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SOIL VAPOR EXTRACTION PROGRESS REPORT AND OPTIMIZATION EVALUATION OPERABLE UNIT 2

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The objectives of this report are to: (1) assess the progress of the soil vapor extraction (SVE) system at the National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory (JPL) in Pasadena, California, and (2) provide recommendations that will help the system achieve the remedial action objections while optimizing life-cycle costs. Specific elements of this report include:

- Summary of system design and operation
- Updated conceptual site model
- Evaluation of system performance and remediation effectiveness
- Evaluation of cost effectiveness
- Identification of optimization recommendations

Site Remediation Activities

A Record of Decision (ROD) for Operable Unit 2 (OU-2) was issued in September 2002 (NASA, 2002) and documented the remedial action for vadose zone soils at the facility. The remedial action objective is to prevent, to the extent practicable, further migration of volatile organic compounds (VOCs) at potential levels of concern from the vadose zone to groundwater to protect an existing drinking water source. The remedial strategy included the use of SVE to remove VOCs from the vadose zone.

The SVE system is operated at one extraction well at a time, on a rotating basis. The SVE pilot study was initiated at extraction well VE-01 in April 1998 and testing was conducted through June 1998. Based on the results of the initial pilot study, operation of the SVE system was continued intermittently from November 1998 to May 2001. The SVE system was re-started at extraction well VE-01 in December 2001 and continued through June 2002 as part of an extended pilot study at the facility. Operation of the SVE system then continued at extraction well VE-03 from October 30, 2002 to April 30, 2003; at extraction well VE-04 from May 28, 2003 to December 4, 2003; and at extraction well VE-02 from April 20, 2004 to October 20, 2004.

The SVE system consists of four vapor extraction wells, a skid-mounted extraction vacuum blower, a moisture separator, and four granular activated carbon (GAC) vessels for treatment of the extracted vapors.

System Performance

The overall performance of the SVE system during the first operational cycle (i.e., operation at each of the four vapor extraction wells) is summarized below:

- Concentrations of VOCs have decreased significantly in the vadose zone through the first operational cycle of the SVE system.

- Carbon tetrachloride (CCl_4) and trichloroethene (TCE) are the primary VOCs with concentrations remaining above the Regional Water Quality Control Board (RWQCB) soil vapor screening levels (RWQCB, 1996).

- Results of the VLEACH™ modeling indicate that the potential mass loading from the remaining source areas will result in groundwater concentrations exceeding the maximum

contaminant levels (MCLs) at two locations, near MP-34 (for TCE) and MP-32 (for CCl_4).

- During the first operational cycle, daily mass removal rates of CCl_4 and TCE were significantly higher for VE-01 (maximum of 14 lbs/day) compared to the other vapor extraction points, including 0.35 lb/day from VE-02, 0.02 lb/day from VE-03, and 0.12 lb/day from VE-04.

- The SVE system has removed approximately 230 pounds of CCl_4 and 30 pounds of TCE since the operation began in April 1998.

- Based on the monthly mass extraction rates and the monthly operational costs, the average cost per pound of VOC mass extracted was approximately $10,000/lb for VE-01, $12,000/lb for VE-02, $100,000/lb for VE-03, and $37,000/lb for VE-04.

Recommendations

Based on the data collected during the first operational cycle, it is recommended that over the next year additional operation of the SVE system target the vapor extraction wells VE-01, VE-02, and VE-03. Further, the screened intervals which coincide with the depths where exceedances have been identified should be targeted during operation. Therefore, the zones which should be targeted for additional operation include VE-01-B, VE-01-C, VE-02-B, VE-03-A, and VE-03-B. Due to the lack of data from several plugged monitoring points near VE-01 and VE-02, it is recommended that samples be collected for laboratory analysis from each of the well screens in these extraction wells to determine if operation of additional screen intervals in these wells is warranted.

Several monitoring probes are plugged, including MP-25 (85 ft), MP-26 (80 ft), MP-28 (120 ft), MP-33 (160, 180 ft), MP-34 (35, 118 ft), MP-35 (95, 155), and MP-37 (120, 140 ft). If possible, these monitoring points should be rehabilitated so that samples can be collected during the next monitoring event to confirm VOC mass estimates and VLEACH™ modeling.

ABBREVIATIONS

1,1-DCE	1,1-dichloroethene
Caltech	California Institute of Technology
CCl_4	carbon tetrachloride
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cfm	cubic feet per minute
ERA	ecological risk assessment
FID	flame ionization detector
Freon™113	1,1,2-trichloro-1,2,2-trifluoroethane
FWEC	Foster Wheeler Environmental Corporation
GAC	granular activated carbon
HHRA	human health risk assessment
JPL	Jet Propulsion Laboratory
MCL	maximum contaminant level
NA	not applicable
NASA	National Aeronautics and Space Administration
ND	non detect
NPL	National Priorities List
OU	Operable Unit
ppmv	parts per million by volume
PVC	polyvinyl chloride
R&D	research and development
RCRA	Resource Conservation and Recovery Act
RI	Remedial Investigation
ROD	Record of Decision
ROI	radius of influence
RWQCB	Regional Water Quality Control Board
SARA	Superfund Amendments and Reauthorization Act
SQAMD	South Coast Air Quality Management District
SVE	soil vapor extraction
TCE	trichloroethene
U.S. EPA	United States Environmental Protection Agency
VOC	volatile organic compound
VSL	vapor screening level

1.0 INTRODUCTION

This report was prepared for the National Aeronautics and Space Administration (NASA) to document progress of the remedial action for Operable Unit 2 (OU-2) (NASA, 2002) at the Jet Propulsion Laboratory (JPL). The NASA-JPL site is on the United States Environmental Protection Agency (U.S. EPA) National Priorities List (NPL) and subject to the provisions of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) as amended by the Superfund Amendments and Reauthorization Act (SARA).

