONS ENGINEERING SCIENCE, INC.

Denver, Colorado

HANGER AVENUE

LEGEND

- INJ3 ● GROUNDWATER INJECTION POINT
- SG3 ● SOIL GAS MONITORING POINT
- MW1 ○ GROUNDWATER MONITORING POINT
- MW6 ● GROUNDWATER MONITORING WELL
- X-X- CHAIN LINK FENCE
- 50.41 GROUNDWATER ELEVATION (FEET ABOVE MEAN SEA LEVEL)



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FIGURE 4.4
GROUNDWATER
POTENTIOMETRIC SURFACE
SEPTEMBER 2001

Site SS015
Travis Air Force Base, California

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PARSONS ENGINEERING SCIENCE, INC.

Denver, Colorado

TABLE 4.2
HYDRAULIC CONDUCTIVITIES AND AVERAGE GROUNDWATER VELOCITIES
SITE SS015
TRAVIS AFB, CALIFORNIA

Monitoring Well	Test Date	Screened Interval (ft bgs) ^{a/}	Hydraulic Conductivity (K)			Estimated Effective Porosity	Hydraulic Gradient (ft/ft) ^{e/}	Average Groundwater Velocity (ft/yr) ^{f/}
			(ft/day) ^{b/}	(cm/sec) ^{c/}	(gpd/ft ²) ^{d/}			
PESMW7	02-Jun-00	6.2 - 21.2	0.0003	9.88E-08	0.002	0.10	0.005	0.005
PES-INJ1	01-Jun-00	11.0 - 21.0	0.0004	1.48E-07	0.003	0.10	0.005	0.008
PES-INJ2	31-May-00	11.0 - 21.0	0.0013	4.48E-07	0.009	0.10	0.005	0.023
	31-Mar-00	11.0 - 21.0	0.0011	3.81E-07	0.008	0.10	0.005	0.020
Average for PES-INJ2			0.0012	4.15E-07	0.009	0.10	0.005	0.021
PES-INJ3	01-Jun-00	11.0 - 21.0	0.0007	2.37E-07	0.005	0.10	0.005	0.012
PES-INJ5	15-Dec-00	12.0 - 22.0	0.0300	1.06E-05	0.224	0.10	0.005	0.548
	15-Dec-00	12.0 - 22.0	0.0336	1.19E-05	0.251	0.10	0.005	0.613
Average for PES-INJ5			0.0318	1.12E-05	0.238	0.10	0.005	0.580
PES-INJ9	14-Dec-00	12.0 - 22.0	0.0350	1.24E-05	0.262	0.10	0.005	0.639
	10-Dec-00	12.0 - 22.0	0.0467	1.65E-05	0.349	0.10	0.005	0.852
Average for PES-INJ9			0.0408	1.44E-05	0.305	0.10	0.005	0.745

^{a/} ft bgs = feet below ground surface.

^{b/} ft/day = feet per day.

^{c/} cm/sec = centimeters per second.

^{d/} gpd/ft² = gallons per day per square foot.

^{e/} ft/ft = foot per foot.

^{f/} ft/yr = foot per year.

4.2 PRE-INJECTION EXTENT OF CHLORINATED ALIPHATIC HYDROCARBONS

Analytical results for chlorinated compounds are summarized in Table 4.3. Laboratory analytical results are included in Appendix A. The chlorinated compound detected in groundwater with the highest concentration during the Phase II baseline sampling event (September 2000) was VC at a concentration of 18,000 µg/L at location PES-MW1. The highest concentration in groundwater of TCE (1,700 µg/L) and *cis*-1,2-DCE (13,000 µg/L) also were at location PES-MW1. Lower concentrations of PCE; 1,1-DCE; *trans*-1,2-DCE; 1,1-DCA; chlorobenzene; and chloroethane were also detected during the baseline sampling event.

The distributions of TCE, *cis*-1,2-DCE, and VC in groundwater from April 2000 (pre-Phase I injection), September 2000, and December 2000 are shown on Figures 4.5 through 4.7, respectively. The September 2000 event was a combination of Phase I monitoring and Phase II baseline sampling, and therefore was the most extensive sampling event. In September 2000, the highest concentrations generally occurred along a narrow area from PES-INJ18 to PES-INJ24. An area of lower concentration occurred directly downgradient from PES-INJ3, a Phase I injection point. This area of lower concentration within the TCE plume suggests that reductive dechlorination has occurred as a result of the Phase I injection. Elevated concentrations of *cis*-1,2-DCE and VC also indicate that reductive dechlorination of PCE and TCE has occurred within the central core of the solvent plume. In general, the highest concentrations were detected along the axis of the monitoring point network, suggesting that Phase II injection and monitoring points were appropriately placed.

4.3 POST-INJECTION PROFILE OF CHLORINATED ALIPHATIC HYDROCARBONS

The first step for evaluating the enhancement of CAH biodegradation is to look at changes in the distribution of contaminants and biodegradation products. Analysis of temporal changes in contaminant concentrations may indicate field-scale contaminant mass loss as a result of biodegradation. Because reductive dechlorination of chlorinated ethenes is a sequential process, changes in the mass fraction of chlorinated ethenes also is an indication that biodegradation is occurring.

4.3.1 Chlorinated Ethenes Over Time

Phase II process monitoring consisted of a single sampling event in September 2001. Concentrations of TCE, *cis*-1,2-DCE, and VC in September 2001 are shown on Figure 4.8. In September 2001, the maximum concentration of TCE was 1,800 µg/L at location PES-MW6, similar to the maximum concentration of TCE (1,700 µg/L at location PES-MW1) measured during the Phase II baseline sampling event in September 2000. Maximum concentrations of *cis*-1,2-DCE (5,300 µg/L at location PES-MW1) and VC (4,800 µg/L at location PES-MW1) were two to three times lower than the maximum concentrations observed in September 2000.

Concentration-versus-time data for chlorinated ethenes from Phase I and Phase II sampling events were examined to assess whether or not trends in chlorinated ethene

TABLE 4.3
CHLORINATED ALIPHATIC HYDROCARBONS IN GROUNDWATER
SITE SS015
TRAVIS AFB, CALIFORNIA

Sample Location	Sample Date	PCE ^{a/} (µg/L) ^{b/}	TCE ^{a/} (µg/L)	1,1-DCE ^{a/} (µg/L)	<i>cis</i> -1,2-DCE (µg/L)	<i>trans</i> -1,2-DCE (µg/L)	VC ^{a/} (µg/L)	1,1-DCA ^{a/} (µg/L)	1,2-DCA (µg/L)	Chlorobenzene (µg/L)	1,2-DCB ^{a/} (µg/L)	1,4-DCB (µg/L)	Chloroethane (µg/L)
Monitoring Wells													
MW-216	29-Apr-00	37	190	<1.0	63	2.0	<2.5	<1.0	<1.0	2.0	<1.0	<1.0	<2.5
	22-Sep-00	160	610	<5.0	190	5.1	6.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	14-Dec-00	130	340	<5.0	160	6.3	1.3J	<5.0	<5.0	4.0J ^{d/}	<5.0	<5.0	<5.0
	13-Sep-01	120	430	<5.0	170	5.9	4.8J	<5.0	<5.0	6.5	<5.0	<5.0	<5.0
MW-216 (DUP ^{c/})	13-Sep-01	120	420	<5.0	170	5.8	4.7J	<5.0	<5.0	6.6	<5.0	<5.0	<5.0
Monitoring Points													
PES-MW1	26-Apr-00	300	2,500	<50	13,000	450	17,000	<1.0	<50	100	3.0	1.0	<2.5
PES-MW1 (DUP)	29-Apr-00	200	1,900	18	11,000	450	13,000	18	<50	100	2.0	<1.0	<2.5
	22-Sep-00	280	1,700	31	14,000	520	18,000	<5.0	<5.0	120	<5.0	<5.0	26
	14-Dec-00	57	590	9.7	4,000	200	2,800	2.8J	<5.0	50	<5.0	<5.0	33
	13-Sep-01	80	990	9.7	5,300	170	4,800	2.0J	<5.0	46	<5.0	<5.0	40
PES-MW2	29-Apr-00	200	460	<1.0	700	29	240	<1.0	<1.0	2.0	<1.0	<1.0	<2.5
	23-Sep-00	230	1,000	5.3	3,500	140	1,300	<5.0	<5.0	14	<5.0	<5.0	5.6
	14-Dec-00	120	600	2.6J	2,100	71	390	<5.0	<5.0	8.1	<5.0	<5.0	2.6J
	14-Sep-01	190	1,100	4.3J	4,600	180	2,800	1.2J	<5.0	17	<5.0	<5.0	6.4
PES-MW3	29-Apr-00	<1.0	880	1.0	310	4.0	6.0	<1.0	<1.0	2.0	<1.0	<1.0	<2.5
	22-Sep-00	160	1,300	<5.0	870	14	7.0	<5.0	<5.0	8.0	<5.0	<5.0	<5.0
	14-Dec-00	120	1,000	1.6J	600	6.6	2.6J	1.4J	<5.0	5.9	<5.0	<5.0	<5.0
	13-Sep-01	12	200	1.2J	390	22	8.8	1.3J	<5.0	6.2	<5.0	<5.0	<5.0
PES-MW4	29-Apr-00	440	1,500	2	690	12	41	1.0	<1.0	6.0	<1.0	<1.0	<2.5
	22-Sep-00	250	1,000	<5.0	2,600	36	90	<5.0	<5.0	12	<5.0	<5.0	<5.0
	14-Dec-00	120	830	2.0J	1,500	17	20	1.0J	<5.0	7.6	<5.0	<5.0	<5.0
	14-Sep-01	5.2	45	1.0J	670	8.6	2,100	1.0J	<5.0	1.0J	<5.0	<5.0	<5.0
PES-MW5	21-Sep-00	120	590	<5.0	700	6.6	8.1	<5.0	<5.0	28.0	<5.0	<5.0	<5.0
	13-Sep-01	41	410	<5.0	510	4.3J	7.9	1.4J	<5.0	14.0	<5.0	<5.0	<5.0
PES-MW6	29-Apr-00	1,000	4,200	8.0	3,600	40	100	4.0	<1.0	45	<1.0	<1.0	<2.5
	22-Sep-00	93	700	6.9	570	95	120	<5.0	<5.0	27	<5.0	<5.0	<5.0
	14-Dec-00	280	2,500	4.6J	3,200	53	65	2.3J	<5.0	28	<5.0	<5.0	1.4J
	13-Sep-01	56	1,800	3.0J	2,500	240	78	1.4J	<5.0	8.9	<5.0	<5.0	<5.0
PES-MW7	28-Apr-00	60	600	1.0	11,000	12	48	1.0	<1.0	5.0	<1.0	<1.0	<2.5
	23-Sep-00	<5.0	270	<5.0	1,900	25	210	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	14-Dec-00	47	130	3.7J	1,500	27	100	1.7J	<5.0	5.4	<5.0	<5.0	1.7J
	14-Sep-01	9.8	78	<5.0	670	4.2J	120	<5.0	<5.0	<5.0	<5.0	<5.0	6.4
PES-MW8	22-Sep-00	28	380	<5.0	930	21	150	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	13-Sep-01	3.6J	35	<5.0	480	8.6	260	<5.0	<5.0	2.3J	<5.0	<5.0	<5.0
PES-MW9	22-Sep-00	540	1,200	<5.0	320	9.1	5.8	<5.0	<5.0	5.6	<5.0	<5.0	<5.0
	12-Sep-01	250	760	1.2J	210	4.6J	5.7	<5.0	<5.0	5.9	<5.0	<5.0	<5.0
PES-MW10	21-Sep-00	<5.0	6.0	<5.0	9.5	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0

TABLE 4.3 (Continued)
CHLORINATED ALIPHATIC HYDROCARBONS IN GROUNDWATER
SITE SS015
TRAVIS AFB, CALIFORNIA

Sample Location	Sample Date	PCE ^{a/} (µg/L) ^{b/}	TCE ^{a/} (µg/L)	1,1-DCE ^{a/} (µg/L)	<i>cis</i> -1,2-DCE (µg/L)	<i>trans</i> -1,2-DCE (µg/L)	VC ^{a/} (µg/L)	1,1-DCA ^{a/} (µg/L)	1,2-DCA (µg/L)	Chlorobenzene (µg/L)	1,2-DCB ^{a/} (µg/L)	1,4-DCB (µg/L)	Chloroethane (µg/L)
PES-MW11	21-Sep-00	<500	550	<5.0	110	25	17	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	13-Sep-01	120	330	2.1J	88	20	24	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW12	21-Sep-00	46	73	<5.0	15	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW13	21-Sep-00	96	300	<5.0	64	13	8.2	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW14	21-Sep-00	64	51	<5.0	240	34	8.9	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW15	23-Sep-00	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW16	21-Sep-00	25	140	<5.0	70	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW16(DUP)	21-Sep-00	26	140	<5.0	73	<5.0	<5.0	<5.0	c	<5.0	<5.0	<5.0	<5.0
Injection Points													
PES-INJ1	29-Apr-00	84	880	<1.0	920	10	47	<1.0	<1.0	5	<1.0	<1.0	<2.5
	14-Dec-00	290	1,200	3.9J	1,700	24	40	1.0J	<5.0	9.5	<5.0	<5.0	<5.0
	Oil 14-Dec-00	860	3,500	<500	8,900	130J	<500	<500	<500	170J	<500	<500	<500
	Oil 14-Sep-01	1,300J	3,700J	<4,900	6,400	<4,900	<4,900	<4,900	<4,900	<4,900	<4,900	<4,900	<4,900
PES-INJ2	29-Apr-00	130	950	3.0	22,000	50	500	<1.0	<1.0	20	<1.0	<1.0	4.0
PES-INJ3	29-Apr-00	50	360	<1.0	620	7.0	43	<1.0	<1.0	2.0	<1.0	<1.0	<2.5
	22-Sep-00	<250	970	<250	1,600	<250	<250	<250	<250	<250	<250	<250	<250
	Oil 22-Sep-00	<2,500	6,000	<2,500	8,800	<2,500	<2,500	<2,500	<2,500	<2,500	<2,500	<2,500	<2,500
	14-Dec-00	7.1	100	<5.0	460	7.7	59	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	Oil 14-Dec-00	900	4,200	<500	6,900	140J	<500	<500	<500	<500	<500	<500	<500
	14-Sep-01	22	180	2.2J	320	21	230	1.4J	<5.0	8.7	<5.0	<5.0	<5.0
PES-INJ18	22-Sep-00	530	2,500	8.0	4,100	260	390	<5.0	<5.0	28	<5.0	<5.0	<5.0
PES-INJ24	21-Sep-00	190	1,300	<5.0	310	13	6.5	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0

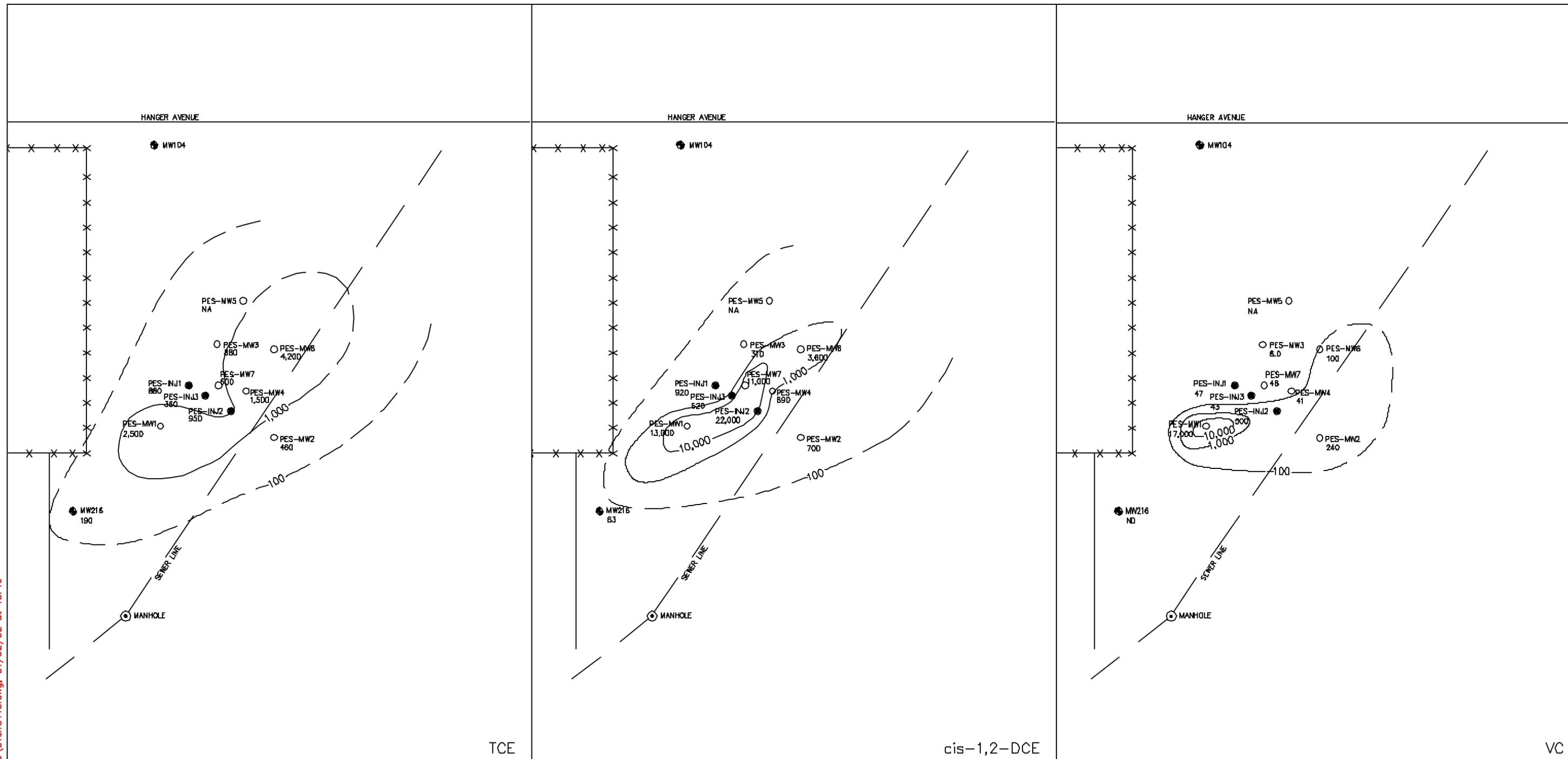
^{a/} PCE = tetrachloroethene, TCE = trichloroethene, DCE = dichloroethene, VC = vinyl chloride, TCA = trichloroethane, DCA = dichloroethane, and DCB=dichlorobenzene

^{b/} µg/L = micrograms per liter.

^{c/} DUP = field duplicate of preceding sample.

^{d/} J-flag indicates the concentration is estimated.

S:\ES\Remed\736116\050000\report\Phase 2 CAD\01dn0413.dwg, 01/02/02 at 10:46



LEGEND

PES-INJ3 ●	VEGETABLE OIL INJECTION POINT	4,200	CONCENTRATION IN MICROGRAMS PER LITER ($\mu\text{g/L}$)
PES-MW1 ○	GROUNDWATER MONITORING POINT	NA	NOT ANALYZED
MW216 ●	GROUNDWATER MONITORING WELL	ND	NOT DETECTED
—x—x—	CHAIN LINK FENCE		
—100—	LINE OF EQUAL CONCENTRATION ($\mu\text{g/L}$) (DASHED WHERE INFERRED)		

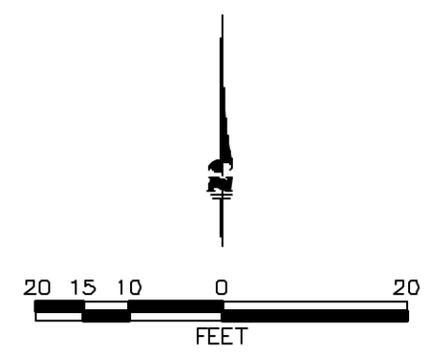
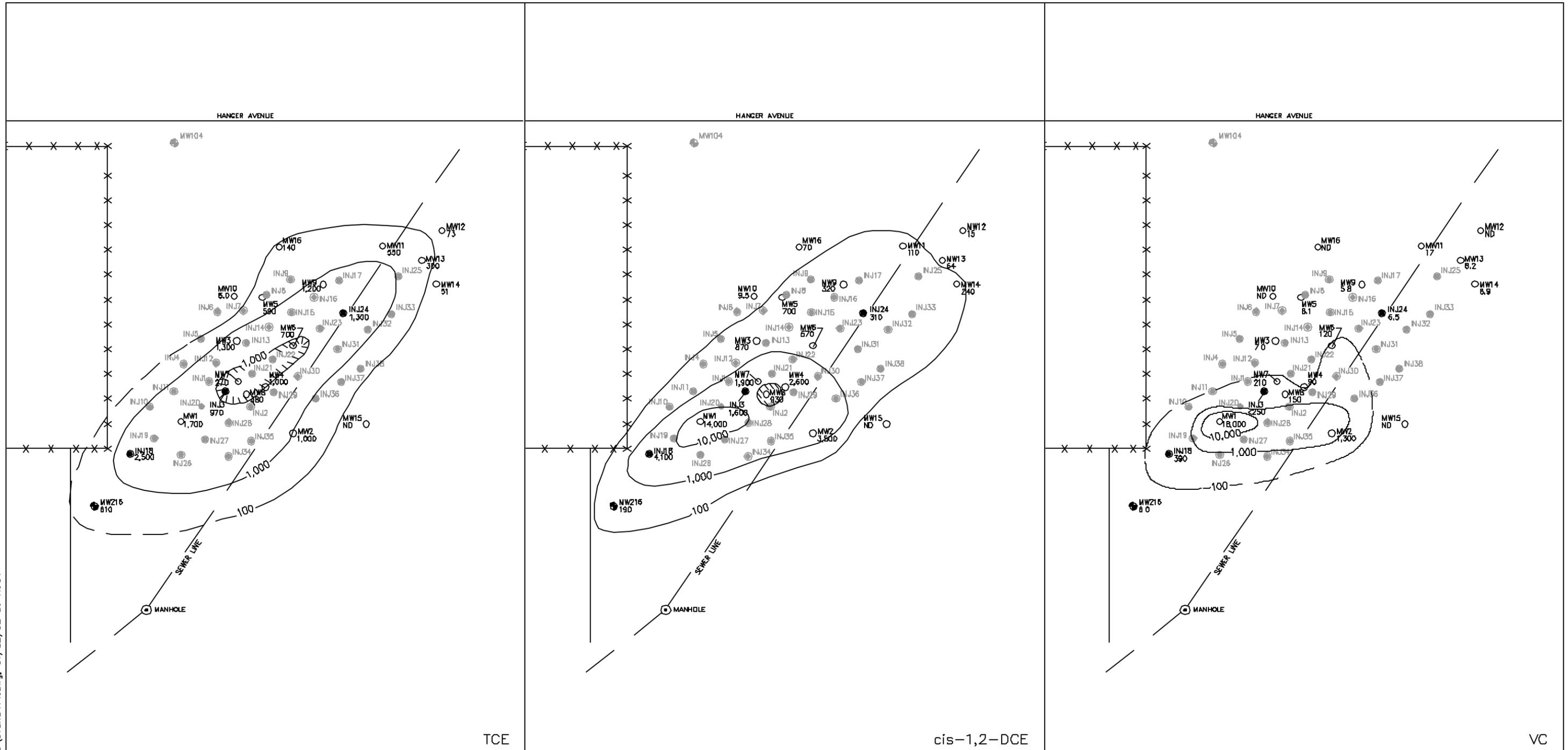


FIGURE 4.5
TCE, cis-1,2-DCE, AND VC
IN GROUNDWATER
APRIL 2000

Site SS015
Travis Air Force Base, California



Denver, Colorado



LEGEND

- | | | | | |
|-------|---|-------------------------------|-----|--|
| INJ3 | ● | VEGETABLE OIL INJECTION POINT | 150 | CONCENTRATION IN MICROGRAMS PER LITER (µg/L) |
| MW1 | ○ | GROUNDWATER MONITORING POINT | NA | NOT ANALYZED |
| MW6 | ⊕ | GROUNDWATER MONITORING WELL | ND | NOT DETECTED |
| —x—x— | | CHAIN LINK FENCE | | |
| | | —100— | | LINE OF EQUAL CONCENTRATION (µg/L) (DASHED WHERE INFERRED) |