1.1 Objectives and Scope

The objectives of this report are to: (1) assess the progress of the soil vapor extraction (SVE) system at the NASA-JPL facility in Pasadena, California, and (2) provide recommendations that will help the system achieve the remedial action objectives while optimizing life-cycle costs. Specific elements of this report include:

- Summary of system design and operation
- Updated conceptual site model
- Evaluation of system performance and remediation effectiveness
- Evaluation of cost effectiveness
- Identification of optimization recommendations

1.2 Facility History

The JPL is a Federally Funded Research and Development Center in Pasadena, California, currently operated under contract by the California Institute of Technology (Caltech) for NASA. JPL's primary activities include the exploration of the earth and solar system by automated spacecraft and the design and operation of the Global Deep Space Tracking Network.

The Army developed and contracted with Caltech between 1939 and 1958 to conduct research and development (R&D) at JPL for ordnance activities. In December 1958, jurisdiction was transferred to NASA at which time R&D efforts at JPL began to focus on aeronautics, space technology, and space transportation. During historic operations at JPL, various chemicals (including chlorinated solvents, solid rocket fuel propellants, cooling tower chemicals, sulfuric acid, and mercury) and other materials were used at the facility.

During the 1940s and 1950s, many buildings at JPL maintained subsurface seepage pits for disposal of sanitary wastes and laboratory chemical wastes collected from drains and sinks within the buildings (Foster Wheeler Environmental Corporation [FWEC], 1999a). Some of the seepage pits received volatile organic compounds (VOCs) and other waste materials that are currently found in vadose zone soil and soil vapor beneath JPL. In the late 1950s and early 1960s, a sanitary sewer system was installed at JPL to handle sewage and wastewater, and the use of seepage pits for sanitary and chemical waste disposal was discontinued. Today, laboratory chemical wastes are either recycled or sent off-facility for treatment and disposal at regulated, Resource Conservation and Recovery Act (RCRA)-permitted hazardous waste facilities.

In 1980, the analyses of groundwater revealed the presence of VOCs in City of Pasadena water supply wells located southeast of JPL in the Arroyo Seco. At about the same time, VOCs were detected in two water supply wells used by the Lincoln Avenue Water Company, located east of the Arroyo Seco (FWEC,

1999a). In 1988, a Preliminary Assessment/Site Inspection was completed at JPL, which indicated that further site characterization was warranted (Ebasco, 1988a and 1988b). Subsequent site investigations were conducted at JPL (Ebasco, 1990a and 1990b) and VOCs were detected in on-facility groundwater at levels above drinking water standards. In 1992, JPL was placed on the NPL of sites subject to regulation under the CERCLA (47189-47187 *Federal Register*, 1992, Vol. 57, No. 199). Potential vadose zone source areas were investigated during the Remedial Investigation (RI), which was conducted from 1994 to 1998 (FWEC, 1999a). As a result of the RI, SVE pilot testing was initiated in 1998 to remove VOCs from the vadose zone.

The JPL facility has been divided into 3 Operable Units. OU-1 is on-facility groundwater at JPL; OU-2 is on-facility vadose zone soil at JPL; and OU-3 is off-facility groundwater adjacent to the JPL property.

2.0 CONCEPTUAL SITE MODEL

This section summarizes the existing conceptual site model and provides some model refinement based on monitoring data collected since the Record of Decision (ROD) for OU-2 (NASA, 2002).

2.1 Facility Setting

Located in Los Angeles County, JPL adjoins the incorporated cities of La Cañada-Flintridge and Pasadena, and is bordered on the east by the unincorporated community of Altadena. A NASA-owned facility, JPL encompasses approximately 176 acres of land and more than 150 buildings and other structures. Of the JPL Facility's 176 acres, approximately 156 acres are federally owned. The remaining land is leased for parking from the City of Pasadena and the Flintridge Riding Club. Development at JPL is primarily located on the southern half, in two regions, an early-developed northeastern area and a later-developed southwestern area. Figure 2-1 shows the location and boundaries of the JPL facility. The facility is bordered by the San Gabriel Mountains to the north, an equestrian club and Fire Station to the southwest, residential neighborhoods to the west, and the Arroyo Seco wash to the east and southeast. JPL is located in the Raymond Basin Watershed, which serves as a source of drinking water for several communities in the area. Using data from the United States Census 2000, it is estimated that approximately 44,000 people reside within 3 miles of JPL.

2.2 Geology

JPL is located immediately south of the southwestern edge of the San Gabriel Mountains, which, together with the San Bernardino Mountains to the east and the Santa Monica Mountains to the west, compose a major part of the east-west trending Transverse Ranges province of California. The Sierra Madre Fault system, located along the southern edge of the San Gabriel Mountains, includes the JPL Thrust Fault located along the northern portion of the JPL.

JPL is located in the northwest part of the Raymond Basin watershed, in the Monk Hill Subarea. Among the communities that use groundwater from the Monk Hill Subarea are Pasadena, La Cañada-Flintridge, and Altadena.

The local stratigraphy at JPL is characterized by unconsolidated alluvium sequences consisting of medium- to coarse-grained sand and gravel, interbedded with some fine sand and silt. The alluvium thickness north of the JPL Thrust Fault ranges from 2 to more than 100 feet above the crystalline bedrock and south of the fault the thickness could extend up to 1,100 feet above the bedrock (FWEC, 2000).

The average thickness of coarse sand intervals ranges from 15 to 20 feet, although beds thicker than 50 feet or more are common in some soil borings. Relatively thick intervals of gravelly sand, sandy gravel, and gravelly sand-sandy gravel are also common beneath the facility though they are slightly less abundant than the coarse sands. Average bedding thickness for these coarse-grained soil types ranges from 5 to 15 feet. Overall, the coarse-grained soil types constitute the thickest intervals of soil identified in the borings at JPL (FWEC, 2000).

Fine-grained intervals of silt and silty-sand are far less abundant in the soil borings than those composed of coarse sand and gravel. Beds of silt were identified in only a few borings throughout the site where they rarely exceeded 1.0 foot in thickness. Silty sand beds ranging from 0.5 to 10 feet in thickness are commonly interbedded with the coarser sand and gravel intervals in many locations, though they do not make up a large percentage of the total thicknesses of the soil encountered during the OU-2 investigation.