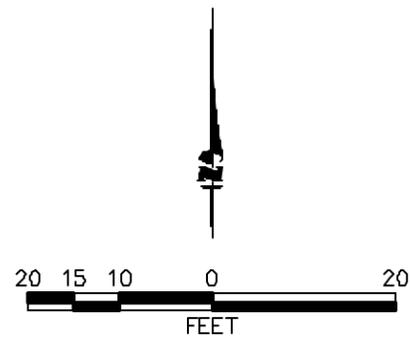


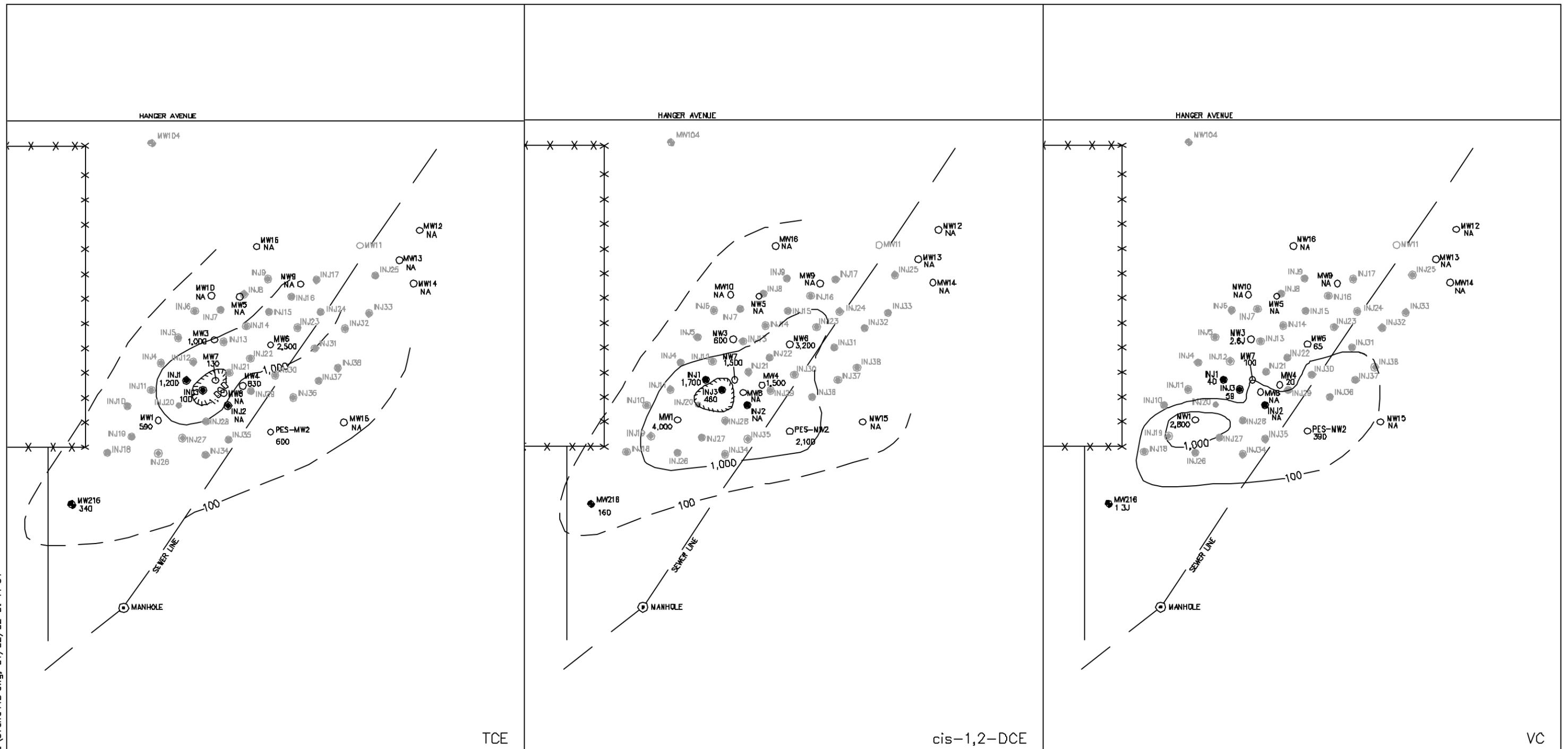
FIGURE 4.6
TCE, cis-1,2-DCE, AND VC
IN GROUNDWATER
SEPTEMBER 2000

Site SS015
Travis Air Force Base, California

PARSONS
PARSONS ENGINEERING SCIENCE, INC.

Denver, Colorado

S:\ES\Remed\736116\05000\report\Phase 2 CAD\01.dwg, D1/02/02 at 11:31



LEGEND

PES-INJ3 ●	VEGETABLE OIL INJECTION POINT	4,200	CONCENTRATION IN MICROGRAMS PER LITER (µg/L)
PES-MW1 ○	GROUNDWATER MONITORING POINT	NA	NOT ANALYZED
MW216 ●	GROUNDWATER MONITORING WELL	ND	NOT DETECTED
—x—x—	CHAIN LINK FENCE		
—100—	LINE OF EQUAL CONCENTRATION (µg/L)		(DASHED WHERE INFERRED)

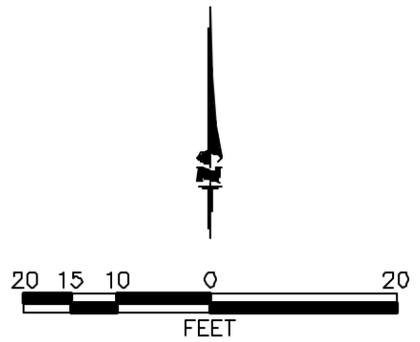


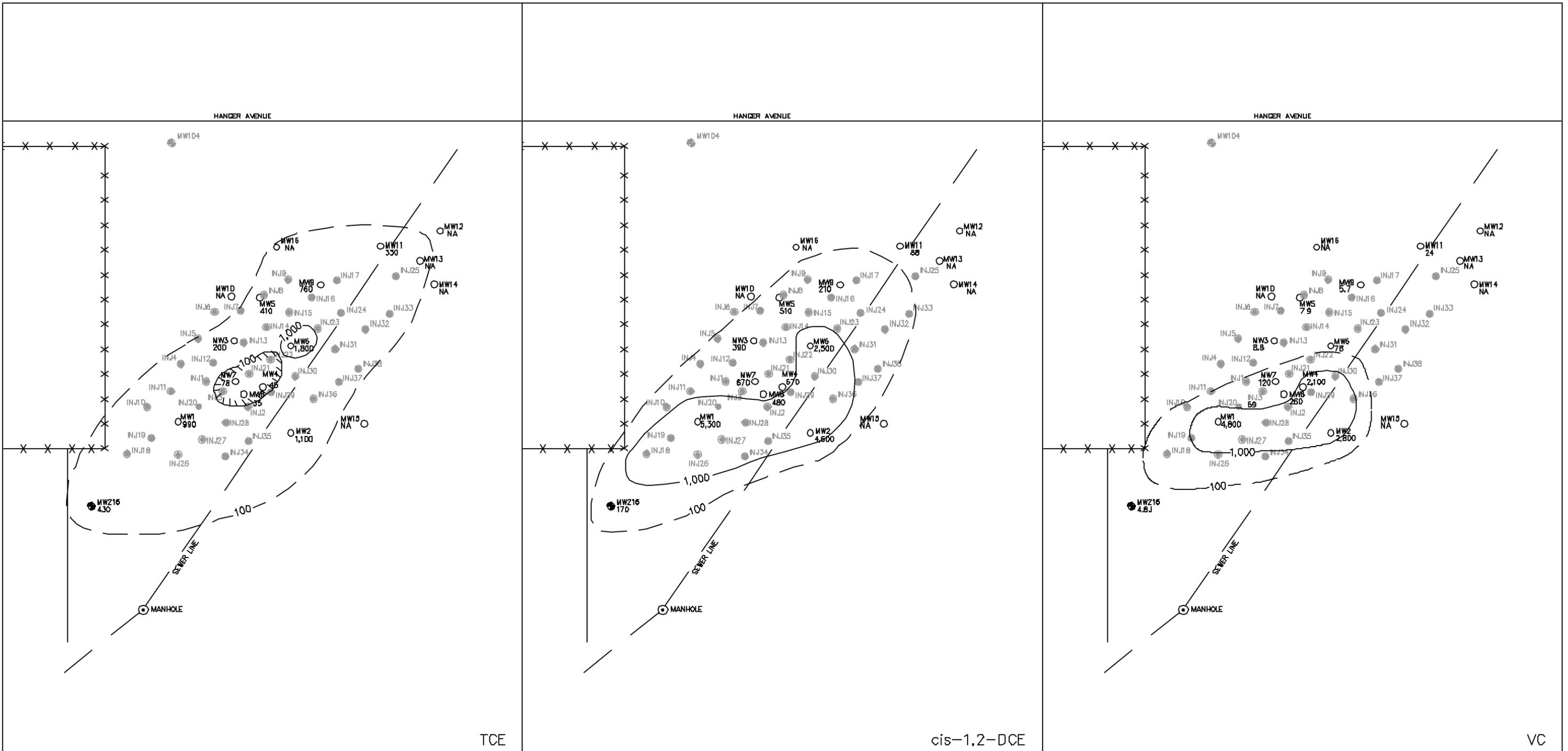
FIGURE 4.7
TCE, cis-1,2-DCE, AND VC
IN GROUNDWATER
DECEMBER 2000

Site SS015
Travis Air Force Base, California

PARSONS
PARSONS ENGINEERING SCIENCE, INC.

Denver, Colorado

S:\ES\Remed\736116\05000\report\Phase 2 CAD\01.dwg.0416.dwg. 01/03/02 at 08:48



LEGEND

- | | | | | |
|-------|---|--|-----|--|
| INJ3 | ● | VEGETABLE OIL INJECTION POINT | 150 | CONCENTRATION IN MICROGRAMS PER LITER (µg/L) |
| MW1 | ○ | GROUNDWATER MONITORING POINT | NA | NOT ANALYZED |
| MW6 | ⊕ | GROUNDWATER MONITORING WELL | ND | NOT DETECTED |
| —x—x— | | CHAIN LINK FENCE | | |
| —100— | | LINE OF EQUAL CONCENTRATION (µg/L) [DASHED WHERE INFERRED] | | |

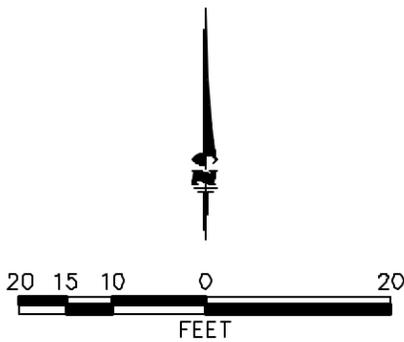


FIGURE 4.8
TCE, cis-1,2-DCE, AND VC
IN GROUNDWATER
SEPTEMBER 2001

Site SS015
Travis Air Force Base, California

PARSONS
PARSONS ENGINEERING SCIENCE, INC.

Denver, Colorado

concentrations are apparent. Concentrations of TCE over time are plotted on Figure 4.9. TCE concentrations from April 2000 to September 2001 all show an overall reduction, with the exception of upgradient well MW216 and downgradient monitoring point PES-MW2. Locations within the radius of influence of the injected vegetable oil show a lower TCE concentration than locations outside the radius of influence (Figures 4.6 through 4.8). This area of lower TCE concentration within the plume core near the injection points suggests that the Phase I and Phase II vegetable oil injections have had an impact on reducing aqueous-phase TCE concentrations at the site.

Trends in concentration for *cis*-1,2-DCE and VC are less apparent, likely due to the fact that these compounds are produced as a result of degradation of more highly chlorinated ethenes. From April 2000 to September 2001, the maximum concentration of *cis*-1,2-DCE in groundwater decreased from 22,000 µg/L at injection point PES-INJ2 to 5,300 µg/L at monitoring point PES-MW1. Similar to the TCE plume, the *cis*-1,2-DCE plume exhibits an area of lower concentrations near the center of the injection points (Figures 4.6 through 4.8). Similarly, from April 2000 to September 2001, the maximum concentration of VC decreased from 17,000 µg/L to 4,800 µg/L at location PES-MW1.

In summary, while trends in chlorinated ethene concentrations tended to vary from sampling event to sampling event, chlorinated ethene data indicate an overall reduction of maximum contaminant concentrations. Based on contaminant trend analysis alone, it is difficult to determine whether this reduction is due to biodegradation, partitioning of dissolved contaminants into the vegetable oil NAPL, lateral spreading of contaminants due to injection, or natural temporal variations in contaminant concentrations. Injection of vegetable oil (both Phase I and Phase II) induced a mounding of the groundwater potentiometric surface, which may have caused some lateral spreading of contaminants in groundwater. In addition to this transient effect resulting from the injections, historical concentration data from upgradient well MW-216 show natural fluctuation in chlorinated ethene concentrations. As a result, strict interpretation of concentration trends may not be the best indicator of enhanced biodegradation at the site. Other supporting evidence of enhanced biodegradation, including molar ratios of parent and daughter products and geochemical changes, are discussed in the following sub-sections.

4.3.2 Presence of Daughter Products and CAH Ratios

The presence of daughter products that were not used in Base operations, particularly *cis*-1,2-DCE, VC, and ethene provides strong evidence that PCE and TCE are being reductively dechlorinated. Progressive transformation of PCE to ethene can be indicated by computing the molar ratio of parent compounds to daughter products at a specific location. For example, because reductive dechlorination proceeds in only one direction (i.e., TCE to *cis*-1,2-DCE and not vice versa), the molar ratio of TCE to *cis*-1,2-DCE would decrease where reductive dechlorination of TCE dominates the contaminant attenuation process. Chlorinated ethene concentrations and molar fractions over time for all locations sampled in September 2001 are included in Appendix C. The following discussion includes an evaluation of data for select monitoring locations at the site.

Chlorinated ethene concentrations and molar fractions over time at upgradient well MW-216 are shown on Figure 4.10. Temporal concentrations of PCE, TCE, *cis*-1,2-DCE, and VC generally exhibit similar trends. Molar fractions of these compounds were

FIGURE 4.9
CONCENTRATIONS OF TRICHLOROETHENE OVER TIME
SITE SS-015
TRAVIS AFB, CALIFORNIA

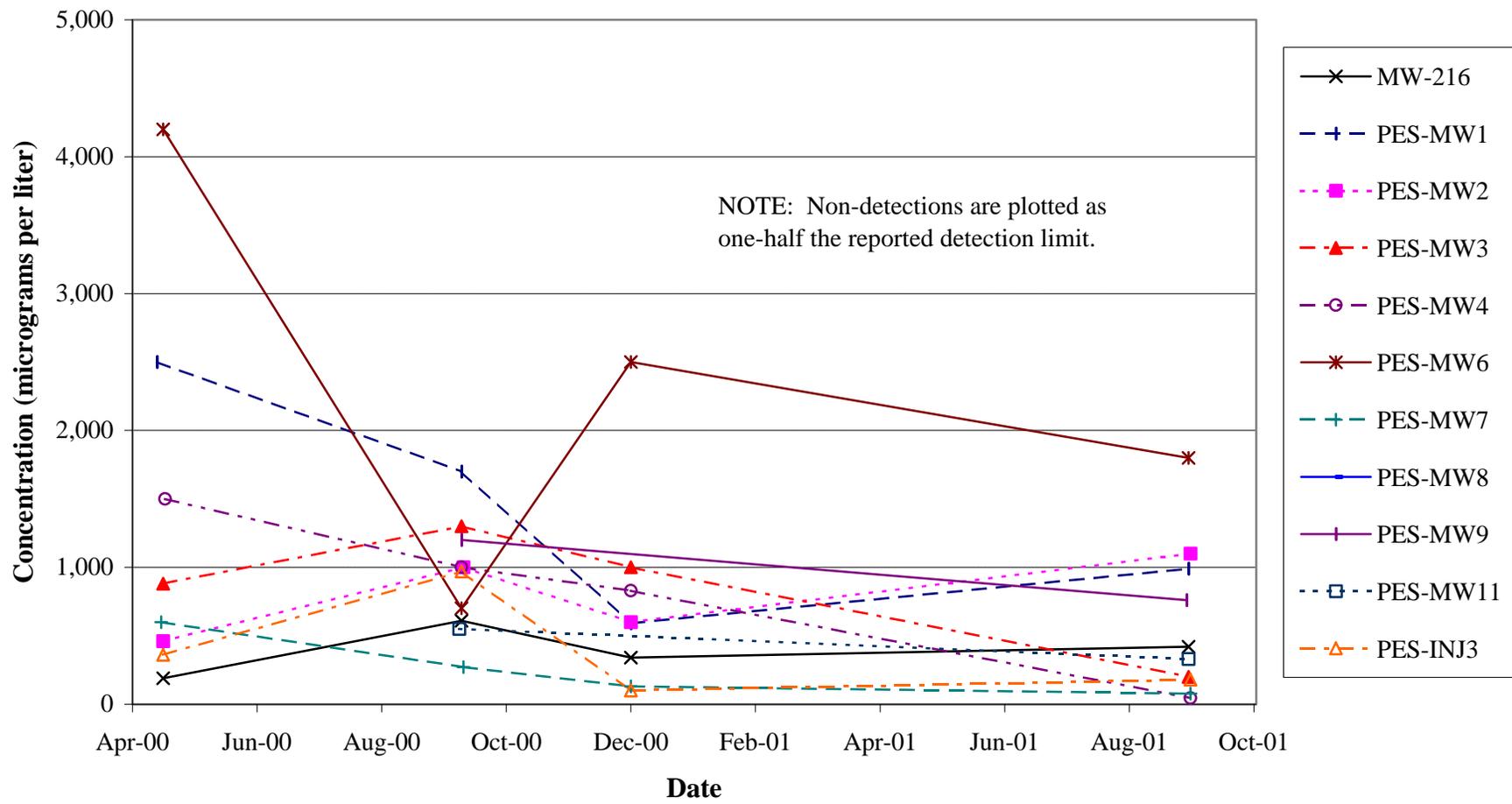


FIGURE 4.10A
CONCENTRATIONS OF CHLORINATED ETHENES
AT UPGRADIENT WELL MW-216
SITE SS-015
TRAVIS AFB, CALIFORNIA

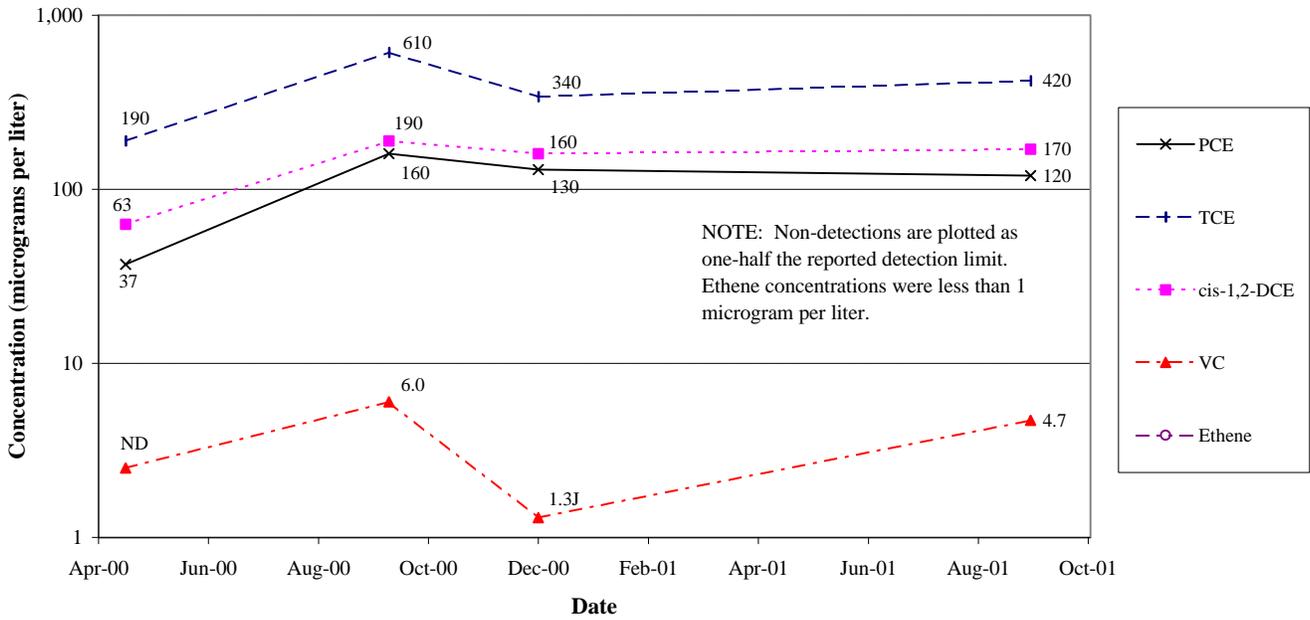
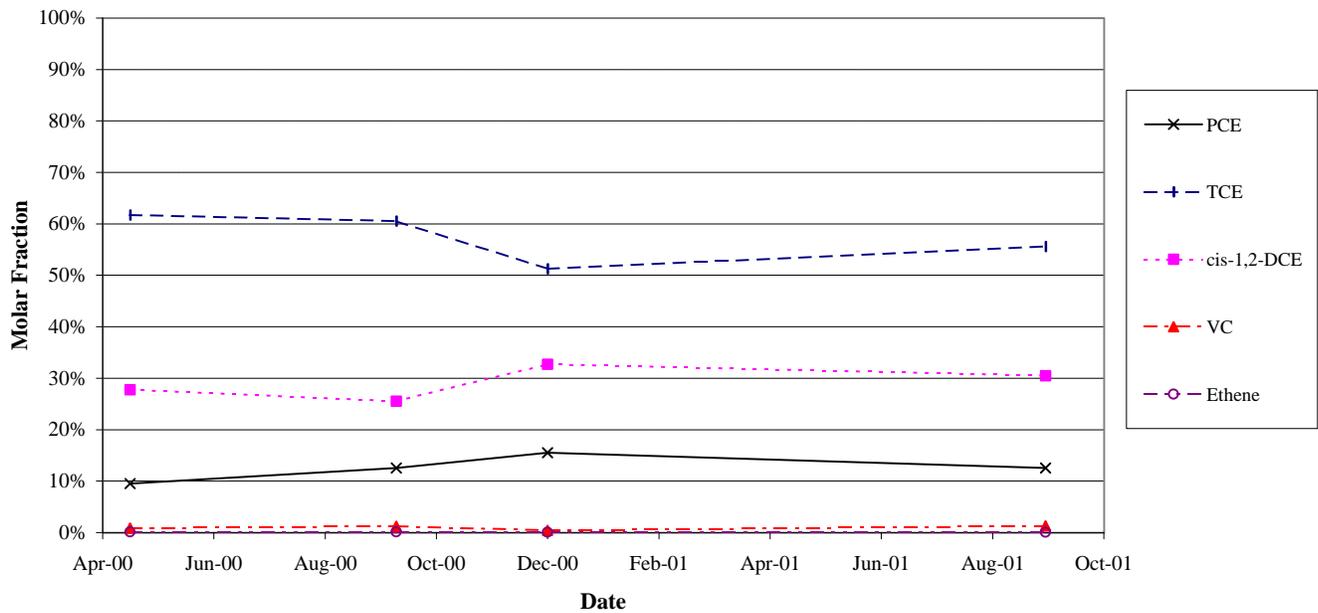


FIGURE 4.10B
MOLAR FRACTIONS OF CHLORINATED ETHENES
AT UPGRADIENT WELL MW-216
SITE SS-015
TRAVIS AFB, CALIFORNIA



relatively stable from April to September 2000, indicating that a significant transformation of any one compound relative to another did not occur. From September to December 2000, a slight decrease in the molar fraction of TCE and a slight increase in the molar fraction of *cis*-1,2-DCE suggests that some transformation of TCE to *cis*-1,2-DCE occurred. From December 2000 to September 2001, molar fractions of all compounds remain relatively constant, with a slight increase in the molar fraction of TCE and a slight decrease in the molar fraction of *cis*-1,2-DCE. As expected at this upgradient location, there is little to suggest that biodegradation has been enhanced.

Within the treatment zone, trends of chlorinated ethene concentrations and molar fractions over time for monitoring point PES-MW4 show all the trends expected of reductive dechlorination (Figure 4.11). Most noticeably, concentrations of PCE and TCE have decreased consistently for each sampling event. PCE decreased from 440 µg/L in April 2000 to 5.2 µg/L in September 2001, a decrease of 98.8 percent. Likewise, TCE decreased from 1,500 µg/L in April 2000 to 45 µg/L in September 2001, a decrease of 97 percent. Concentrations of *cis*-1,2-DCE first increased from 690 µg/L in April 2000 to 2,600 µg/L in September 2000, likely due to degradation of TCE. However, as TCE and PCE were depleted after September 2000, the generation of *cis*-1,2-DCE was exceeded its degradation to VC. Concentrations of *cis*-1,2-DCE decreased to 670 µg/L in September 2001, while concentrations of VC increased from less than 100 µg/L to 2,100 µg/L in September 2001. Evidence that dechlorination is proceeding to completion is indicated by an increase in the concentrations of ethene from less than 1 µg/L in December 2000 to 29 µg/L in September 2001.

Trends in molar fractions for location PES-MW4 (Figure 4.11) also reflect substantial reductive dechlorination. As PCE and TCE are degraded, the respective molar fractions for these compounds decreases. The molar fraction of *cis*-1,2-DCE first increased as TCE was dechlorinated to *cis*-1,2-DCE. However, once the mass (i.e., moles) of PCE and TCE were depleted relative to *cis*-1,2-DCE, the molar fraction of *cis*-1,2-DCE decreased as the moles of *cis*-1,2-DCE degraded to VC exceeded that of TCE degraded to *cis*-1,2-DCE. At the same time, the VC molar fraction is expected to increase as VC is the daughter product of *cis*-1,2-DCE degradation. This is prominently shown in Figure 4.11B, as the molar fraction of VC dramatically increased from December 2000 to September 2001. As VC also is degraded, ethene is produced and an increase in both concentration and molar fraction of ethene was observed from December 2000 to September 2001. Clearly, reductive dechlorination has been stimulated at location PES-MW4 by both the Phase I and Phase II injections.

Chlorinated ethene concentrations and molar fractions over time for injection area monitoring point PES-MW3 are shown on Figure 4.12. From April to September 2000, all chlorinated ethene concentrations increased while ethene decreased. This increase in concentrations may be a result of natural variation or due to displacement of groundwater due to the Phase I injection as discussed earlier. However, from September 2000 to September 2001 all chlorinated ethene concentrations decreased, with the exception of VC which remained relatively stable. Molar fractions for TCE and *cis*-1,2-DCE exhibit decreasing and increasing trends during this time period, respectively. This suggests that reductive dechlorination of TCE to *cis*-1,2-DCE occurred, although at a slower rate than observed at location PES-MW4. In the future, one might expect to see the molar fraction

FIGURE 4.11A
CONCENTRATIONS OF CHLORINATED ETHENES
AT PLUME CORE MONITORING POINT PES-MW4
SITE SS-015
TRAVIS AFB, CALIFORNIA

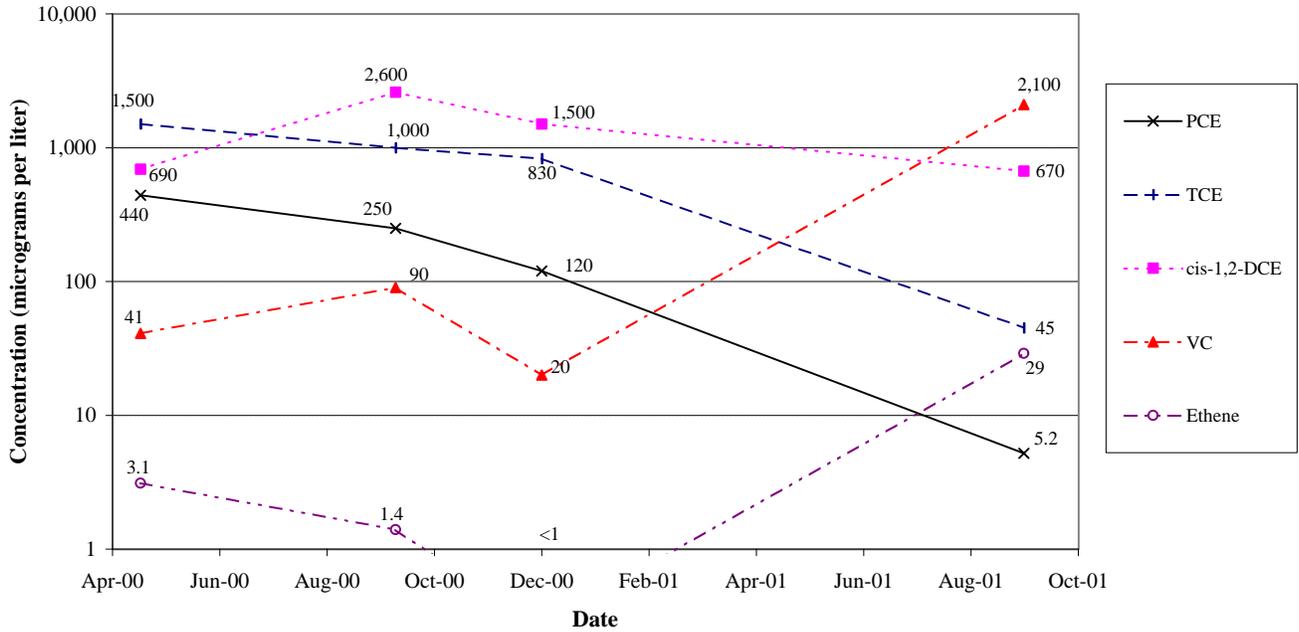


FIGURE 4.11B
MOLAR FRACTIONS OF CHLORINATED ETHENES
AT PLUME CORE MONITORING POINT PES-MW4
SITE SS-015
TRAVIS AFB, CALIFORNIA

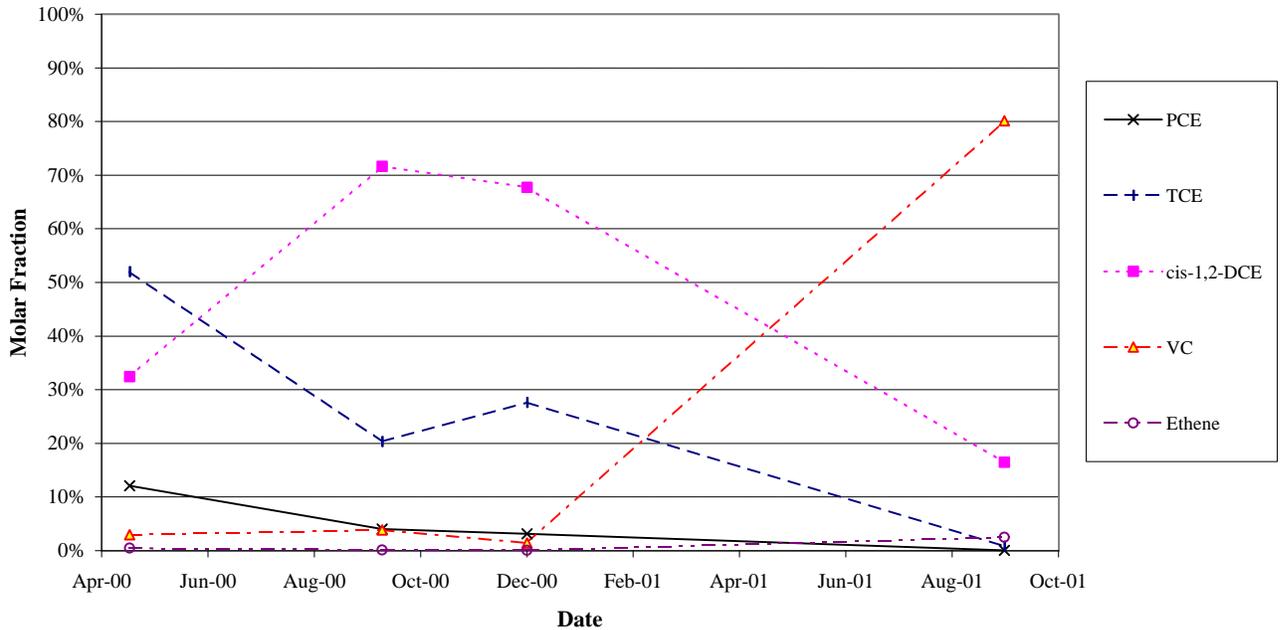
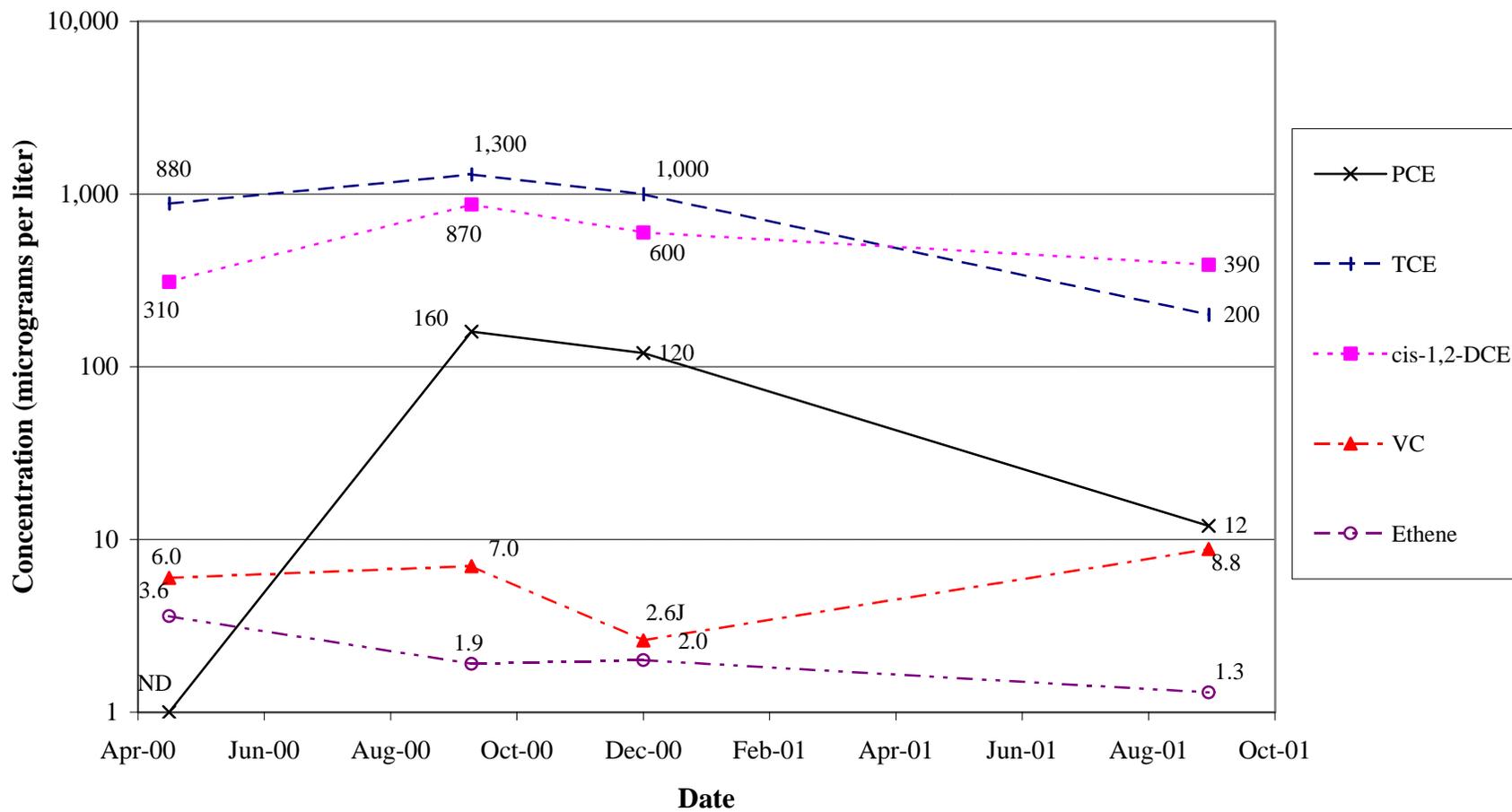


FIGURE 4.12A
CONCENTRATIONS OF CHLORINATED ETHENES
AT MONITORING POINT PES-MW3
SITE SS-015
TRAVIS AFB, CALIFORNIA



of VC continue to increase as TCE is depleted and *cis*-1,2-DCE is further degraded to VC.

Other monitoring locations that also show evidence of reductive dechlorination include PES-MW2, PES-MW6, PES-MW7, PES-MW8, PES-MW9 and PES-INJ3 (Appendix C), but not to the extent observed at location PES-MW4. Significant increases in ethene concentrations from December 2000 to September 2001 were observed (in addition to PES-MW4) at PES-MW2 (from 1.4 µg/L to 11 µg/L), PES-MW7 (from 2.0 µg/L to 23 µg/L), and PES-MW8 (from 3.1 µg/L to 24 µg/L). This suggests that a limited amount of reductive dechlorination at Site SS015 has proceeded to completion.

In summary, trends in chlorinated ethene concentrations and molar fractions indicate that reductive dechlorination has been stimulated at the site by both the Phase I and Phase II injections. Transformation of PCE to TCE and TCE to *cis*-1,2-DCE appear to be the most common and consistent reduction steps, but that *cis*-1,2-DCE and VC also are being degraded. An overall decrease in chlorinated ethene concentrations is occurring across the site. While partitioning of chlorinated ethenes into the vegetable oil NAPL may account for some reduction in aqueous-phase concentrations, molar fraction data indicate that a significant amount of contaminant reduction is due to reductive dechlorination.

4.3.3 Chlorinated Aliphatic Hydrocarbons In Oil

In addition to CAHs in groundwater, CAH concentrations in oil also were analyzed for in samples collected from location PES-INJ1 (December 2000 and September 2001) and PES-INJ3 (September 2000 and December 2000) (Table 4.3). The maximum concentration of PCE in oil was 1,300J µg/L (estimated concentration) at location PES-INJ1 in September 2001, and the maximum concentration of TCE in oil was 6,000 µg/L at location PES-INJ1 in September 2000. The maximum concentration of *cis*-1,2-DCE in oil was 8,900 µg/L at location PES-INJ1 in December 2000, while VC was not detected above laboratory reporting limits. These elevated concentrations of CAHs in vegetable oil purged from the Phase I injection points indicates that partitioning from groundwater into the oil occurred.

The concentrations of PCE, TCE, and *cis*-1,2-DCE in oil at injection points PES-INJ1 and PES-INJ3 are up to six times higher than those detected in the aqueous phase samples from the same location and time. This is expected, because CAHs have a greater affinity for dissolution into an oil phase than to the aqueous phase. While partitioning of CAHs from the aqueous phase into the oil phase appears to be significant and may account for some aqueous phase contaminant reduction, it should be noted that the total volume of oil injected (approximately 227 gallons) is several orders of magnitude less than the volume of groundwater in the Phase I and Phase II treatment zone (on the order of tens of thousands of gallons). Therefore, the actual mass of CAHs that partitions into the vegetable oil is less than that remaining in the aqueous phase. Once an initial aqueous- and oil-phase equilibrium is reached, CAHs are released from the oil to groundwater at a rate dependent upon dissolution and/or degradation of the vegetable oil, and degradation of contaminants in the dissolved phase. In any event, contaminants are released back to groundwater within a zone of adequate substrate and optimal conditions for reductive dechlorination.

4.4 GEOCHEMICAL RESULTS

In addition to the distribution of contaminants and daughter products, other evidence can be used to support the interpretation that enhanced biodegradation of chlorinated solvents is occurring. By comparing concentrations, distributions, and trends of electron donors, electron acceptors, and byproducts of microbially mediated reactions, the types of biodegradation processes operating at Site SS015 can be identified. Geochemical parameters, including redox potential, alkalinity, and other changes in groundwater chemistry also can provide supporting evidence of enhanced biodegradation.

4.4.1 Fuel Hydrocarbons as Electron Donors

Analytical results for fuel-related hydrocarbons are presented in Table 4.4. Fuel hydrocarbons detected at Site SS015 primarily consist of benzene, toluene, ethylbenzene, and xylenes (BTEX). Maximum concentrations of benzene (300 µg/L), toluene (100 µg/L), ethylbenzene (100 µg/L), and total xylenes (36 µg/L) were detected at monitoring point PES-MW1 over the period from April to September 2000. Concentrations of BTEX decreased at PES-MW1 in December 2000 and September 2001. Elevated concentrations of BTEX also were present at monitoring points PES-MW2 and PES-MW7, while all other monitoring locations had very low concentrations (less than 10 µg/L) of total BTEX. This suggests that only low-level, localized sources of fuel hydrocarbons are present at the site, particularly near monitoring point PES-MW1. The concentrations of BTEX present at PES-MW1 are likely sufficient to serve as an electron donor for reductive dechlorination, given the elevated concentrations of *cis*-1,2-DCE and VC detected at this location. Other fuel compounds detected at low concentrations (less than 10 µg/L) included trimethylbenzenes, naphthalene, isopropyl benzene, and *p*-isopropyltoluene.

4.4.2 Total Organic Carbon as an Indicator of Substrate Addition and Radius of Influence

Total organic carbon (TOC) in groundwater (unfiltered sample) was analyzed for during the September 2001 sampling event. Analytical results for TOC are presented in Table 4.5, and the distribution of TOC is shown on Figure 4.13. Background concentrations of TOC for locations MW216, PES-MW9 and PES-MW11 averaged 5 to 6 mg/L. Within the area of vegetable oil injection, concentrations of TOC in groundwater (free of visible vegetable oil) range from 8.7 mg/L to a maximum of 110 mg/L at PES-MW8. Therefore, the Phase I and Phase II oil injections have been successful in providing elevated levels of dissolved organic substrate to the aquifer.

Concentrations of bromide also were measured in select monitoring points in September and December 2000, and in all monitoring points sampled in September 2001 (Table 4.5 and Figure 4.13). Bromide was added to water used for the Phase I injection to trace the zone of influence of the injection on the aquifer body. Bromide was detected at concentrations above a detection limit of 0.10 mg/L at locations MW216 (2 mg/L), PES-MW6 (36 mg/L), PES-MW7 (8.8 mg/L), and PES-MW9 (2.1 mg/L). In December 2000, bromide was detected at locations PES-MW7 and PES-MW6, located approximately 5 and 15 feet from the Phase I injection points, respectively. In September 2001, lower concentrations of bromide were detected at locations MW216 and

TABLE 4.4
SUMMARY OF FUEL HYDROCARBONS IN GROUNDWATER
SITE SS015
TRAVIS AFB, CALIFORNIA

Sample Location	Sample Date	Benzene (µg/L) ^{c/}	Toluene (µg/L)	Ethyl-benzene (µg/L)	o-Xylene (µg/L)	m+p-Xylene (µg/L)	Total BTEX ^{d/} (µg/L)	1,3,5-TMB ^{b/} (µg/L)	1,2,4-TMB (µg/L)	Napthalene (µg/L)	Isopropyl-benzene (µg/L)	p-Isopropyl-toluene (µg/L)
Monitoring Wells												
MW-216	29-Apr-00	<1.0	<1.0	<1.0	<1.0	<2.0	ND ^{d/}	<1.0	<1.0	<1.0	<1.0	<1.0
	22-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
	14-Dec-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
	13-Sep-01	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
MW-216 (DUP ^{c/})	13-Sep-01	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
Monitoring Points												
PES-MW1	26-Apr-00	200	100	100	11	25	436	2.0	<1.0	1.0	3.0	2.0
PES-MW1 (DUP ^{d/})	28-Apr-00	150	50	100	9.0	20	329	1.0	<1.0	<1.0	<1.0	<1.0
	22-Sep-00	300	92	<5.0	10	19	421	<5.0	<5.0	<5.0	<5.0	<5.0
	14-Dec-00	88	10	<5.0	<5.0	2.3J	100	<5.0	<5.0	<5.0	<5.0	<5.0
	13-Sep-01	41	2.9J ^{d/}	<5.0	<5.0	1.0J	45	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW2	29-Apr-00	6.0	1.0	<1.0	<1.0	<2.0	7.0	<1.0	<1.0	<1.0	<1.0	<1.0
	23-Sep-00	25	<5.0	<5.0	<5.0	<10	25	<5.0	<5.0	<5.0	<5.0	<5.0
	14-Dec-00	14	<5.0	<5.0	<5.0	<10	14	<5.0	<5.0	<5.0	<5.0	<5.0
	14-Sep-01	26	1.2J	<5.0	<5.0	<10	27	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW3	29-Apr-00	1.0	3.0	<1.0	<1.0	<2.0	4.0	<1.0	<1.0	<1.0	<1.0	<1.0
	22-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
	14-Dec-00	2.1J	<5.0	<5.0	<5.0	<10	2.1J	<5.0	<5.0	<5.0	<5.0	<5.0
	13-Sep-01	1.9J	<5.0	<5.0	<5.0	<10	1.9J	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW4	29-Apr-00	2.0	2.0	<1.0	<1.0	<2.0	5.0	<1.0	<1.0	<1.0	<1.0	<1.0
	22-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
	14-Dec-00	2.1J	<5.0	<5.0	<5.0	<10	2.1J	<5.0	<5.0	<5.0	<5.0	<5.0
	14-Sep-01	1.0J	<5.0	<5.0	<5.0	<10	1.0J	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW5	21-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
	13-Sep-01	<5.0	<5.0	<5.0	<5.0	<11	ND	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW6	29-Apr-00	5.0	<1.0	<1.0	<1.0	<2.0	5.0	<1.0	<1.0	<1.0	<1.0	<1.0
	22-Sep-00	5.2	<5.0	<5.0	<5.0	<10	5.2	<5.0	<5.0	<5.0	<5.0	<5.0
	14-Dec-00	5.8	<5.0	<5.0	<5.0	<10	5.8	<5.0	<5.0	<5.0	<5.0	<5.0
	13-Sep-01	2.5J	1.1J	<5.0	<5.0	<10	3.6	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW7	28-Apr-00	2.0	72	2.0	3.0	5.0	84	<1.0	3.0	5.0	<1.0	<1.0
	23-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
	14-Dec-00	2.1J	3.3J	<5.0	<5.0	<10	6.4J	<5.0	<5.0	<5.0	<5.0	<5.0
	14-Sep-01	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0

TABLE 4.4 (Continued)
SUMMARY OF FUEL HYDROCARBONS IN GROUNDWATER
SITE SS015
TRAVIS AFB, CALIFORNIA

Sample Location	Sample Date	Benzene (µg/L) ^{c/}	Toluene (µg/L)	Ethylbenzene (µg/L)	o-Xylene (µg/L)	m+p-Xylene (µg/L)	Total BTEX ^{a/} (µg/L)	1,3,5-TMB ^{b/} (µg/L)	1,2,4-TMB (µg/L)	Napthalene (µg/L)	Isopropylbenzene (µg/L)	p-Isopropyltoluene (µg/L)
PES-MW8	22-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
	13-Sep-01	1.2J	<5.0	<5.0	<5.0	<10	1.2J	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW9	22-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
	12-Sep-01	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW10	21-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW11	21-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	7.8	<5.0
	13-Sep-01	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW12	21-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW13	21-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW14	21-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW15	23-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW16	21-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
PES-MW16 (DUP)	21-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
Injection Points												
PES-INJ1	26-Apr-00	3.0	8.0	<1.0	<1.0	<2.0	11	<1.0	<1.0	<1.0	<1.0	<1.0
	14-Dec-00	3.9J	2.7J	<5.0	<5.0	<10	6.6J	<5.0	<5.0	<5.0	<5.0	<5.0
	Oil	14-Dec-00	<500	<500	<500	<500	110J	110J	<500	<500	<500	<500
	Oil	14-Sep-01	<4900	<4900	<4900	<4900	<4900	<4900	<4900	<4900	<4900	<4900
PES-INJ2	27-Apr-00	12	1.0	<1.0	<1.0	<2.0	13	<1.0	<1.0	<1.0	<1.0	<1.0
PES-INJ3	29-Apr-00	2.0	<1.0	<1.0	<1.0	<2.0	2.0	<1.0	<1.0	<1.0	<1.0	<1.0
	22-Sep-00	<250	<250	<250	<250	<500	ND	<250	<250	<250	<250	<250
	Oil	22-Sep-00	<2500	<2500	<2500	<2500	<5000	ND	<2500	<2500	<2500	<2500
	14-Dec-00	1.0J	<5.0	<5.0	<5.0	<10	1.0J	<5.0	<5.0	<5.0	<5.0	<5.0
	Oil	14-Dec-00	<500	<500	<500	<500	<1,000	ND	<500	<500	<500	<500
	14-Sep-01	3.3J	2.3J	<5.0	<5.0	<10	5.6J	<5.0	<5.0	<5.0	<5.0	<5.0
PES-INJ18	22-Sep-00	6.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
PES-INJ24	21-Sep-00	<5.0	<5.0	<5.0	<5.0	<10	ND	<5.0	<5.0	<5.0	<5.0	<5.0
Quality Assurance/Quality Control Samples												
Trip Blank	26-Apr-00	<1.0	<1.0	<1.0	<1.0	<2.0	ND	<1.0	<1.0	<1.0	<1.0	<1.0

^{a/} Total Benzene, Toluene, Ethylbenzene, and Xylenes (BTEX).