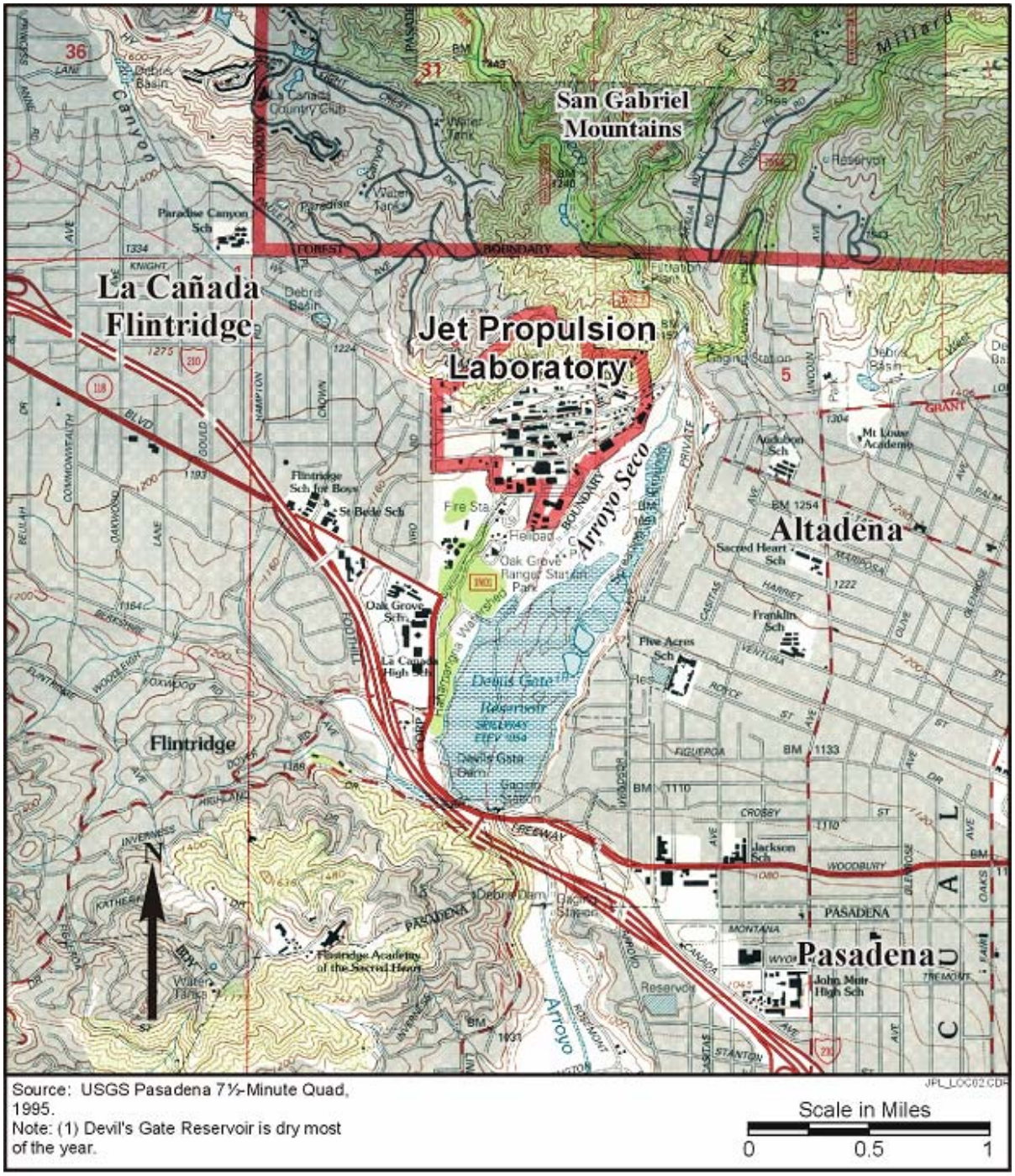

Figure 2-1. Map of JPL and Surrounding Area

2.3 Exposure Pathways

After being placed on the NPL in 1992, potential source areas were investigated within OU-2 during the RI, which lasted from 1994 to 1998 (FWEC, 1999a). As part of the RI, a Human Health Risk Assessment (HHRA) was performed to evaluate potential exposures to chemicals in vadose zone soil at JPL. These

potential exposures were quantitatively evaluated for the hypothetical on-facility resident, the commercial worker, and the construction worker. (Note that NASA has no intent to use JPL for residential sites in the foreseeable future. However, NASA based the risk assessments on potential residential use to provide the most conservative and protective results.) Direct exposures through inhalation, dermal contact, and incidental ingestion pathways were evaluated.

The RI also included an Ecological Risk Assessment (ERA), where chemical exposures were quantitatively evaluated for the deer mouse and the American kestrel. These species were used in the assessment because they generally have the highest exposure due to their diet and bioaccumulation in the food chain.

The HHRA and ERA were conducted using the analytical results from soil and soil vapor samples collected during site investigation activities at OU-2. The HHRA and ERA indicated that chemicals present in near-surface soils (<30 below ground surface [bgs]) at JPL do not pose an unacceptable risk to humans or to plant and animal life (FWEC, 1999a). However, VOCs were detected at elevated concentrations in soil vapor samples collected beneath JPL at depths extending to the water table. These VOCs could migrate to groundwater, which is a current source of drinking water. Therefore, leaching of VOCs from soil to groundwater is the exposure pathway addressed by the OU-2 remedial action. It was determined that remediation of VOCs was appropriate to prevent migration to groundwater (NASA, 2002).

2.4 Nature and Extent of Chemicals in OU-2

During the RI and periodic soil vapor monitoring, four VOCs were frequently detected in soil vapor samples at elevated concentrations. These four VOCs are carbon tetrachloride (CCl_4), 1,1,2-trichloro-1,2,2-trifluoroethane (Freon™113), trichloroethene (TCE), and 1,1-dichloroethene (1,1-DCE). The estimated horizontal and vertical extent of VOCs in soil vapor prior to operation of the SVE system is shown in Figures 2-2 and 2-3.

As part of the OU-2 ROD, VOC mass estimates were calculated using a three-dimensional computer modeling software package, EarthVision™ Volumetrics program, using data from the collected prior to SVE operation (1996-1998). Table 2-1 summarizes the historic (1996-1998) range of VOC concentrations in the vadose zone and the corresponding VOC mass estimates.

SVE pilot testing was initiated in 1998 during which over 200 pounds (lbs) of VOCs were removed from the vadose zone based on chemical analysis of the extracted vapor. The SVE system was expanded in 2002 and was operated periodically through October 2004, during which time an additional 60 lbs of VOCs were removed (Section 3.0 provides a summary of the SVE system operations). Table 2-2 summarizes the most recent range of VOC concentrations (August 2003 to July 2004) in the vadose zone and the corresponding VOC mass estimates. The most current estimates of the horizontal and vertical extent of VOCs in soil vapor is shown in Figures 2-4 and 2-5. Results of all soil vapor monitoring conducted from October 1998 to present are presented in Appendix A.

As indicated on figure 2-5, many of the soil vapor monitoring locations are plugged. These missing data are likely reducing the accuracy of the mass estimates.