^{b/} TMB = trimethylbenzene.

^{c/} µg/L = micrograms per liter.

^{d/} DUP = field duplicate of preceding sample.

^{e/} J-flag indicates the concentration is estimated.

TABLE 4.5
GROUNDWATER GEOCHEMICAL DATA
SITE SS015
TRAVIS AFB, CALIFORNIA

Sample Location	Sample Date	Temp (°C) ^{a/}	pH (su) ^{b/}	Conductivity (mS/cm) ^{c/}	Dissolved Oxygen (mg/L) ^{d/}	Redox Potential (mV) ^{e/}	Total Organic Carbon (mg/L)	Nitrite+ Nitrate ^{f/} (mg/L)	Nitrate ^{f/} (mg/L)	Nitrite ^{f/} (mg/L)	Manganese (mg/L)	Ferrous Iron (mg/L)	Sulfate (mg/L)	Hydrogen Sulfide (mg/L)	Chloride (mg/L)	Carbon Dioxide (mg/L)	Alkalinity (mg/L)	Bromide (mg/L)	Methane (µg/L) ^{g/}	Ethane (µg/L)	Ethene (µg/L)
Monitoring Wells																					
MW-216	29-Apr-00	19.5	6.88	6.06	1.38	244	NA ^{e/}	<0.05	NA	NA	0.58	<0.01	NA	<0.01	370	55	125	NA	5.9	0.035	0.093
	22-Sep-00	20.8	6.51	5.14	0.18	155	NA	NA	1.9	<0.10	NA	<0.01	3,346	<0.01	610	90	480	NA	15	0.067	0.230
	14-Dec-00	20.6	6.76	5.15	0.65	213	NA	NA	3.0	<0.10	0.1	0.03	1,700	0.03	360	155	563	NA	3.5	0.023	0.075
	13-Sep-01	21.7	6.90	6.79	<0.1	93	6.1	NA	<0.10	<0.10	<0.1	0.03	3,900	<0.1	380	125	629	2.0	10	0.069	0.054
Monitoring Points																					
PES-MW1	28-Apr-00	20.1	6.61	7.55	0.42	172	NA	<0.05	NA	NA	>1.10	0.51	NA	0.10	710	>100	350	NA	63	0.288	470
	22-Sep-00	20.6	6.25	5.85	0.19	127	NA	NA	8.6	<0.10	NA	<0.01	2,554	<0.01	710	280	1,920	NA	150	0.850	1,200
	14-Dec-00	18.6	6.42	5.44	0.60	5	NA	NA	<0.10	<0.10	13.0	0.17	1,300	<0.01	700	1,140	1,730	NA	160	0.750	850
	12-Sep-01	20.7	6.67	7.52	0.50	-35	17	NA	<0.10	<0.10	9.0	0.15	3,200	<0.1	800	250	1,360	<0.10	610	0.770	110
PES-MW2	29-Apr-00	16.9	6.87	6.71	4.58	138	NA	<0.05	NA	NA	0.32	0.55	NA	<0.01	720	18	80	NA	13.2	3.10	5.51
	23-Sep-00	20.4	6.61	5.11	0.61	114	NA	1.0	NA	NA	NA	1.74	3,504	NR	NA	90	960	NA	52	1.20	7.00
	14-Dec-00	17.7	6.76	5.12	1.33	26	NA	NA	<0.10	<0.10	3.0	0.27	1,100	0.04	NA	254	1,050	NA	26	0.720	1.40
	14-Sep-01	20.8	7.02	7.17	0.66	73	26	NA	<0.10	<0.10	<0.5	0.18	2,900	<0.1	1,000	75	1,020	<0.10	110	1.00	11
PES-MW3	29-Apr-00	19.5	6.40	7.31	5.50	52	NA	<0.05	NA	NA	>1.10	0.59	NA	<0.01	890	18	90	NA	113	1.62	3.60
	22-Sep-00	21.3	6.76	7.66	0.63	-136	NA	NA	9.0	<0.10	NA	0.98	5,455	<0.01	870	110	1,040	NA	99	0.740	1.90
	14-Dec-00	18.3	7.07	5.78	1.04	-112	NA	NA	<0.10	<0.10	4.0	<0.01	3,100	0.06	930	228	930	NA	10	0.420	2.00
	13-Sep-01	21.4	6.97	8.65	0.28	-194	12	NA	<0.10	<0.10	4.0	4.80	3,100	<0.1	1,000	175	1,360	<0.10	66	0.490	1.30
PES-MW4	30-Apr-00	19.1	NR	6.99	6.58	264	NA	<0.05	NA	NA	0.62	1.10	NA	<0.01	810	30	140	NA	37	1.48	3.12
	22-Sep-00	21.2	6.67	6.92	0.61	-14	NA	NA	7.9	<0.10	NA	1.18	4,788	<0.01	780	100	920	NA	75	0.740	1.40
	14-Dec-00	18.3	6.84	5.15	1.10	34	NA	NA	<0.10	<0.10	2.0	<0.1	2,000	0.10	NA	434	925	NA	1.4	0.052	0.270
	14-Sep-01	20.3	6.69	5.82	0.54	-268	91	NA	<0.10	<0.10	3.0	3.60	1,100	<0.01	840	40	1,530	<0.10	400	4.200	29
PES-MW5	29-Apr-00	20.3	7.03	7.59	4.50	80	NA	NA	NA	NA	>1.10	1.18	NA	<0.01	NA	>100	200	NA	NA	NA	NA
	21-Sep-00	20.9	6.68	7.02	0.60	-49	NA	NA	5.6	<0.10	NA	<0.01	3,230	<0.01	620	190	1,000	NA	61	0.180	0.460
PES-MW5 (DUP)	21-Sep-00	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	62	0.170	0.460
	12-Sep-01	20.9	6.98	7.29	0.48	51	8.8	NA	<0.10	<0.10	<0.1	<0.03	3,400	<0.1	770	40	1,120	<0.10	29	0.120	0.400
PES-MW6	28-Apr-00	17.3	6.92	8.29	0.87	151	NA	0.27	NA	NA	>1.10	2.23	NA	<0.01	1,000	90	250	<1.0	63	0.642	0.907
	22-Sep-00	21.4	6.62	6.37	0.45	31	NA	NA	23	<0.10	NA	0.15	3,950	<0.01	990	180	1,240	<0.10	89	0.840	1.90
	14-Dec-00	18.6	6.77	5.72	0.62	-35	NA	NA	<0.10	<0.10	5.0	0.50	1,800	0.05	1,100	789	1,195	36	86	0.300	1.50
	12-Sep-01	20.6	7.00	8.08	<0.01	-129	8.7	NA	<0.10	<0.10	<0.1	14.0	2,300	0.10	1,200	150	1,700	<0.10	180	0.340	1.00
PES-MW7	29-Apr-00	20.5	6.23	7.15	4.70	138	NA	0.11	NA	NA	>1.10	1.47	NA	<0.01	720	33	135	NA	9.9	0.276	0.916
	23-Sep-00	21.2	6.60	2.15	0.53	-256	NA	NA	6.1	<0.10	NA	1.75	2,365	0.50	710	220	1,400	<2.0	130	0.870	1.90
	14-Dec-00	17.9	6.69	4.88	0.42	-200	NA	NA	2.5	<0.10	5.0	0.90	1,200	0.02	760	272	1,560	8.8	79	1.90	2.00
	12-Sep-01	20.4	6.90	6.36	2.15	-283	74	NA	<0.10	<0.10	NA	12.00	1,900	0.20	990	200	1,870	<0.10	380	0.960	23
PES-MW8	22-Sep-00	21.9	6.64	6.90	0.27	-210	NA	NA	9.5	<0.10	NA	3.61	2,812	1.0	790	300	1,320	NA	120	2.00	3.10
	12-Sep-01	20.3	6.84	5.91	0.75	-275	110	NA	6.4	<0.10	3.5	23.00	580	0.2	820	125	1,020	<0.10	3,500	0.180	24
PES-MW9	22-Sep-00	19.6	6.55	4.95	0.24	129	NA	NA	5.2	<0.10	2.0	<0.01	2,871	<0.01	670	65	640	NA	98	0.710	2.70
	12-Sep-01	19.8	6.95	6.85	<0.01	20	5.0J	NA	<0.10	<0.10	<0.3	<0.01	4,000	<0.1	750	200	420	2.1	83	0.046	0.220

TABLE 4.5 (Continued)
GROUNDWATER GEOCHEMICAL DATA
SITE SS015
TRAVIS AFB, CALIFORNIA

Sample Location	Sample Date	Temp (°C) ^{a/}	pH (su) ^{b/}	Conductivity (mS/cm) ^{c/}	Dissolved	Redox	Total Organic	Nitrite+	Nitrate ^{f/} (mg/L)	Nitrite ^{f/} (mg/L)	Manganese (mg/L)	Ferrous	Hydrogen		Carbon		Alkalinity (mg/L)	Bromide (mg/L)	Methane (µg/L) ^{g/}	Ethane (µg/L)	Ethene (µg/L)
					Oxygen (mg/L) ^{d/}	Potential (mV) ^{e/}	Carbon (mg/L)	Nitrate ^{f/} (mg/L)				Iron (mg/L)	Sulfate (mg/L)	Sulfide (mg/L)	Chloride (mg/L)	Dioxide (mg/L)					
PES-MW10	21-Sep-00	20.5	6.61	6.18	1.07	-226	NA	NA	1.8	<0.10	2.8	0.29	2,976	<0.01	720	75	360	NA	8.1	0.400	0.710
PES-MW10 (DUP)	21-Sep-00	NA	NA	NA	NA	NA	NA	NA	1.8	<0.10	NA	NA	NA	NA	750	NA	NA	NA	NA	NA	NA
PES-MW11	21-Sep-00	20.4	6.53	5.08	0.76	-17	NA	NA	4.9	<0.10	2.7	0.88	2,234	<0.01	570	140	640	NA	950	0.095	0.630
	12-Sep-01	20.6	6.75	6.30	0.23	-92	5.9	NA	<0.10	<0.10	3.8	8.97	2,200	<0.1	770	105	510	<0.10	170	0.040	0.640
PES-MW12	21-Sep-00	21.0	6.42	5.12	0.38	-181	NA	NA	2.9	<0.10	3.1	3.07	2,482	<0.01	1,900	140	320	NA	76	0.630	1.100
PES-MW13	21-Sep-00	20.6	6.48	4.66	0.68	-5	NA	NA	3.4	<0.10	4.2	0.85	1,954	<0.01	390	160	520	NA	200	0.130	0.590
PES-MW14	21-Sep-00	20.7	6.46	4.64	0.23	-2	NA	NA	6.2	<0.10	2.8	<0.01	2,042	<0.01	490	195	540	NA	260	0.680	1.40
PES-MW15	23-Sep-00	19.7	6.79	4.94	1.10	206	NA	NA	6.7	<0.10	NA	0.63	2,580	<0.01	670	120	760	NA	47	0.670	1.60
PES-MW16	21-Sep-00	20.1	6.80	6.60	0.77	-207	NA	NA	4.1	<0.10	4.2	<0.01	2,924	<0.01	1,400	80	760	NA	22	1.20	1.20
Injection Points																					
PES-INJ1	30-Apr-00	20.6	6.87	7.11	3.88	255	NA	<0.05	NA	NA	>1.10	0.50	NA	<0.01	810	55	175	NA	11.4	0.537	0.988
	14-Dec-00	16	6.63	4.46	0.88	-325	NA	NA	2.6	<0.10	2.0	1.43	2,500	0.04	780	692	925	NA	NA	NA	NA
PES-INJ2	29-Apr-00	19.8	6.14	7.35	5.38	84	NA	0.18	NA	NA	>1.10	0.20	NA	<0.01	730	70	160	NA	47	1.629	3.153
PES-INJ3	30-Apr-00	18.9	6.94	6.22	4.24	168	NA	<0.05	NA	NA	0.19	0.95	NA	<0.01	700	>100	155	<1.0	23	0.251	0.546
	21-Sep-00	22.0	6.43	1.52	0.35	-232	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	14-Dec-00	16.7	7.60	4.67	0.42	-293	NA	NA	5.1	<0.10	13.0	3.30	500	0.03	670	994	1,410	NA	NA	NA	NA
PES-INJ18	22-Sep-00	20.6	6.49	5.19	0.83	87	NA	NA	1.9	<0.10	4.6	0.40	2,980	<0.01	470	100	760	NA	170	1.20	6.0
PES-INJ24	21-Sep-00	20.6	6.59	5.83	0.72	-125	NA	NA	8.1	<0.10	NA	4.89	5,765	<0.01	730	170	760	NA	120	0.700	0.260

^{a/} °C = degrees Centigrade.

^{b/} su = standard pH units.

^{c/} mS/cm = millisiemens per centimeter.

^{d/} mg/L = milligrams per liter.

^{e/} mV = millivolts.

^{f/} Nitrate+Nitrite analyzed by USEPA Method E353.3. Nitrate and nitrite each measured separately by USEPA SW9060.

^{g/} µg/L = micrograms per liter.

^{e/} NA = not analyzed.

S:\ES\Remed\736116\05000\report\Phase 2 CAD\01dn0417.dwg, 01/02/02 at 11:50

HANGER AVENUE

LEGEND

- INJ3 ● GROUNDWATER INJECTION POINT
- SG3 ● SOIL GAS MONITORING POINT
- MW1 ○ GROUNDWATER MONITORING POINT
- MW6 ● GROUNDWATER MONITORING WELL
- X-X- CHAIN LINK FENCE
- 8.8/2.1 TOTAL ORGANIC CARBON/BROMIDE IN MILLIGRAMS PER LITER (MG/L)
- ND NOT DETECTED
- * CONCENTRATION DETECTED IN DECEMBER 2000
- 10- LINE OF EQUAL TOC CONCENTRATION (MG/L) (DASHED WHERE INFERRED)

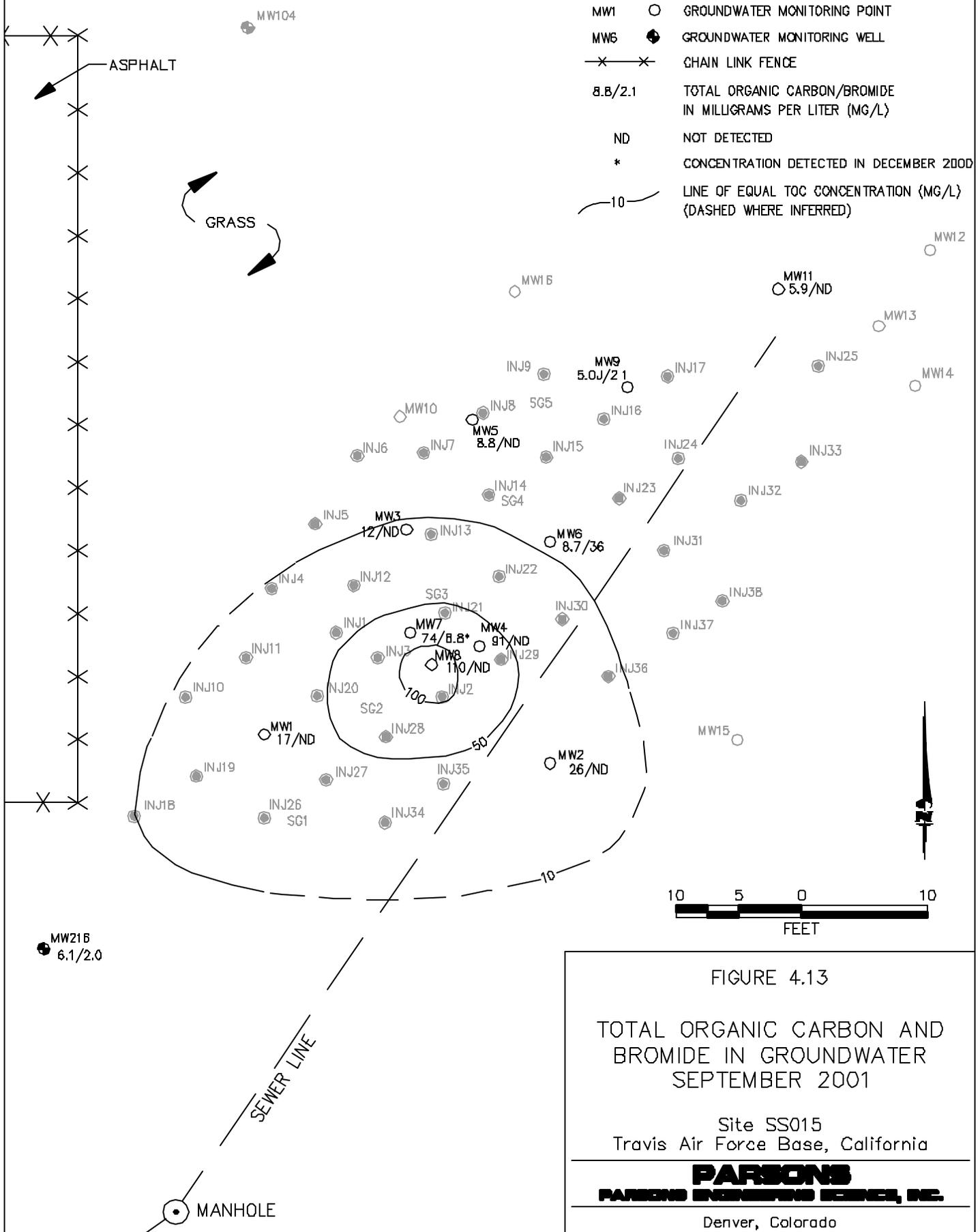


FIGURE 4.13

TOTAL ORGANIC CARBON AND BROMIDE IN GROUNDWATER SEPTEMBER 2001

Site SS015
Travis Air Force Base, California

PARSONS
PARSONS ENGINEERING SCIENCE, INC.

Denver, Colorado

PES-MW9. MW216 is located approximately 13 feet from the nearest Phase II injection point (PES-INJ18), and PES-MW9 is located approximately 7 feet from Phase II injection point PES-INJ9. The distance from MW216 to PES-MW9 is approximately 65 feet. Therefore, the Phase I and Phase II injections have been successful in distributing fluids from the injection over a large area of the injection network.

4.4.3 Alternate Electron Acceptors and Metabolic Byproducts

Biodegradation of organic compounds, whether natural or anthropogenic, brings about measurable changes in the chemistry of groundwater in the affected area. Concentrations of compounds used as electron acceptors (e.g., DO, nitrate, and sulfate) are depleted, and byproducts of electron acceptor reduction (e.g., ferrous iron and methane) are enhanced. By measuring these changes, it is possible to evaluate what biological processes have been induced or enhanced by substrate addition. Results of alternate electron acceptor and metabolic byproduct analyses for Site SS015 are presented in Table 4.5. The following paragraphs discuss those parameters most useful in evaluating site biodegradation processes.

4.4.3.1 Dissolved Oxygen

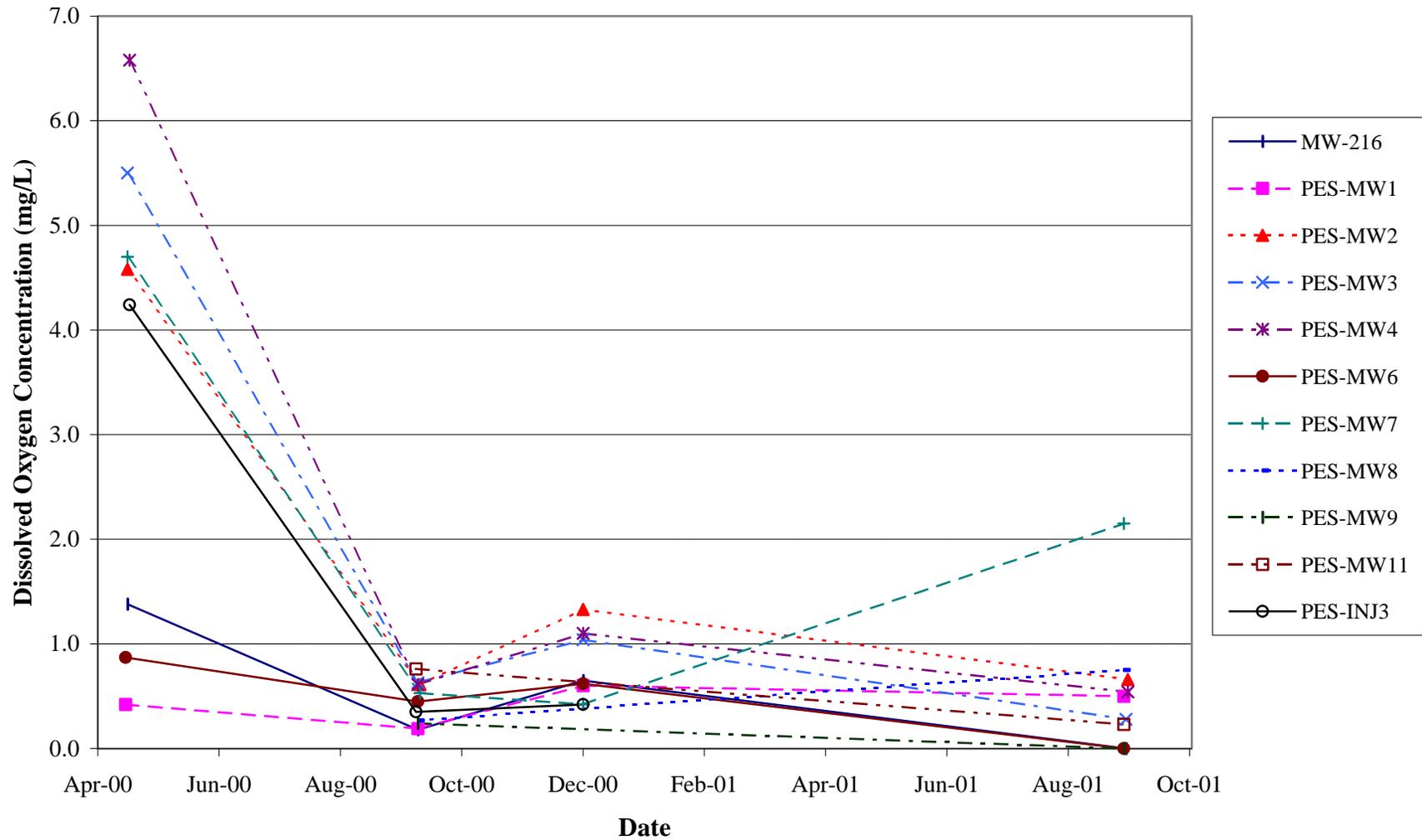
DO concentrations were measured at monitoring locations during all sampling events (Table 4.5). During the Phase I baseline monitoring event, DO concentrations ranged from 0.42 mg/L to 6.58 mg/L, with the lowest concentration measured in monitoring point PES-MW1; this monitoring point is located in an area of elevated concentrations of CAHs and fuel hydrocarbons. With the exception of locations PES-MW1 and PES-MW6, pre-injection DO concentrations within the test area indicate aerobic conditions (DO greater than 1 mg/L). However, due to the low yield of the monitored formation, many monitoring points purged dry before accurate DO readings can be obtained. Therefore, caution is advised in interpreting DO data to indicate aerobic conditions as oxygen may have been inadvertently introduced during the sampling process.