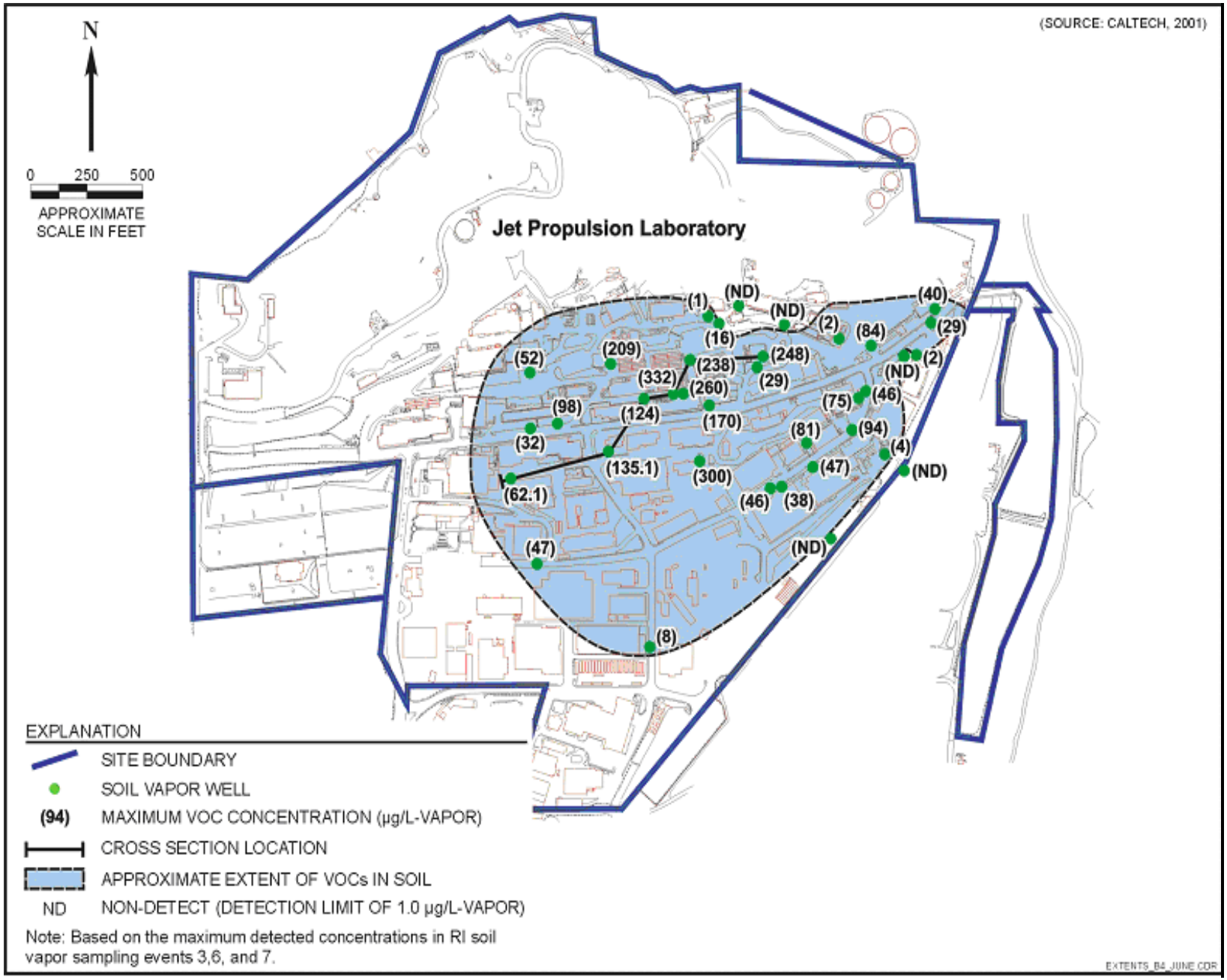

Figure 2-2: Plan View of VOC Soil Vapor Plume (May-June 1998)