Decreased DO concentrations after organic substrate addition relative to baseline concentrations is a strong indication that biological activity was stimulated. DO concentrations over time are shown on Figure 4.14. Between April and September 2000, DO concentrations were reduced to less than 1.0 mg/L in all monitoring locations, including MW-216. DO concentrations varied slightly from September 2000 to September 2001, but with few exceptions remained less than 1.0 mg/L. This indicates that the addition of vegetable oil as an organic substrate has induced anaerobic, reducing conditions within the test area groundwater.

4.4.3.2 Nitrate and Nitrite

After DO has been depleted in the microbiological treatment zone, nitrate may be used as an electron acceptor for anaerobic biodegradation via denitrification. Nitrate concentrations below background in areas with high organic carbon concentrations and low DO are indicative of denitrification. The oxidation of organic carbon via the process of denitrification (using nitrate as an electron acceptor) yields a relatively large amount of free energy to microbial populations. Because nitrate may compete with CAHs as an

FIGURE 4.14
DISSOLVED OXYGEN OVER TIME
SITE SS015
TRAVIS AFB, CALIFORNIA



alternate electron acceptor, nitrate concentrations less than 1 mg/L are desired for significant reductive dechlorination to occur (USEPA, 1998).

Concentrations of nitrate/nitrite [as nitrogen (N)] in groundwater were analyzed by USEPA Method E353.3 in April 2000. Baseline concentrations using this method were less than 1 mg/L. Concentrations of nitrate and nitrite in groundwater were analyzed separately by USEPA Method SW9060 in September 2000, December 2000, and September 2001. Concentrations of nitrate measured in September 2000 ranged up to 23 mg/L at PES-MW6. In December 2000 and September 2001, nitrate concentrations were decreased at all monitoring points within the treatment zone. For example, at monitoring point PES-MW6, nitrate levels decreased from 23 mg/L in September 2000 to less than 0.10 mg/L in December 2000. It appears that method SW9060 may be more sensitive to existing nitrate concentrations than method E353.3. Furthermore, the reduction in nitrate concentrations from September 2000 to September 2001 suggests that available nitrate was utilized as an electron acceptor. However, because nitrate concentrations were relatively low in September 2001 (generally less than 1 mg/L), it is anticipated that available nitrate in the treatment zone has been depleted to non-competitive levels.

4.4.3.3 Ferrous Iron

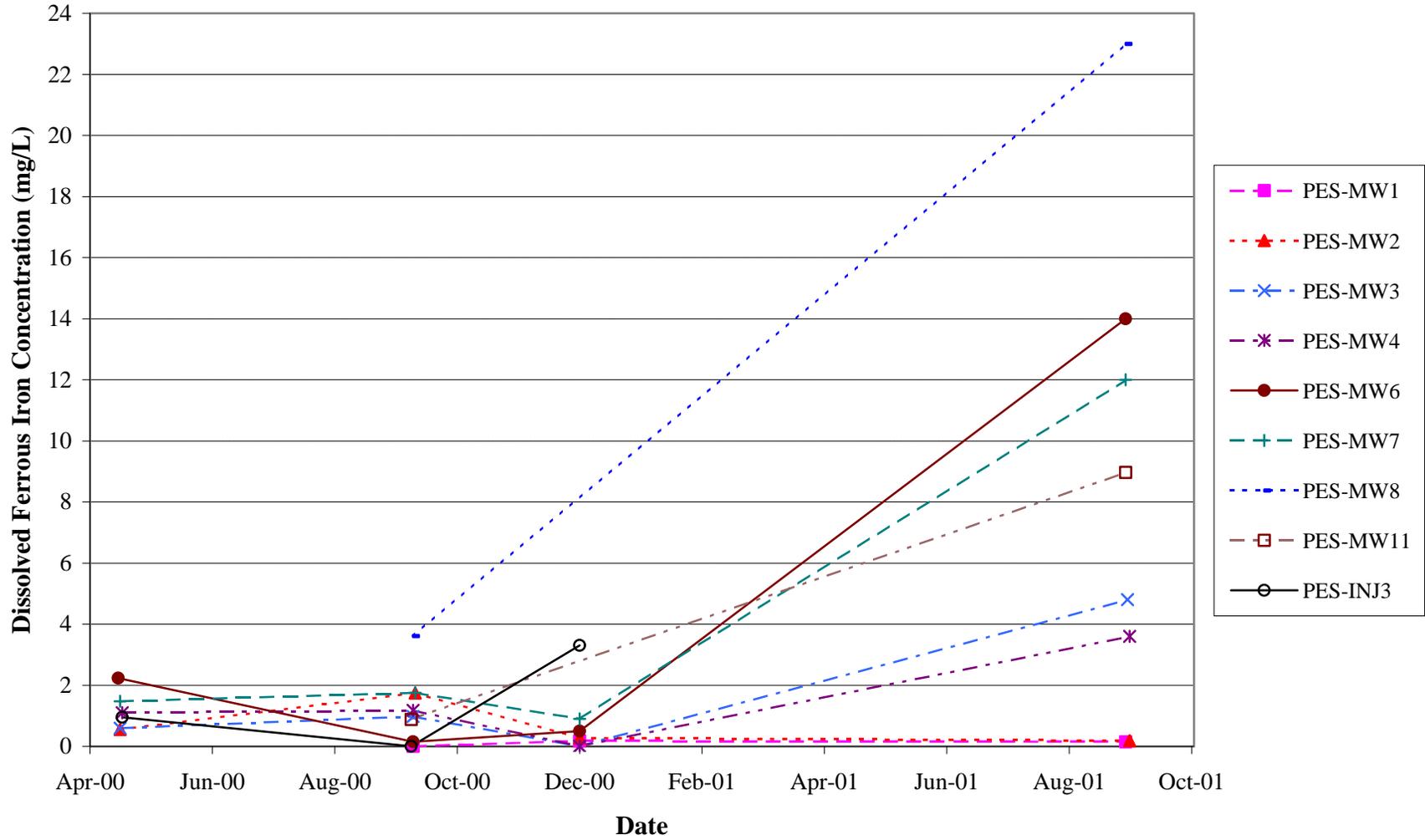
The reduction of ferric iron [iron (III)] has been shown to be a major metabolic pathway for some microorganisms (Lovley and Phillips, 1988; Chapelle, 1993). Ferrous iron [iron (II)] concentrations measured in groundwater samples are summarized in Table 4.5 and plotted over time on Figure 4.15. All iron (II) concentrations in the Phase I baseline (April 2000) groundwater samples were less than 2.5 mg/L. From April to December 2000, concentrations of iron (II) were variable, increasing at some locations while decreasing at others, but remaining less than 2.0 mg/L, with the notable exception of location PES-INJ3. During the September 2001 sampling event, six wells exhibited a significant increase in ferrous iron concentration. Notable increases were observed at monitoring points PES-MW6 and PES-MW8, where concentrations increased from 0.50 mg/L to 14 mg/L and from 3.6 mg/L to 23 mg/L, respectively. This suggests that iron (III) hydroxide was reduced to soluble iron (II) during biodegradation of organic substrate in the injection area. The increase in iron (II) indicates that microbial reduction of bio-available iron (III) was occurring at the site as a result of addition of vegetable oil.

4.4.3.4 Sulfate

Sulfate also may be used as an electron acceptor (sulfate reduction) during microbial degradation of an organic substrate under anaerobic conditions (Grbic-Galic, 1990). Sulfate concentrations were measured in groundwater samples collected during each of the sampling events (Table 4.5) For April 2000, the data are not of sufficient quality for reporting because of field error in recognizing the elevated sulfate concentrations at this site and achieving adequate sample dilution for analysis. Sulfate concentrations in groundwater samples at the SS015 Site collected in September 2000 ranged from 1,954 mg/L at monitoring point PES-MW13 to 5,455 mg/L at monitoring point PES-MW3.

From September to December 2000, sulfate concentrations decreased by approximately one-half, ranging from 1,100 mg/L at PES-MW2 to 3,100 mg/L at PES-

FIGURE 4.15
FERROUS IRON OVER TIME
SITE SS015
TRAVIS AFB, CALIFORNIA



MW3 (Figure 4.16). From December 2000 to September 2001, sulfate concentrations increased at six locations and decreased at four locations. However, sulfate concentrations generally remained lower than those observed in September 2000. Overall, a significant decrease in the naturally high concentrations of sulfate at the site suggests that sulfate reduction is a dominant biodegradation process, and that sulfate is a significant competing electron acceptor to reduction of CAHs.

4.4.3.5 Methane, Ethane, and Ethene in Groundwater

Although anaerobic degradation of CAHs may occur under nitrate-, iron- and sulfate-reducing conditions (Vogel *et al.*, 1987; Chapelle, 1993), the most rapid reductive dechlorination rates occur under methanogenic conditions (Bouwer, 1994). However, methanogenic organisms are known to compete with dechlorinating organisms for hydrogen (electron donor) produced by fermentation of organic substrate. Strongly elevated methane concentrations may be an indication that most all organic substrate is being used to support methanogenesis, at the expense of dechlorination reactions.

Methane, ethane, and ethene concentrations were measured in groundwater samples collected during all sampling events (Table 4.5). Phase I baseline concentrations of methane ranged from 5.9 µg/L at well MW-216 to 113 µg/L at monitoring point PES-MW3. Methane concentrations over time are shown on Figure 4.17. During the Phase I test from April to December 2000, methane concentrations increased noticeably at only three locations (PES-MW1, PES-MW6, and PES-MW7). During the September 2001 sampling event, methane concentrations were higher than the previous sampling event at eight locations. Most notably, methane increased from 120 µg/L in September 2000 to 3,500 µg/L in September 2001 at monitoring point PES-MW8. Only three locations (PES-MW5, PES-MW9, and PES-MW11) exhibited a decrease in methane concentration in September 2001. A substantial decrease occurred at monitoring point PES-MW11 (from 950 µg/L in September 2000 to 170 µg/L in September 2001) without an apparent cause. Monitoring point PES-MW11 is located downgradient of the zone of influence of the vegetable oil injection (Figure 3.4). Overall, these data suggest that methanogenesis is occurring at the site and was significantly enhanced by the Phase II injection.

Ethene and ethane are end products of reductive dechlorination. An increase in ethene and ethane concentration is a strong indication that complete degradation of chlorinated ethenes has occurred. From April 2000 to December 2000, ethene concentrations generally decreased or remained stable (Figure 4.18). However, from December 2000 to September 2001, ethene concentrations increased significantly at locations PES-MW2, PES-MW4, PES-MW7, and PES-MW8 (Table 4.5). The most noticeable increase occurred at location PES-MW4, where ethene increased from less than 1 µg/L to 29 µg/L. Ethane concentrations exhibited a similar trend, with significant increases from December 2000 to September 2001 occurring at locations PES-MW4 and PES-MW7 (Table 4.5).

In summary, methanogenesis has been enhanced and at least a portion of the chlorinated ethenes present at the site have been completely detoxified to ethene or ethane as a result of the Phase II injection. In particular, locations PES-MW2, PES-MW4, PES-MW7, and PES-MW8 exhibited notable increases in ethene concentrations. While methanogens may be competing with dechlorinating organisms for hydrogen produced by

FIGURE 4.16
SULFATE OVER TIME
SITE SS015
TRAVIS AFB, CALIFORNIA

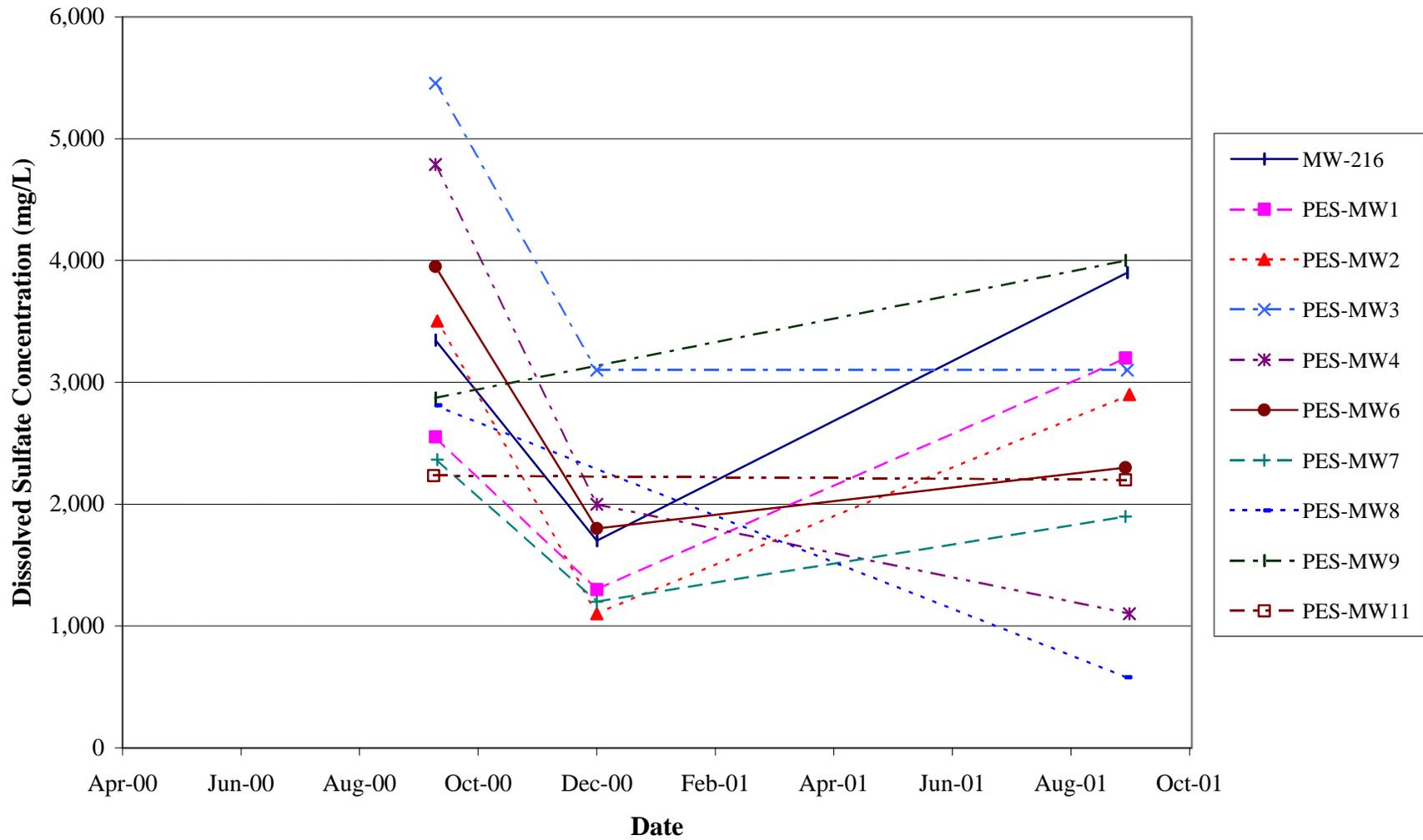


FIGURE 4.17
DISSOLVED METHANE OVER TIME
SITE SS015
TRAVIS AFB, CALIFORNIA

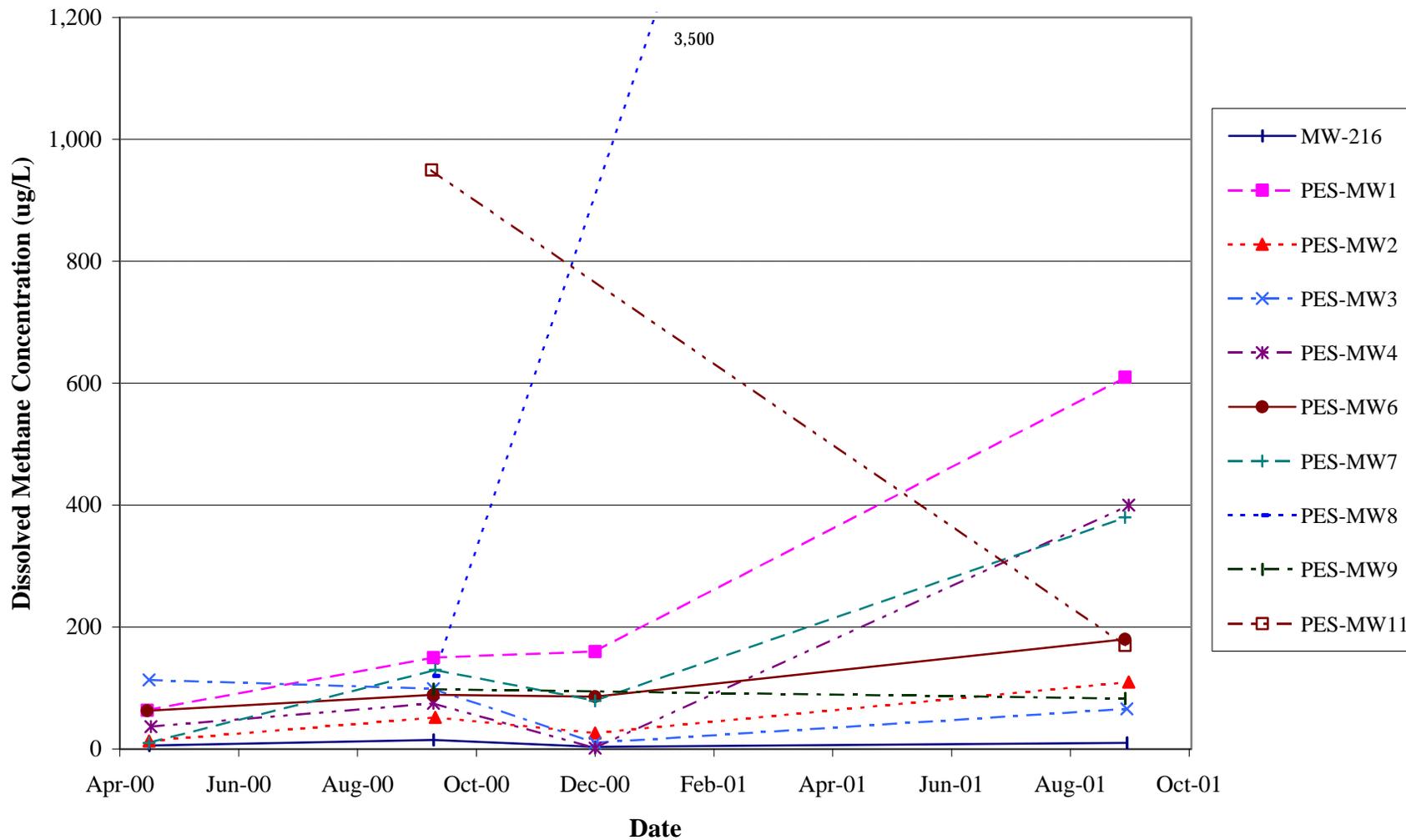
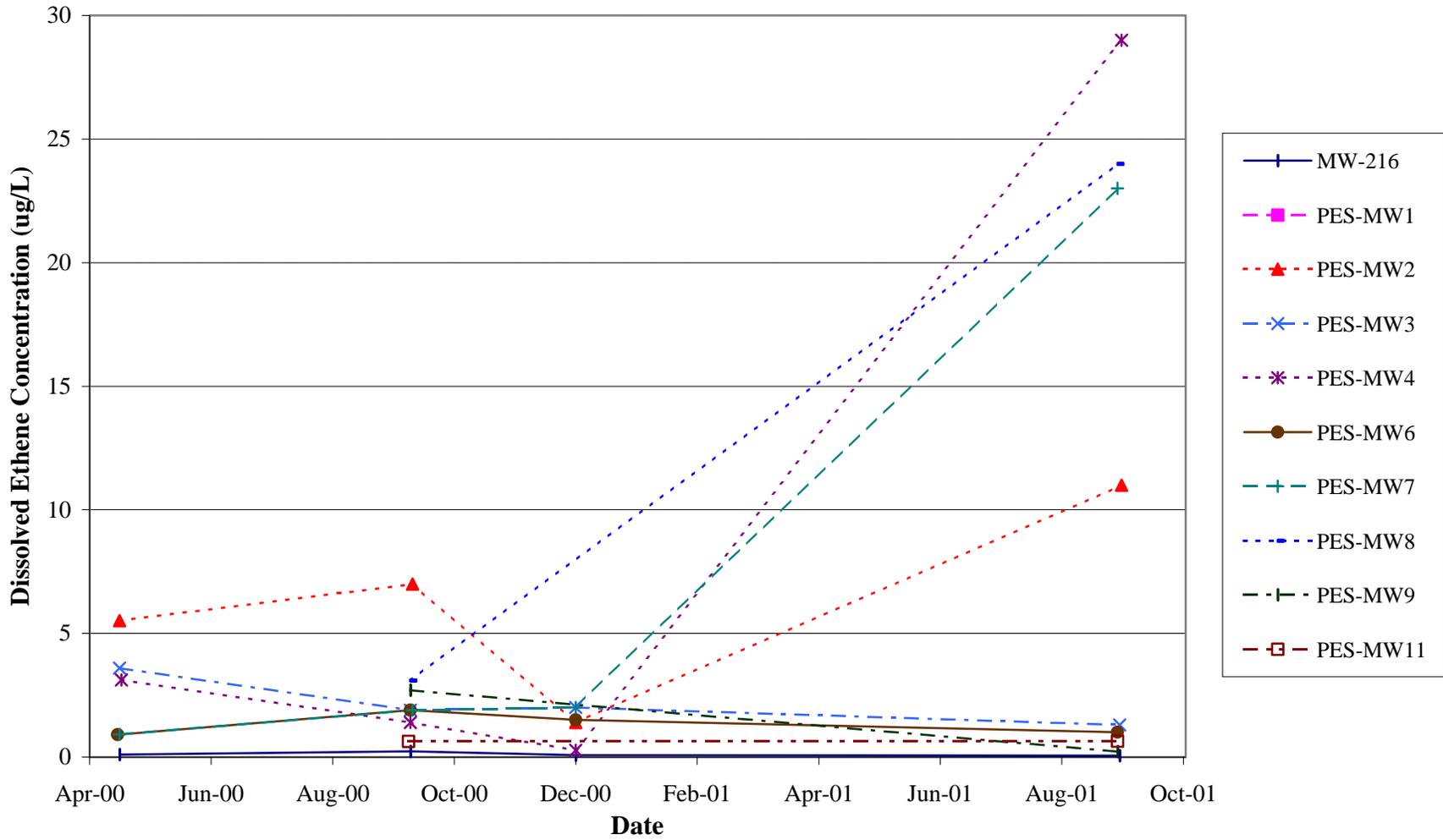


FIGURE 4.18
ETHENE OVER TIME
SITE SS015
TRAVIS AFB, CALIFORNIA



microbial fermentation of vegetable oil, an active population of dechlorinating organisms is present at the site that is capable of complete degradation of CAHs to ethene.

4.4.4 ORP as an Indicator of Redox Processes

Redox potential, or ORP, is a fairly quantitative measure of the relative tendency of a solution to accept or transfer electrons. The redox potential of a groundwater system depends on which electron acceptors are being reduced by microbes during oxidation of organic compounds. In general, reactions yielding more energy tend to take precedence over processes that yield less energy (Stumm and Morgan, 1981; Godsey, 1994; Reinhard et al., 1984). Oxygen reduction would be expected in an aerobic environment with microorganisms capable of aerobic respiration, because oxygen reduction yields significant energy (Bouwer, 1992; Chapelle, 1993). However, once the available DO is depleted and anaerobic conditions dominate the interior regions of a contaminant plume, anaerobic microorganisms can utilize other electron acceptors in the following order of preference: nitrate (denitrification), manganese (manganese reduction), ferric iron (iron reduction), sulfate (sulfate reduction), and finally carbon dioxide (methanogenesis). Each successive redox reaction provides less energy to the system, and each step down in redox energy yield is paralleled by an ecological succession of microorganisms capable of facilitating the pertinent redox reactions.