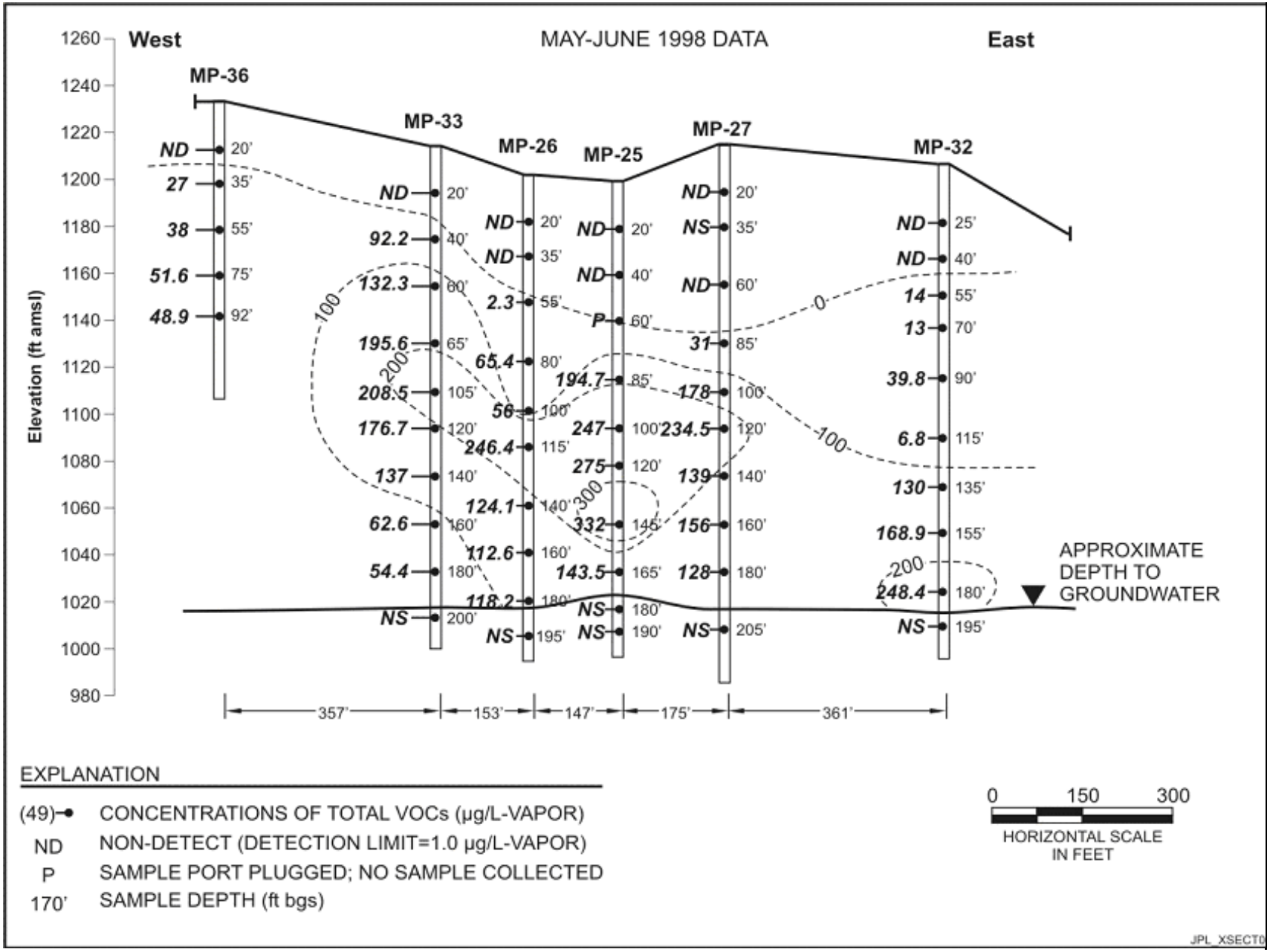

Figure 2-3. Vertical Cross Section of VOC Soil Vapor Plume (May-June 1998)

Table 2-1. Summary of Historic Soil Vapor Sampling Results (1996-1998)

Chemical	Range of Concentrations (µg/L)	Estimated VOC Mass in the Vadose Zone[(a)] (lbs)
CCl_4	ND-402	468
1,1-DCE	ND-9.8	3
Freon™113	ND-113	113
TCE	ND-47	52
Total VOCs	NA	636

Note: NA= Not Applicable

(a) Mass estimated using EarthVision™ Volumetrics program calculation.

Table 2-2. Summary of Recent Soil Vapor Sampling Results (August 2003)

Chemical	Range of Concentrations (µg/L)	Estimated VOC Mass in the Vadose Zone[(a)] (lbs)
CCl_4	ND – 11	10.7
1,1-DCE	ND – 2.5	2.2
Freon™113	ND – 9.2	4.8
TCE	ND – 33	23.2
Total VOCs	NA	40.9