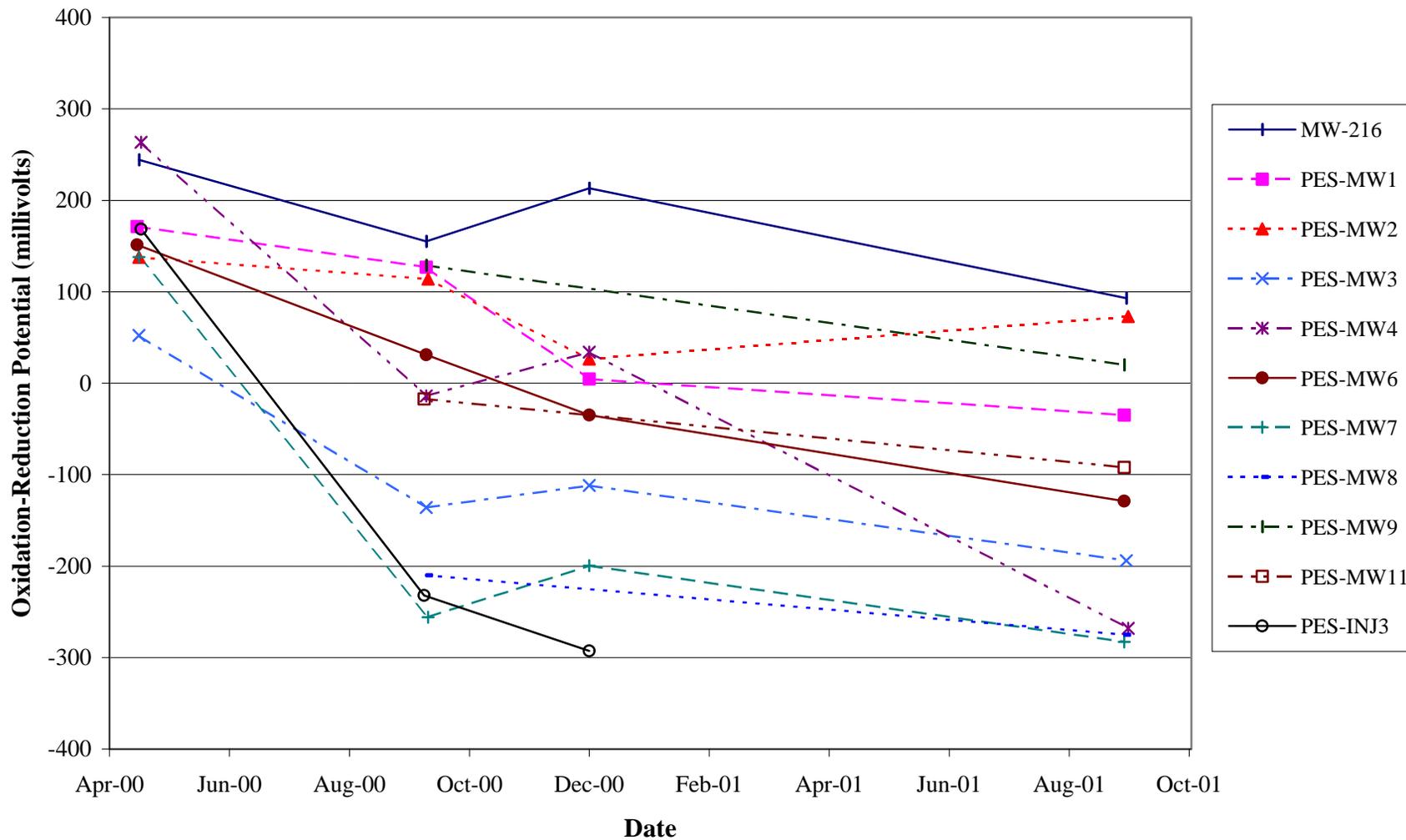
ORP was measured at groundwater monitoring locations during all sampling events, and results are listed in Table 4.5 and plotted on Figure 4.19. Phase I baseline ORPs for groundwater at the site ranged from 52 mV to 264 mV, which is outside the optimal range for reductive dechlorination. Overall, ORPs declined at all monitoring locations from April to September 2001. Between September and December 2000, ORPs decreased further at four locations and increased at four locations. ORPs measured in September 2001 ranged from -283 mV (PES-MW7) to 93 mV (MW216), indicating a substantial overall decrease in groundwater ORP.

In September 2001, only three locations (MW216, PES-MW2, and PES-MW9) had ORPs greater than 0 mV. These locations are either upgradient or downgradient of the injection zone and are not likely to be directly influenced by the Phase I and Phase II injections. Within the area of the vegetable oil injection points, all ORPs decreased over time to less than 0 mV in September 2001. This overall decrease in ORP indicates that the groundwater environment has become increasingly reducing as a result of the Phase I and Phase II injections, and is sufficiently reducing to support ferric iron reduction, sulfate reduction and methanogenesis. These are optimal conditions for reductive dechlorination to occur.

4.4.5 Additional Geochemical Indicators

Other geochemical data collected for this evaluation can be used to further interpret and support the contaminant, electron donor, electron acceptor, and byproduct data previously discussed. These parameters provide additional qualitative indications of what processes may be operating at the site.

FIGURE 4.19
OXIDATION-REDUCTION POTENTIAL OVER TIME
SITE SS015
TRAVIS AFB, CALIFORNIA



4.4.5.1 Chloride as an Indicator of Reductive Dechlorination

Chloride ions are removed from chlorinated solvents and enter solution during biodegradation, whether via reductive dechlorination or aerobic oxidation. Therefore, chloride concentrations in groundwater should increase above baseline levels in areas where reductive dechlorination is being stimulated.

Chloride concentrations are presented in Table 4.5, and Figure 4.20 shows the concentration of chloride over time at select monitoring locations. Chloride concentrations at upgradient well MW-216 were variable, first increasing and then returning to approximately pre-Phase I injection levels. Chloride at monitoring points within the treatment zone all increased to some extent from April to September 2001 (Figure 4.20). Although the increases in chloride concentrations were generally less than 100 mg/L from April 2000 to September 2001, the consistency with which they increased over time suggests that reductive dechlorination has been stimulated by the Phase I and Phase II vegetable oil injections.

4.4.5.2 Carbon Dioxide and Alkalinity

Carbon dioxide is produced during the biodegradation of anthropogenic or native organic carbon compounds. In aquifers that have carbonate minerals as part of the matrix, carbon dioxide forms carbonic acid, which dissolves these minerals, increasing the alkalinity of the groundwater. An increase in carbon dioxide and alkalinity (measured as calcium carbonate [CaCO_3]) in the treatment zone can be used to infer that organic carbon (i.e., vegetable oil), and possibly less-chlorinated solvents, have been destroyed through aerobic and anaerobic microbial respiration.

Carbon dioxide concentrations were measured in groundwater samples collected during each sampling event (Table 4.5 and Figure 4.21). Baseline carbon dioxide concentrations measured at the site ranged from 18 mg/L to greater than 100 mg/L. Concentrations in all locations increased from April to September 2000, with an even greater increase from September to December 2000. However, with the exception of location PES-MW9, carbon dioxide concentrations decreased substantially from December 2000 to September 2001. The cause of the increasing and decreasing trends is not readily apparent. While an increase in carbon dioxide concentration indicates that microbial biodegradation has been stimulated at the site, the reversal in trend in 2001 does not support this interpretation.

Alkalinity is a measure of the ability of groundwater to buffer changes in pH. Phase I baseline concentrations of total alkalinity (as CaCO_3) in groundwater at the site varied from 80 mg/L to 350 mg/L. Total alkalinity increased significantly from April to September 2000 (Figure 4.22), ranging up to 1,920 mg/L at well PES-MW1. Total alkalinity continued to increase from September 2000 to September 2001 at locations MW216, PES-MW2, PES-MW3, PES-MW4, PES-MW6, and PES-MW7; however, alkalinity decreased at PES-MW1, PES-MW8, PES-MW9, and PES-MW11 during the same period. Overall, alkalinity concentrations remained significantly elevated relative to baseline conditions. Elevated alkalinity within the plume area indicates that biodegradation has been enhanced, and appears to be sufficient to buffer potential changes in pH caused by biologically mediated reactions. Levels of pH in the study area

FIGURE 4.20
CHLORIDE OVER TIME
SITE SS015
TRAVIS AFB, CALIFORNIA

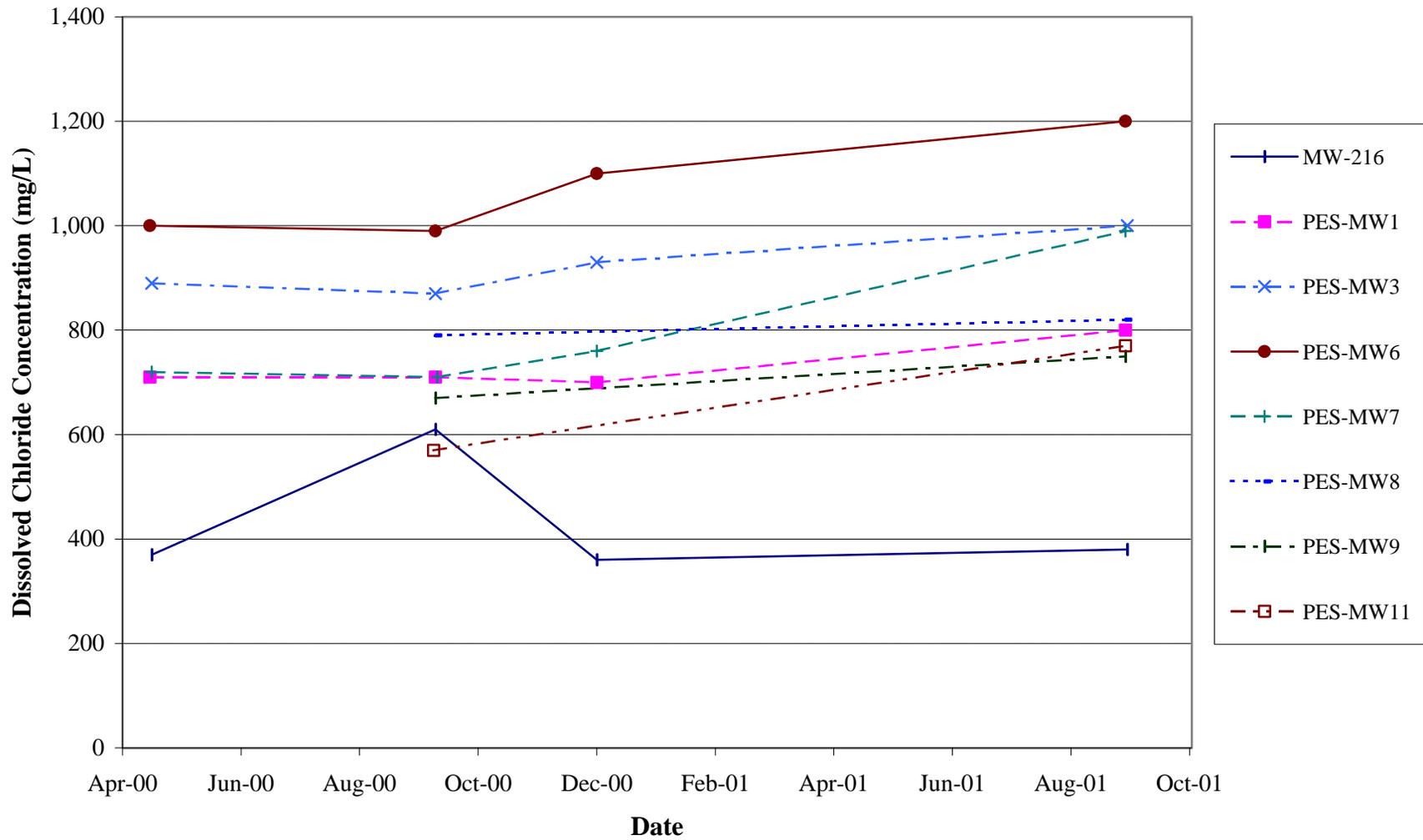


FIGURE 4.21
DISSOLVED CARBON DIOXIDE OVER TIME
 SITE SS015
 TRAVIS AFB, CALIFORNIA

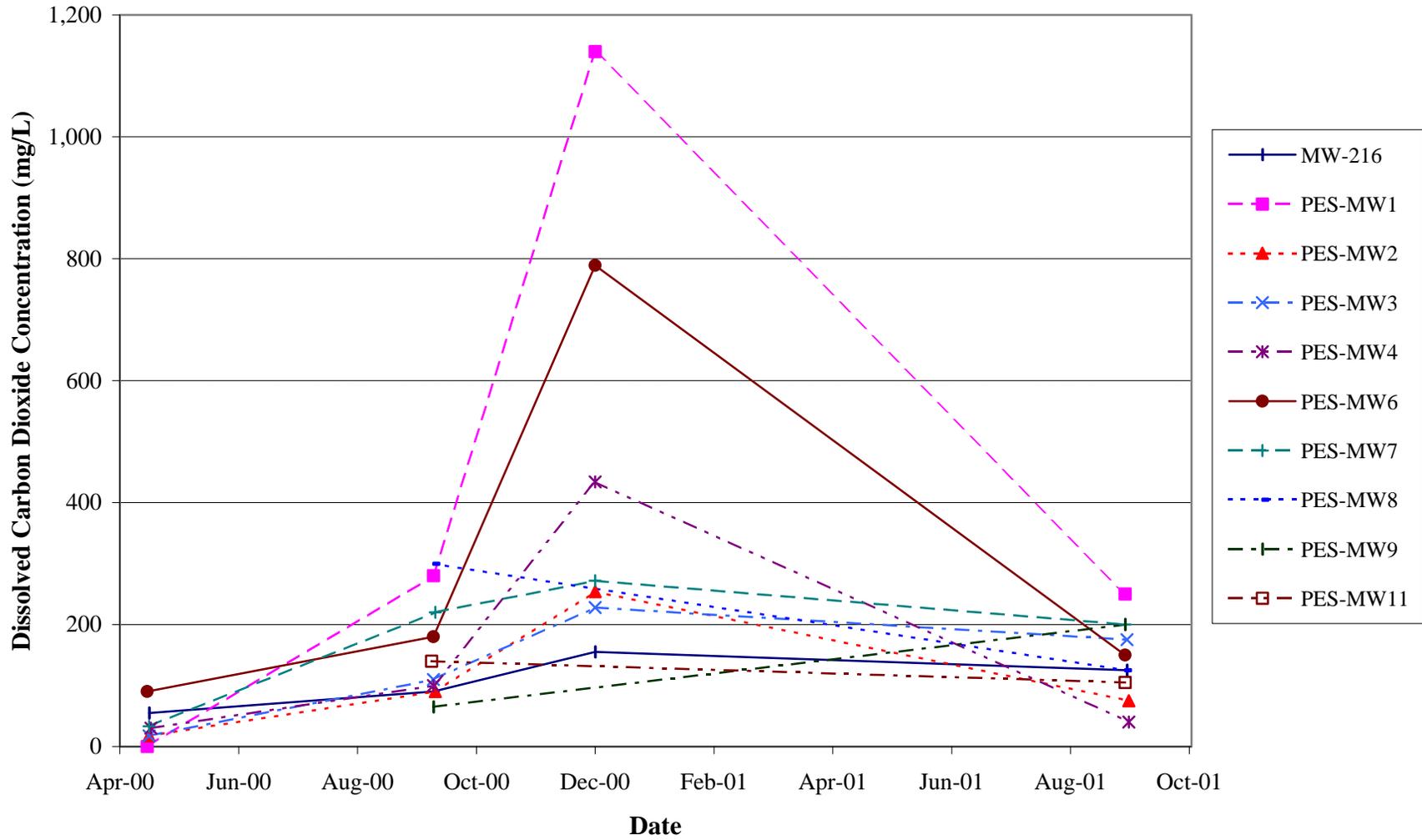
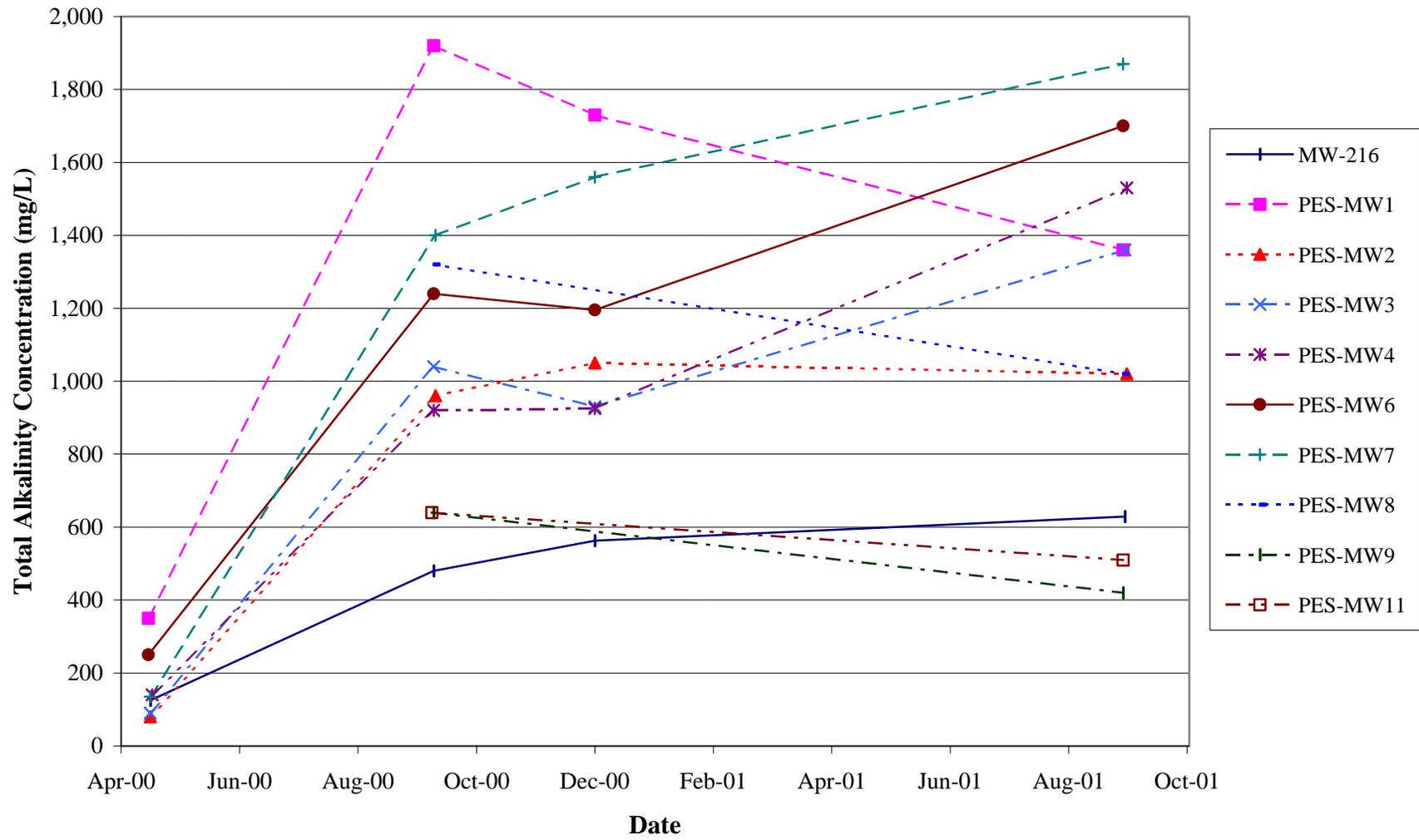


FIGURE 4.22
ALKALINITY OVER TIME
SITE SS015
TRAVIS AFB, CALIFORNIA



remained stable or increased only slightly from April to September 2001 (ranging from 6.23 to 7.60 standard units [su]).

4.5 SOIL VAPOR RESULTS

Two soil vapor monitoring points were installed upgradient of the injection points (PES-SG1 and PES-SG2), and three soil vapor monitoring points were installed downgradient of the injection points (PES-SG3, PES-SG4, and PES-SG5), as shown on Figure 3.1. Soil vapor monitoring point construction details are listed in Table 3.2. Soil vapor monitoring was conducted in April 2000, December 2000, and September 2001 for methane, oxygen, and carbon dioxide (Table 4.6).

Methane concentrations ranged from less than the detection limit (less than 0.1 part per million, volume per volume [ppmv]) to 0.1 ppmv, suggesting that methanogenesis in groundwater is not occurring at a rate sufficient for volatilization of methane to the vadose zone. Oxygen ranged from 17 percent to 23 percent in April 2000, although these concentrations are questionable considering the difficulty experienced in extracting sufficient flow rates for sample collection. Oxygen levels measured in December 2000 and September 2001 ranged from 19.0 to 21.9 percent. These levels indicate aerobic conditions in the vadose zone. A slight decrease in oxygen concentrations was observed in September 2001 at locations PES-SG2 and PES-SG3. Carbon dioxide concentrations in April and December 2000 ranged from 0.2 to 0.4 percent; levels generally increased in September 2001, ranging from 0.3 percent to 3.7 percent. Taken all together, these measurements indicate that biodegradation processes occurring in groundwater are not having an adverse impact on levels of methane, oxygen, or carbon dioxide in soil vapor within the vadose zone. A slight increase in carbon dioxide and a slight decrease in oxygen levels may have been caused by the Phase II injection.

4.6 METALS IN GROUNDWATER

Addition of an organic substrate into an aquifer has the potential to lower the groundwater ORP. Under highly reducing conditions, metals may be reduced to a more soluble form. Because certain metals are known to be toxic to human health and the environment, an increase in the dissolved concentration of these metals may be an adverse result of any substrate addition. To monitor this potential problem, groundwater samples from select locations were analyzed for three metals (arsenic, selenium, and manganese) during each sampling event (Table 4.7).

Concentrations of arsenic were not detected (less than a reporting limit of 0.010 mg/L) at monitoring location PES-MW6, with the exception of an estimated concentration of 0.009J mg/L in September 2001. At monitoring location PES-MW7, arsenic levels increased slightly from less than 0.010 mg/L in September 2000 to 0.25 mg/L in December 2000, but then decreased to an estimated concentration of 0.007J mg/L in September 2001. Similarly, arsenic increased from less than 0.010 mg/L in April 2000 to 0.046 mg/L in September 2000 at injection location PES-INJ3, but then decreased to below the detection limit in December 2000.

TABLE 4.6
SOIL GAS FIELD DATA
SITE SS015
TRAVIS AFB, CALIFORNIA

Sampling Location	Date	Oxygen (percent)	Methane (ppmv) ^{a/}	Carbon Dioxide (percent)
Vapor Monitoring Points				
PES-SG1	April 29, 2000	-- ^{b/}	--	--
	December 13, 2000	20.6	<0.1	0.3
	September 12, 2001	21.6	<0.1	0.3
PES-SG2	April 29, 2000	23.0	<0.1	0.2
	December 13, 2000	20.6	<0.1	0.3
	September 12, 2001	19.0	<0.1	2.9
PES-SG3	April 29, 2000	--	--	--
	December 13, 2000	20.4	0.1	0.4
	September 12, 2001	19.4	<0.1	3.7
PES-SG4	April 29, 2000	17.0	<0.1	0.2
	December 13, 2000	20.7	0.1	0.2
	September 12, 2001	21.1	<0.1	2.1
PES-SG5	April 29, 2000	--	--	--
	December 13, 2000	20.7	<0.1	0.2
	September 12, 2001	21.5	<0.1	1.0
PES-MW7	September 12, 2001	21.9	<0.1	<0.1

^{a/} ppmv = parts per million volume per volume.

^{b/} -- = Analyte not measured, formation yielded inadequate vapor flow.

TABLE 4.7
METALS IN GROUNDWATER
SITE SS015
TRAVIS AFB, CALIFORNIA

Sample Location	Sample Date	Arsenic (mg/L) ^{a/}	Selenium (mg/L)	Manganese (mg/L)
Monitoring Points				
PES-MW6	28-Apr-00	<0.010	<0.020	1.6
	22-Sep-00	<0.010	<0.020	3.1
	14-Dec-00	<0.010	<0.020	3.4
	13-Sep-01	0.009J	0.017J	7.2
PES-MW7	23-Sep-00	<0.010	<0.020	2.6
	14-Dec-00	0.025	<0.020	4.1
	14-Sep-01	0.007J ^{b/}	0.010J	3.9
Injection Points				
PES-INJ3	30-Apr-00	<0.010	<0.020	1.4
	21-Sep-00	0.046	<0.020	3.8
	14-Dec-00	<0.010	0.016J	17

^{a/} mg/L = milligrams per liter.

^{b/} J-flag indicates the concentration is estimated.

Selenium concentrations were less than the reporting limit of 0.020 mg/L at all three sampling locations, including an estimated concentration of 0.016J mg/L detected at PES-INJ3 in December 2000, and an estimated concentration of 0.017J mg/L detected at PES-MW6 in September 2001. These results indicate that solubilization of arsenic and selenium is not of current concern at Site SS015.

Concentrations of manganese (II) increased at all three locations over time. However, reduction of manganese (IV) to more soluble manganese (II) is known to be a common occurrence with biodegradation of organic carbon, and is expected to occur. The levels of manganese detected at the site suggest that manganese will not increase to levels that are harmful to human health or the environment.