Note: NA= Not Applicable

(a) Mass estimated using EarthVision™ Volumetrics program calculation

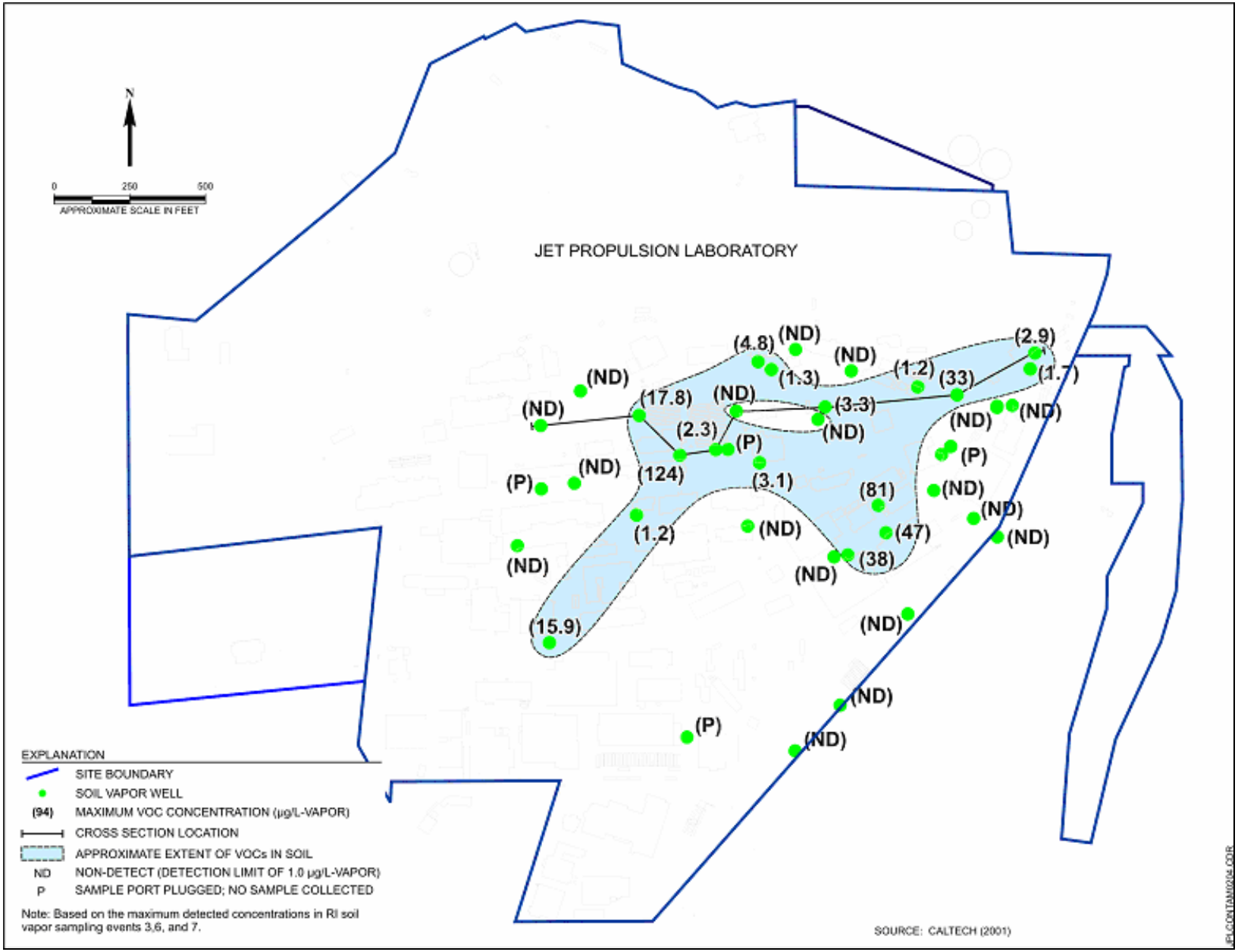

Figure 2-4. Plan View of VOC Soil Vapor Plume (August 2003)

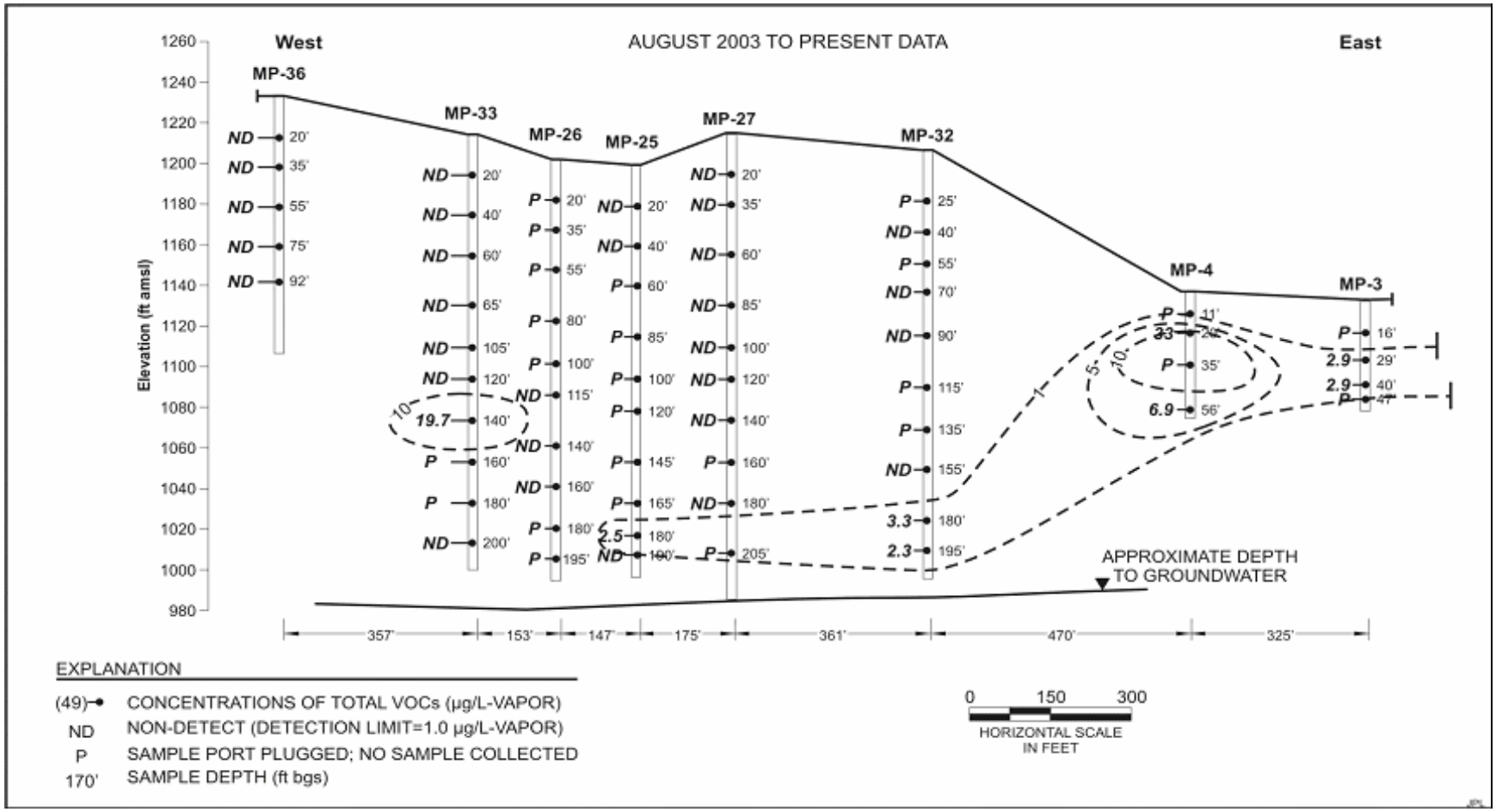

Figure 2-5. Plan View of VOC Soil Vapor Plume (August 2003)

This section summarizes SVE system design and operation.