4.7 POST-INJECTION AQUIFER TESTS RESULTS

Aquifer (slug) tests were conducted before the Phase I oil injection on points PES-INJ1, PES-INJ2, PES-INJ3, and PES-MW7 (Table 4.2). Phase I post-injection aquifer tests were performed in December 2000 on injection points PES-INJ1 and PES-INJ2. However, post-injection hydraulic conductivities could not be derived from the data collected from these tests. This may be due to free vegetable oil in the injection points affecting the flow of water in and out of the well bore. Therefore, insufficient post-injection data are available at this time to determine how oil injection affected hydraulic conductivity.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

This section presents conclusions and recommendations for the Phase II expanded field feasibility test for enhanced *in-situ* bioremediation of chlorinated solvents via vegetable oil injection at Site SS015, Travis AFB, California.

5.1 CONCLUSIONS

5.1.1 Observed Changes in Site Geochemistry

Addition of vegetable oil has induced anaerobic conditions across the study area. DO and ORP both decreased after both the Phase I and Phase II injections. ORP values indicate that the groundwater environment is sufficiently reducing to support ferric iron reduction, sulfate reduction, and methanogenesis. Relatively low background concentrations of nitrate indicate that nitrate reduction, or denitrification, is not a significant redox process at the site.

Sulfate concentration data suggest that sulfate reduction is the dominant TEAP occurring at the site, and that sulfate is competing with CAHs as an electron acceptor in site groundwater. As sulfate reduction continues, this condition may change, with an increasing utilization of organic substrate to support reductive dechlorination of chlorinated compounds.

Following the Phase II injection, substantial increases in methane concentration indicate that methanogenesis has been enhanced. Similar increases in ethene and ethane concentrations indicate that at least a portion of the CAHs at the site are being completely detoxified to ethene or ethane. While sulfate reducers and methanogens may be competing with dechlorinating organisms for hydrogen produced by microbial fermentation of vegetable oil, an active population of dechlorinating organisms is present at the site that is capable of complete degradation of PCE to ethene.

5.1.2 Actual/Significant Changes in Contaminant Concentrations

The extent and magnitude of CAHs in groundwater was best defined by the September 2000 sampling event (Figure 4.6), which included process monitoring of Phase I monitoring points and baseline sampling of Phase II monitoring points. The core of the CAH groundwater plume extends from just downgradient of well MW-216 toward the northeast as defined by monitoring points PES-MW11 through PES-MW14. The groundwater plume trends along a sewer line present at the site, suggesting that backfill

for the sewer line is a preferential pathway for groundwater flow, or that the sewer line itself is a possible source of contaminants.

Overall, the maximum concentration of TCE decreased over time, with a decrease in the concentration of TCE occurring at locations PES-MW1, PES-MW3, PES-MW4, PES-MW6, PES-MW7, and PES-INJ3. Locations within the radius of influence of the injected vegetable oil exhibit a lower TCE concentration than locations outside the radius of influence. This area of lower TCE concentration within the plume core near the injection points suggests that the Phase I and Phase II vegetable oil injections have reduced aqueous-phase TCE concentrations. In addition to biodegradation, some of the observed decrease in TCE concentrations in the plume core is likely a result of partitioning of TCE from the aqueous phase into the vegetable oil NAPL.

Maximum concentrations of *cis*-1,2-DCE and VC in groundwater decreased over time. However, trends in concentration for *cis*-1,2-DCE and VC are less apparent, likely due to the fact that these compounds are produced as a result of degradation of higher chlorinated ethenes. Similar to the TCE plume, concentrations of *cis*-1,2-DCE are lower near the center of the injection point array (Figures 4.6 through 4.8).

To help evaluate partitioning of chlorinated ethenes from water into the oil, concentrations of CAHs were measured in vegetable oil samples collected from injection wells PES-INJ1 and PES-INJ3. Elevated concentrations of CAHs in vegetable oil purged from the Phase I injection points indicate that partitioning from groundwater into the oil is occurring. This is expected, because CAHs have a greater affinity for dissolution into an oil phase than an aqueous phase.

While partitioning of CAHs from the aqueous phase into the oil phase appears to be significant and may account for some aqueous phase contaminant reduction, the actual mass of CAHs that partitioned into the vegetable oil is substantially less than that remaining in the aqueous phase. Once an initial aqueous- and oil-phase equilibrium is reached, CAHs are released from the oil to groundwater at a rate dependent upon dissolution and/or degradation of the vegetable oil, and degradation of contaminants in the dissolved phase. In any event, contaminants are released back to groundwater within a zone of adequate substrate and optimal conditions for reductive dechlorination.

Based on contaminant trend analysis alone, it is difficult to determine whether the overall reduction in concentrations of CAHs is primarily due to biodegradation, partitioning of dissolved contaminants into the vegetable oil NAPL, lateral spreading of contaminants due to injection, or to natural temporal variations in contaminant concentration. However, other supporting evidence of enhanced biodegradation, including changes in groundwater geochemistry and molar ratios of parent and daughter products, indicate that a substantial portion of the reduction in contaminant concentrations is due to reductive dechlorination.

5.1.3 Daughter Product Formation and Persistence

The presence of daughter products that were not used in Base operations, particularly *cis*-1,2-DCE, VC, and ethene, provides strong evidence that PCE and TCE are being reductively dechlorinated. Within the treatment zone, chlorinated ethene concentrations

and molar fractions over time for monitoring well PES-MW4 exhibit the trends expected of reductive dechlorination (Figure 4.11). Most noticeably, concentrations and molar fractions of PCE, TCE, and *cis*-1,2-DCE decreased, while concentrations and molar fractions of VC and ethene increased. Evidence that some reductive dechlorination is proceeding to completion is indicated by an increase in the concentrations of ethene and ethane. Other monitoring locations that also exhibited evidence of reductive dechlorination include PES-MW2, PES-MW3, PES-MW6, PES-MW7, PES-MW8, PES-MW9 and PES-INJ3, although not to the extent as observed at location PES-MW4.

Trends in chlorinated ethene concentrations and molar fractions indicate that reductive dechlorination has been stimulated at the site by both the Phase I and Phase II injections. An overall decrease in chlorinated ethene concentrations is occurring across the site. Transformation of PCE to TCE and TCE to *cis*-1,2-DCE appear to be the most common and consistent reduction steps, but a measurable amount of *cis*-1,2-DCE and VC also are being degraded. While partitioning of chlorinated ethenes into the vegetable oil NAPL may account for some reduction in aqueous-phase concentrations, molar fraction data indicate that a significant amount of contaminant reduction is due to reductive dechlorination.

5.1.4 Degree of Electron Donor Utilization for Reductive Dechlorination

It appears that a significant percentage of the substrate mass may be utilized for microbially mediated redox processes other than reductive dechlorination of chlorinated compounds. In particular, Phase II process monitoring indicates that both sulfate reduction and methanogenesis may adversely utilize a significant percentage of substrate (i.e., this mass is not being used to enhance reductive dechlorination of CAHs). However, contaminant reductions such as those seen at monitoring point PES-MW4 suggest that substantial reductive dechlorination is occurring in groundwater at the site. Once a significant reduction in sulfate concentration has occurred, utilization of substrate mass for reductive dechlorination will likely increase. However, for this to occur a relatively unlimited substrate mass (i.e., electron donor) must be present, either in the form of vegetable oil or biomass. Therefore, additional volumes of vegetable oil may be necessary at this site if the mass of substrate is depleted prior to remediation of CAHs in groundwater.

5.2 RECOMMENDATIONS

Results of the Phase II evaluation indicate that enhanced reductive dechlorination of CAHs is occurring at Site SS015 as a result of vegetable oil addition. However, naturally high concentrations of sulfate appear to be a significant competing electron acceptor. Further depletion of sulfate in the shallow groundwater will likely result in more rapid reductive dechlorination of chlorinated compounds. Injection of additional vegetable oil would help to overcome the competing reaction of sulfate reduction. Due to failure of a majority of injection point annular seals during the Phase II test, only 165 of a planned 440 gallons of vegetable oil were injected. Therefore, Parsons recommends that the failed injection points be replaced and the Phase II injection brought to completion.

The hydraulic conductivity of the injection zone measured at the site is very low, with average groundwater velocities calculated to be less than 1 foot per year. However, the

observed distribution of the oil and detection of bromide at downgradient location PES-MW6 suggests that the accuracy of this calculation is questionable, and that a more conductive interval is present at depths of 15 to 19 feet bgs. Therefore, Parsons recommends that aquifer (slug) tests be conducted in existing conventional 2-inch-diameter monitoring wells (MW-216, MW-104, and MW-105) to better characterize hydraulic conductivity at the site. These wells are constructed with adequate sand packs and have been well developed; therefore, the difficulties encountered performing slug tests in small-diameter well points should not be experienced. Use of alternative aquifer testing techniques, such as constant-drawdown tests, should be considered to determine the post-injection hydraulic conductivity in small diameter monitoring points within the radius of influence of the vegetable oil. All monitoring points also should be sampled for bromide, to better determine tracer breakthrough, groundwater flow direction, and groundwater seepage velocity.

Several parameters that would be useful for determining the effectiveness of substrate addition, electron donor demand and utilization, and the groundwater redox processes that are occurring at the site are not currently part of the monitoring program. Parsons recommends that TOC, total inorganic carbon, volatile fatty acids, and dissolved hydrogen be added to the monitoring program, at least for one sampling event. Analyses of additional nutrient parameters (total nitrogen and phosphorous) are also warranted. Continued monitoring at 6-month intervals is recommended.

SECTION 6

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APPENDIX A
SEPTEMBER 2001 ANALYTICAL DATA

APPENDIX B
SEPTEMBER 2001 FIELD TEST DATA

APPENDIX C

TRENDS IN CONCENTRATION AND MOLAR FRACTION

APPENDIX D

APPLIED COST AND PERFORMANCE REPORT

COST AND PERFORMANCE REPORT

***IN-SITU* BIOREMEDIATION OF CHLORINATED SOLVENTS
VIA VEGETABLE OIL ADDITION AT SITE SS015,
TRAVIS AIR FORCE BASE, CALIFORNIA**

March 2002

Prepared for:

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TABLE 1. SUMMARY INFORMATION

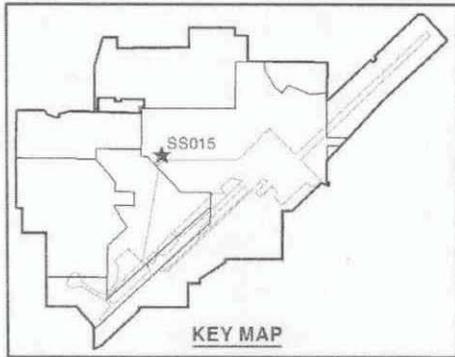
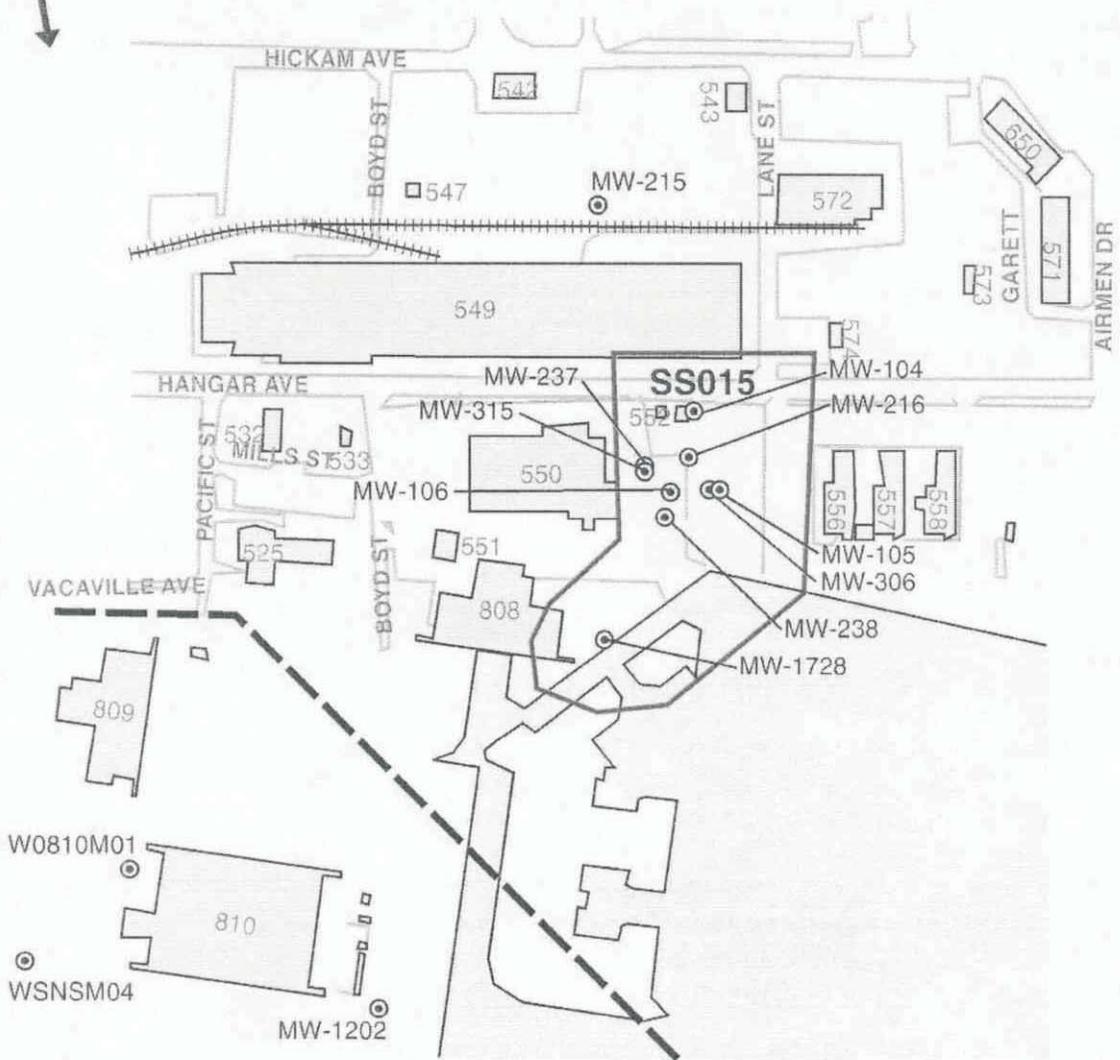
Site Name, Location	Site SS015, Travis Air Force Base, California
EPA ID Number:	Not Applicable
Mechanism(s)	Anaerobic Reductive Dehalogenation
Technology	Organic Substrate Addition (Vegetable Oil)
Configurations	Direct Subsurface Injection
Technology Scale	Pilot (Phase I) and Full (Phase II) Scale
Media/Matrix Treated	Groundwater
Contaminants Targeted	Chlorinated Ethenes (PCE, TCE, DCE, VC)
Period of Operation	Phase I – April 2000 to December 2000 Phase II – December 2000 to April 2002 (ongoing monitoring)

1.0 SITE HISTORY/SOURCE OF CONTAMINATION

Site SS015 comprises approximately 3.5 acres of Travis Air Force Base (AFB) and is located in the northwestern part of the East Industrial Operable Unit (EIOU). Site SS015 consists of the Solvent Spill Area (SSA) and Facilities 550 and 552 (Figure 1). The SSA area was previously used for stripping paint from aircraft. Solvent spills were reported to have occurred in the area east of Facility 550; however, actual dates of spill occurrences are unknown. Facility 550 formerly housed a corrosion control shop, a metals processing shop, a fiberglass shop, and nondestructive inspection operations. Past practices at the corrosion control shop included discharging wastes to a floor drain that was connected to a sanitary sewer. Wastes generated included paints, thinners, acids, and stripping wastes. Facility 552 consists of a fenced, bermed concrete pad constructed in 1964. The pad was most recently used as a temporary hazardous waste collection point. Radomes were chemically stripped of paint near Facility 552 from 1964 to 1980. Stored wastes included paint, chromic acid, and solvents generated during aircraft maintenance operations at Facility 550.

As part of the Groundwater Interim Record of Decision (ROD), Site SS015 was designated for a natural attenuation assessment and groundwater monitoring. Chemicals of concern (COCs) include: tetrachloroethene (PCE); trichloroethene (TCE); 1,1-dichloroethene (1,1-DCE) and the dichloroethene isomers *cis*-1,2-dichloroethene (*cis*-1,2-DCE) and *trans*-1,2-dichloroethene (*trans*-1,2-DCE); vinyl chloride (VC); 1,4-dichlorobenzene (1,4-DCB); 1,2-dichloroethane (1,2-DCA); bis(2-ethylhexyl)phthalate; nickel; and total petroleum hydrocarbons (TPH). The work under this project focuses on primarily on the enhanced bioremediation of chlorinated ethenes (i.e., PCE, TCE, DCE, and VC).

REGIONAL
GROUNDWATER
FLOW DIRECTION



- LEGEND**
- ROADS
 - ++++ RAILROADS
 - SITE BOUNDARY
 - - - - OPERABLE UNIT BOUNDARY
 - ▭ PAVEMENT AREAS
 - ⊙ MONITORING WELL

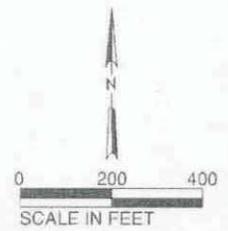


FIGURE 1
SITE PLAN AND
MONITORING WELL LOCATION
 Site SS015
 Travis AFB, California

PARSONS
 Denver, Colorado

(From CH2MHILL, 1999a)
 draw736166.cdr scan nap 3/25/02

2.0 GEOLOGY/HYDROGEOLOGY/CONTAMINANT CHARACTERISTICS

The site geology consists of interbedded silt and silty clay, with a few silty sand layers. These unconsolidated sediments overlie weathered shale bedrock at a depth of approximately 25 feet below ground surface (bgs). Groundwater is unconfined at depths of 8 to 12 feet bgs. Average groundwater seepage velocity is estimated to be approximately 1 foot per year, but preferential flow paths of higher velocity may be present.

The chlorinated compound detected at the highest concentration during baseline sampling in April 2000 was *cis*-1,2-DCE at a concentration of 22,000 micrograms per liter ($\mu\text{g/L}$). VC was detected at a maximum concentration of 17,000 $\mu\text{g/L}$, and TCE was detected at a maximum concentration of 4,200 $\mu\text{g/L}$. Lower concentrations of PCE, 1,1-DCE, *trans*-1,2-DCE, 1,1-DCA, 1,2-DCA, chlorobenzenes, and chloroethane also were detected during the baseline sampling event. Elevated concentrations of *cis*-1,2-DCE and VC indicate that limited reductive dechlorination of PCE and TCE has occurred naturally within the central core of the solvent plume.

TABLE 2. SITE CHARACTERISTICS

Matrix Characteristic	Value
Soil Type	Interbedded Silt and Silty Clay
Soil Permeability	Not Available
Depth to Groundwater	8 to 12 feet below ground surface
Fraction Organic Carbon	Not Available
Thickness of Aquifer	15 to 20 feet
DNAPL Presence	Not Indicated
Hydraulic Conductivity	0.03 to 0.04 feet per day
Effective Porosity	10 percent (estimated)
Hydraulic Gradient	0.005 foot per foot
Groundwater Velocity	Approximately 1 foot per year

3.0 TECHNOLOGY DESCRIPTION

Chlorinated solvents, also termed chlorinated aliphatic hydrocarbons (CAHs), can be transformed, directly or indirectly, by biological processes. Chlorinated solvents may undergo biodegradation through three different pathways: use as an electron acceptor, use as an electron donor, or cometabolism, which is degradation resulting from exposure to a

catalytic enzyme fortuitously produced during an unrelated process. At a given site, one or all of these processes may be operating, although at many sites the use of CAHs as electron acceptors appears to be the most likely.

Under anaerobic conditions, biodegradation of chlorinated solvents usually proceeds through a process called reductive dechlorination. This is the only common biological reaction known to degrade PCE, TCE, TCA, carbon tetrachloride, and chlorinated benzenes with more than three chlorines. During reductive dechlorination, the chlorinated hydrocarbon is used as an electron acceptor, not as a source of carbon, and a chloride atom is removed and replaced with a hydrogen atom. Reductive dechlorination generally occurs sequentially. For the chlorinated ethenes, dechlorination progresses from PCE to TCE to DCE to VC to ethene.

Reductive dechlorination has been demonstrated under nitrate-, iron-, and sulfate-reducing conditions, but the most rapid biodegradation rates, affecting the widest range of CAHs, occur under methanogenic conditions (Bouwer, 1994). Because CAH compounds are used as electron acceptors, there must be an appropriate source of carbon for microbial growth in order for reductive dehalogenation to occur. An evaluation of chlorinated ethene groundwater data at Site SS015 suggests that the natural biodegradation of chlorinated ethenes is electron-donor limited. Food-grade soybean vegetable oil is being used to remediate the CAH plume at the site by overcoming the observed electron donor limitation.

The most common approach utilized to date to stimulate reductive dehalogenation has been addition of a carbon source dissolved in groundwater. This approach may prove effective in some applications, but in many cases may have difficulty competing with pump-and-treat remedial systems because the carbon source must be continuously injected. Other approaches involving the emplacement of solid materials that release carbon are promising, but the cost of the solid carbon addition will be high.

Vegetable oil has been injected to create the reduction-oxidation (redox) and electron donor conditions necessary to promote the microbial reductive dehalogenation of chlorinated solvents in groundwater. Vegetable oil is an inexpensive, innocuous, edible (i.e., food-grade) carbon source. The separate phase nature of vegetable oil allows for slow dissolution into groundwater, thus making it a slow-release carbon source. Because vegetable oil is a non-aqueous phase liquid (NAPL), the potential exists that a single, low-cost injection could provide sufficient carbon to drive reductive dechlorination for many years. Thus, the carbon substrate will only be injected one time, which will significantly reduce overall costs. A secondary benefit is partitioning of the dissolved chlorinated solvents into the vegetable oil NAPL. This is beneficial because aqueous-phase chlorinated solvent concentrations will be lowered until equilibrium conditions are reached.

The Phase I field test included the installation of a well point network consisting of three injection points and seven groundwater monitoring points in the suspected Site SS-015 source area using direct-push technology. A total of 62 gallons of refined soybean oil and 16 gallons of water were injected into three injection points in June 2000. Due to the low permeability of soils at Site SS-015, vegetable oil was injected at pressures sufficient to fracture the formation. Radius of influence testing indicates that oil was distributed primarily along relatively permeable silt and silty sand seams at depths of 15 to 19 feet

bgs. Secondary distribution of oil is inferred to have occurred along vertical fractures. The extent of oil distribution was not uniform, ranging from approximately 1 to 5 feet from the injection points.

The Phase II field test included the installation of a well point network consisting of an additional 35 injection points and 9 monitoring points in September 2000 using direct-push technology (Figure 2). The Phase II injection event was conducted after the Phase I process monitoring event in December 2000. A total of 165 gallons of vegetable oil was injected in two scenarios. The first scenario involved straight oil injection followed by a water flush. The second scenario involved injection of an oil-in-water emulsion.

4.0 TECHNOLOGY PERFORMANCE

Addition of vegetable oil has induced anaerobic and reducing conditions sufficient to support ferric iron reduction, sulfate reduction, and methanogenesis. Relatively low background concentrations of nitrate indicate that nitrate reduction, or denitrification, is not a significant reduction process at the site. Sulfate concentration data suggest that sulfate reduction is the dominant terminal electron accepting process (TEAP) occurring at the site, and that sulfate is competing as an electron acceptor against the reductive dechlorination of chlorinated compounds. As sulfate continues to be reduced, this condition may change, with an increasing utilization of organic substrate to support reductive dechlorination of chlorinated compounds.

Following the Phase II injection, substantial increases in methane concentration indicate that methanogenesis has been induced. Similar increases in ethene and ethane concentrations indicate that a significant amount of chlorinated ethenes are being completely detoxified to ethene or ethane. While sulfate reducers and methanogens may be competing with dechlorinating organisms for hydrogen produced by microbial fermentation, an active population of dechlorinating organisms is present at the site that is capable of complete degradation of PCE to ethene.

Significant reductions in PCE and TCE occurred at several locations, particularly within the radius of influence of the injected vegetable oil. Overall, the maximum concentration of TCE decreased from 4,200 micrograms per liter ($\mu\text{g/L}$) in April 2000 to a maximum of 1,800 $\mu\text{g/L}$ in September 2001 (Figure 3). An area of lower TCE concentration within the plume core near the injection points suggests that the Phase I and Phase II vegetable oil injections have had an impact on reducing aqueous-phase TCE concentrations at the site. In addition to biodegradation, some reduction in TCE concentration at these locations is likely a result of partitioning of TCE from the aqueous phase into the vegetable oil non-aqueous phase liquid (NAPL).

Trends in concentration for *cis*-1,2-DCE and VC are less apparent, likely due to the fact that these compounds are produced as a result of degradation of higher chlorinated ethenes. From April 2000 to September 2001, the maximum concentration of *cis*-1,2-DCE in groundwater decreased from 22,000 $\mu\text{g/L}$ to 5,300 $\mu\text{g/L}$. Similar to the TCE plume, the *cis*-1,2-DCE plume shows an area of lower concentrations near the injection points. From April 2000 to September 2001 the maximum concentration of VC similarly decreased from 17,000 $\mu\text{g/L}$ to 4,800 $\mu\text{g/L}$ at location PES-MW1.

HANGER AVENUE

LEGEND

- INJ3 ⊙ GROUNDWATER INJECTION POINT
- SG3 ● SOIL GAS MONITORING POINT
- MW1 ○ GROUNDWATER MONITORING POINT
- MW6 ⊕ GROUNDWATER MONITORING WELL
- x — CHAIN LINK FENCE

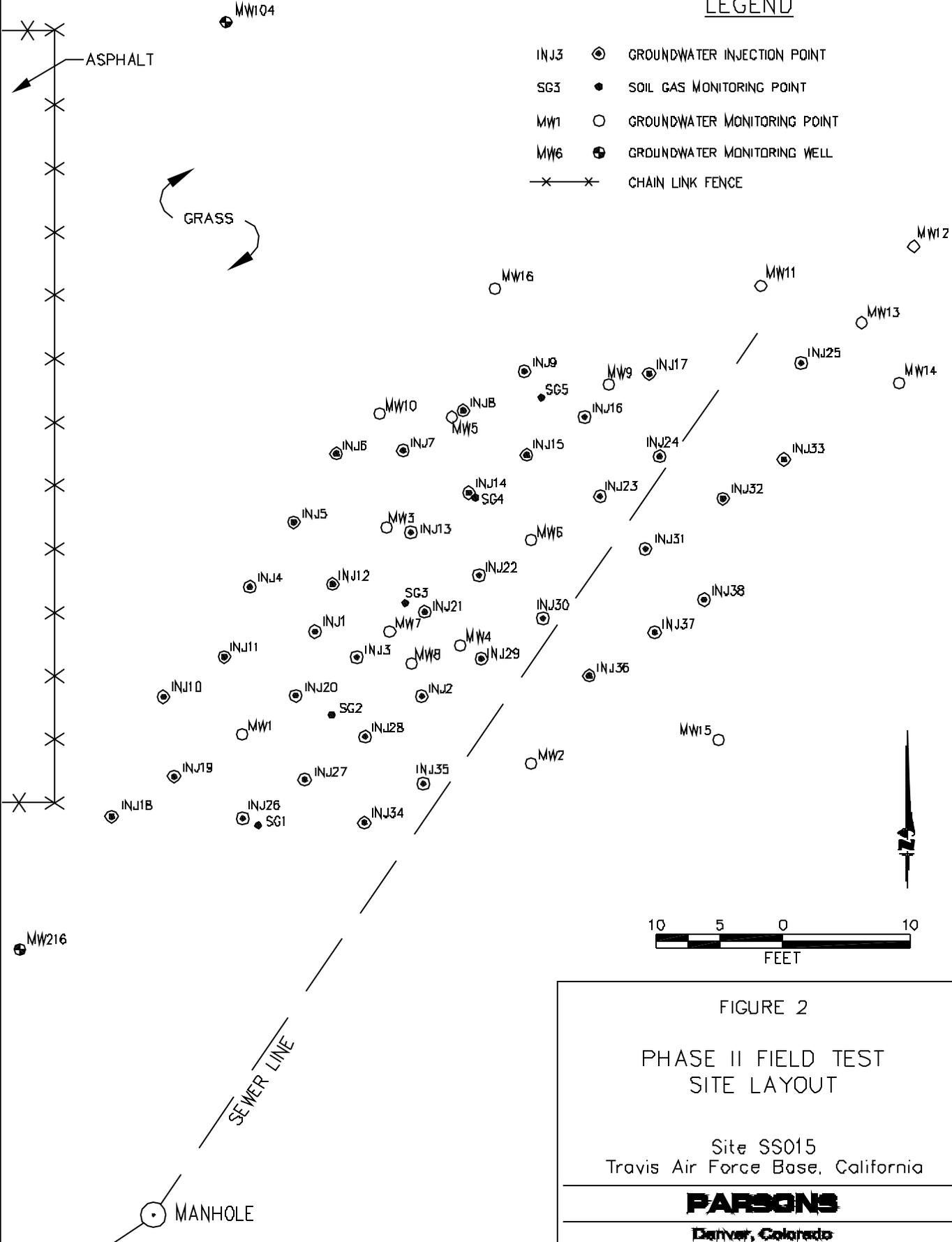


FIGURE 2

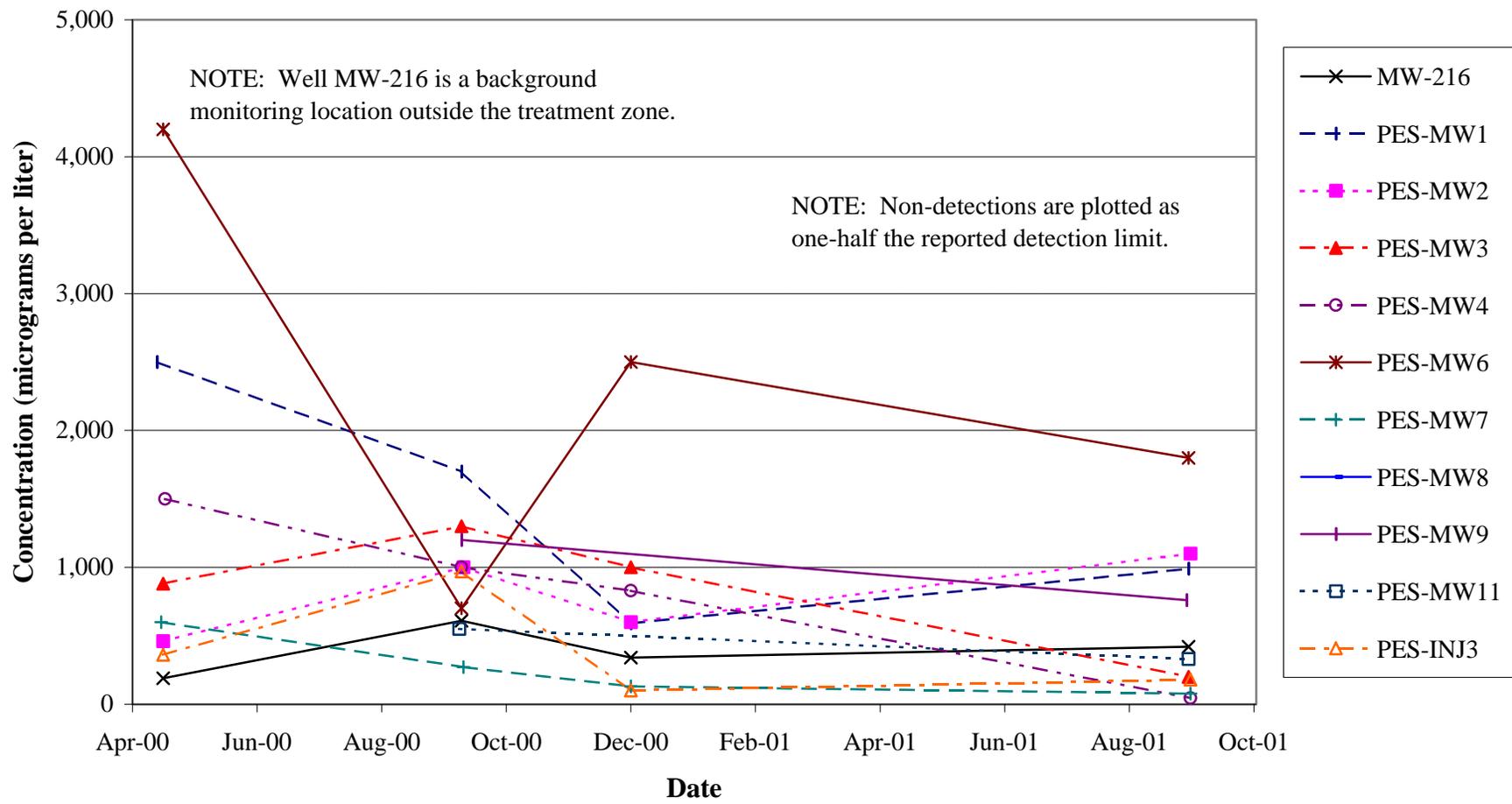
PHASE II FIELD TEST
SITE LAYOUT

Site SS015
Travis Air Force Base, California

PARSONS
Denver, Colorado

S:\ES\Remed\736116\050000\report\Phase 2 CAD\01dn0407.dwg, 03/25/02 JLH

FIGURE 3
CONCENTRATIONS OF TRICHLOROETHENE OVER TIME
SITE SS-015
TRAVIS AFB, CALIFORNIA



Elevated concentrations of CAHs in vegetable oil purged from the Phase I injection points indicates that partitioning from groundwater into the oil is occurring. This is expected, because CAHs have a greater affinity for dissolution into an oil phase relative to an aqueous phase. While partitioning of CAHs from the aqueous phase into the oil phase appears to be significant and may account for some aqueous phase contaminant reduction, it should be noted that the total volume of oil injected (approximately 227 gallons) is several orders of magnitude less than the volume of groundwater present in the Phase I and Phase II treatment zone (on the order of tens of thousands of gallons). Therefore, the actual mass of CAHs that partitions into the vegetable oil is less than that which will remain in the aqueous phase. Once an initial aqueous- and oil-phase equilibrium is reached, CAHs are released from the oil to groundwater at a rate dependent upon dissolution and/or degradation of the vegetable oil, and degradation of contaminants in the dissolved phase. In any event, contaminants are released back to groundwater within a zone of adequate substrate and optimal conditions for reductive dechlorination.

Other supporting evidence of enhanced biodegradation, including changes in concentration and in molar ratio of parent and daughter products, indicate that a substantial portion of the reduction in contaminant concentration is due to reductive dechlorination. The presence of daughter products that were not used in Base operations, particularly *cis*-1,2-DCE, VC, and ethene, provides strong evidence that PCE and TCE are being reductively dechlorinated. Progressive transformation of PCE to ethene can be indicated by computing the molar ratio of parent compounds to daughter products at a specific location.

For example, within the treatment zone, trends of chlorinated ethene concentrations and molar fractions over time for monitoring well PES-MW4 exhibit trends characteristic of reductive dechlorination (Figures 4A and 4B). Most noticeably, concentrations of PCE and TCE have decreased consistently for each sampling event. PCE decreased from 440 µg/L in April 2000 to 5.2 µg/L in September 2001, a decrease of 98.8 percent. Likewise, TCE decreased from 1,500 µg/L in April 2000 to 45 µg/L in September 2001, a decrease of 97 percent. Concentrations of *cis*-1,2-DCE first increased from 690 µg/L in April 2000 to 2,600 µg/L in September 2000, likely due to sequential degradation of PCE and TCE. However, as PCE and TCE were depleted after September 2000, the generation of *cis*-1,2-DCE was exceeded by the degradation of this compounds to VC. Concentrations of *cis*-1,2-DCE decreased to 670 µg/L in September 2001, while concentrations of VC increased from less than 100 µg/L to 2,100 µg/L. Evidence that dechlorination is proceeding to completion is indicated by an increase in the concentrations of ethene from less than 1 µg/L in December 2000 to 29 µg/L in September 2001.

Trends in molar fractions for location PES-MW4 also reflect substantial reductive dechlorination. As PCE and TCE are degraded, the respective molar fraction for these compounds decreases. The molar fraction of *cis*-1,2-DCE first increased as TCE is dechlorinated to *cis*-1,2-DCE. However, once the mass (i.e., moles) of PCE and TCE are depleted relative to *cis*-1,2-DCE, the molar fraction of *cis*-1,2-DCE decreased as the moles of *cis*-1,2-DCE degraded to VC exceeds that of TCE degraded to *cis*-1,2-DCE. At the same time, the VC molar fraction shows a dramatic increase from December 2000 to September 2001. As VC also is degraded, ethene is produced and an increase in both concentration and molar fraction of ethene was observed. Clearly, reductive

FIGURE 4A
CONCENTRATIONS OF CHLORINATED ETHENES
AT PLUME CORE MONITORING POINT PES-MW4
SITE SS-015
TRAVIS AFB, CALIFORNIA

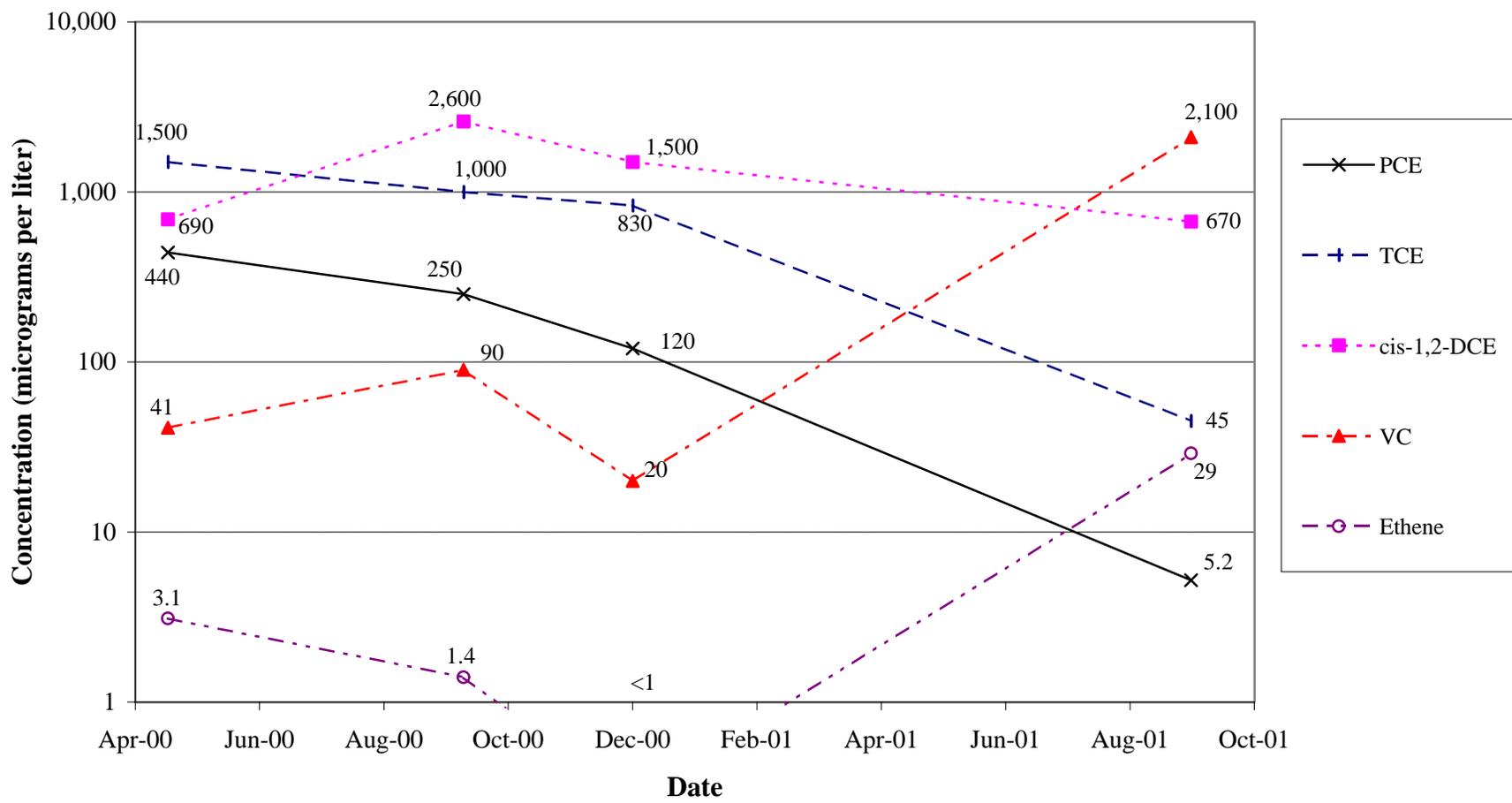
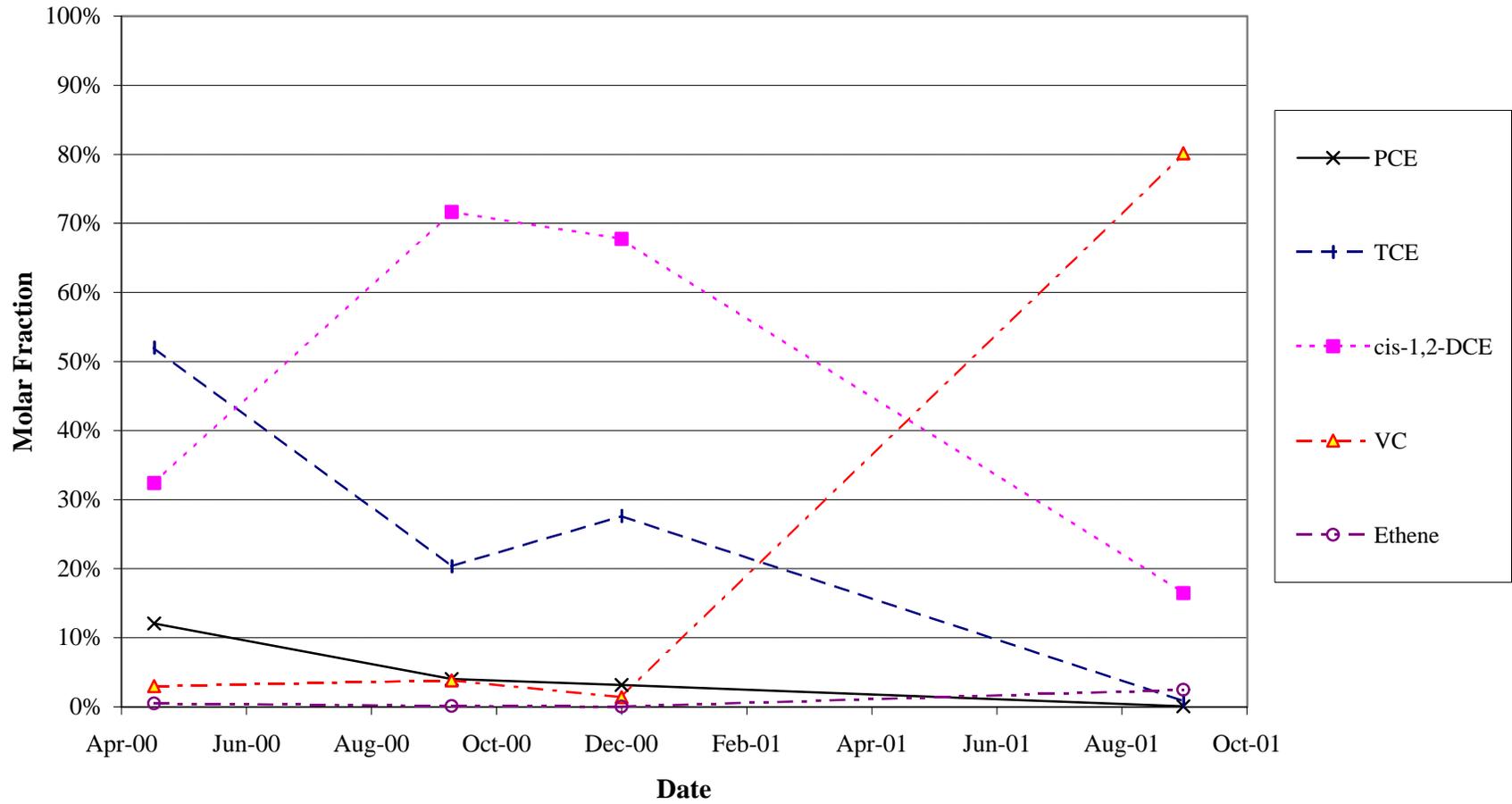


FIGURE 4B
MOLAR FRACTIONS OF CHLORINATED ETHENES
AT PLUME CORE MONITORING POINT PES-MW4
SITE SS-015
TRAVIS AFB, CALIFORNIA



dechlorination has been stimulated at location PES-MW4 by both the Phase I and Phase II injections.

Other monitoring locations also show evidence of reductive, although not to the extent as observed at location PES-MW4. Significant increases in ethene concentrations following the Phase II injection were observed. This strongly suggests that reductive dechlorination at Site SS015 is proceeding to completion.

In summary, trends in chlorinated ethene concentrations and molar fractions indicate that reductive dechlorination has been stimulated at the site by both the Phase I and Phase II injections. An overall decrease in chlorinated ethene concentrations is occurring across the site. Transformation of PCE to TCE and TCE to *cis*-1,2-DCE appear to be the most common and consistent reduction steps, but a significant amount of *cis*-1,2-DCE and VC also are being degraded. While partitioning of chlorinated ethenes into the vegetable oil NAPL may account for some reduction in aqueous-phase concentrations, molar fraction data indicate that a significant amount of contaminant reduction is due to reductive dechlorination.

5.0 FUTURE RECOMMENDATIONS

Results of the Phase II evaluation indicate that reductive dechlorination of CAHs is occurring at Site SS015 as a result of vegetable oil addition. However, high naturally occurring concentrations of sulfate appear to be a significant competing electron acceptor. To overcome the competing reaction of sulfate reduction, injection of additional vegetable oil will likely be required.

6.0 TECHNOLOGY COSTS

Cost of the Phase I pilot test totaled \$58,400. For comparison of costs to other remediation technologies, the cost of the Phase II full-scale test are listed on Table 3. Capital cost for the full scale application were \$56,800. Cost for annual process monitoring are \$24,000 per year. Additional process monitoring (annual) will likely be required for an additional 3 to 4 years.

7.0 SUMMARY OBSERVATIONS AND LESSONS LEARNED

The injection of edible vegetable oil created conditions conducive for the reductive dehalogenation of chlorinated ethenes (PCE, TCE, DCE, and VC) in groundwater at Site SS015. A pilot study was performed prior to full-scale operation. The pilot study demonstrated that reductive dehalogenation could be enhanced with addition of organic substrate in the form of food-grade soybean oil. Adequate distribution of the vegetable oil was aided by using injection pressures greater than the overburden pressure, thus fracturing the formation.

Process monitoring following the Phase II injection indicate that reductive dechlorination has been stimulated, with substantial increases in the daughter products VC and ethene. These data strongly suggest that a significant amount of reductive dechlorination at Site SS015 is proceeding to completion (i.e., ethene), even in the presence of elevated sulfate concentrations. However, it is still unknown whether the quantity of substrate added will be sufficient to remediate the site to regulatory criteria, or

whether the substrate will be depleted by competing electron acceptor processes such as sulfate reduction and methanogenesis.

TABLE 3. PHASE II TECHNOLOGY COSTS

Element	Cost (\$)
Capital Cost	
Planning and Preparation	\$12,000
Mobilization/Demobilization/Per Diem	\$3,200
Site Labor	\$18,000
Equipment and Appurtenances	
- Injection and Monitoring Points	\$3,100
- Injection System	\$1,000
- Substrate (vegetable oil)	\$1,100
- Monitoring Equipment and Supplies	\$2,200
Baseline Laboratory Analyses	\$2,600
Surveying	\$1,000
Reporting	\$12,000
Total Capital Costs	\$56,200
Operating Costs (Annual Process Monitoring)	
Mobilization/Demobilization/Per Diem	\$2,500
Direct Labor (Process Monitoring)	\$7,500
Sampling Equipment and Supplies	\$2,000
Laboratory Analysis	\$6,000
Reporting	\$6,000
Total Operating Costs	\$24,000

8.0 CONTACT INFORMATION

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9.0 REFERENCES

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