3.1 System Design

The location of each extraction well is shown on Figure 3-1. Each vapor extraction well consists of two to four discrete screened intervals (based on the depth to groundwater) with a bentonite seal between screens. Each casing in constructed of 2-inch diameter Schedule 80 polyvinyl chloride (PVC), and screened sections are 0.020 inch slots. Screened intervals for each extraction well are summarized in Table 3-1

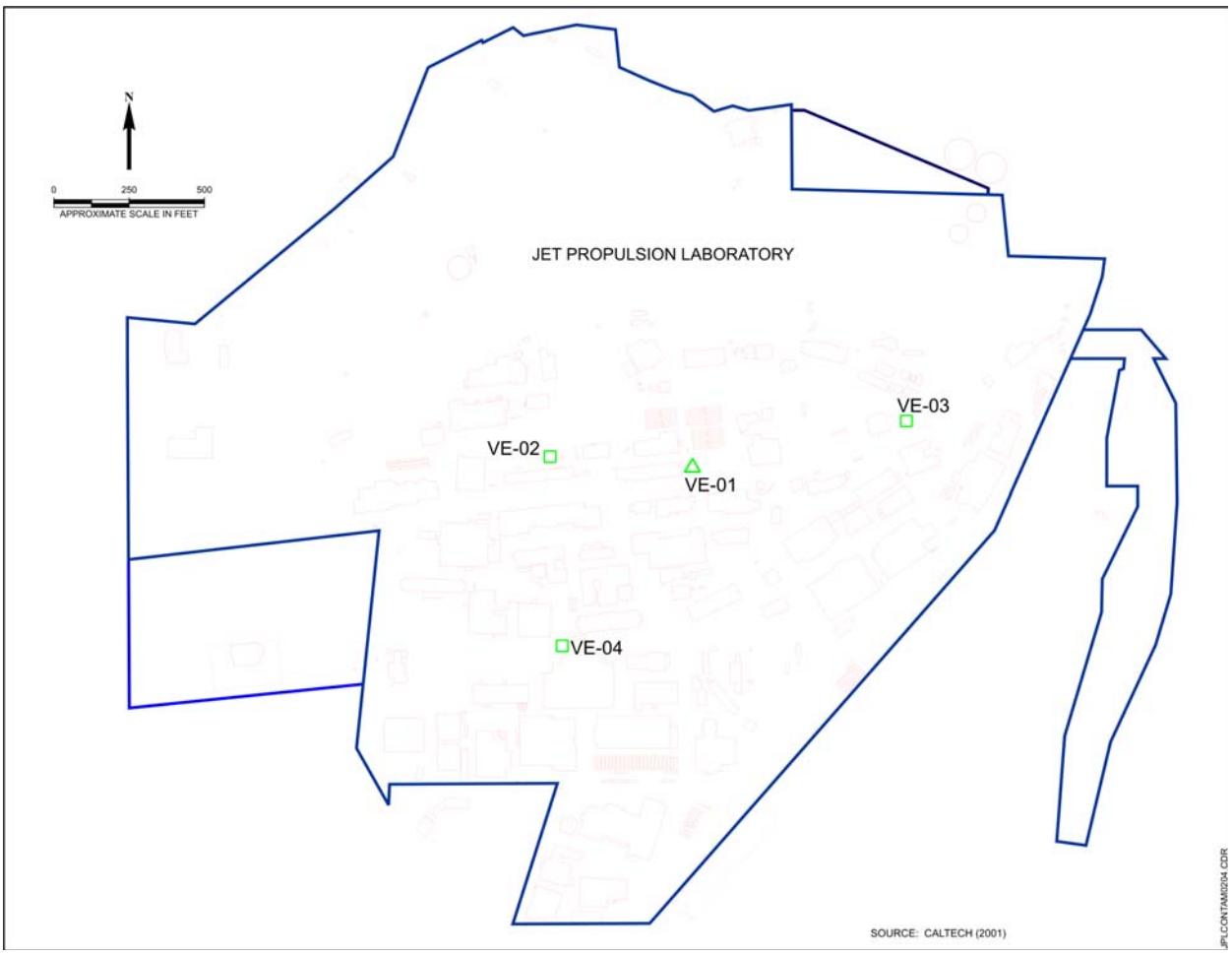

Figure 3-1: Vapor Extraction Well Locations

Table 3-1. Summary of Vapor Extraction Well Screened Intervals

Extraction Well	First Screened Interval (ft bgs)	Second Screened Interval (ft bgs)	Third Screened Interval (ft bgs)	Fourth Screened Interval (ft bgs
VE-01	44 to 84	94 to 134	145 to 185	NA
VE-02	20 to 75	88 to 98; 108 to 143	155 to 210	224 to 279[(a)]
VE-03	25 to 85	99 to 159	NA	NA
VE-04	12 to 62	76 to 126	140 to 195	NA

(a) The fourth screened interval in VE-02 collapsed following construction and is not usable.

The SVE system operates at one extraction well at a time, and consists of the following equipment:

- A skid-mounted extraction vacuum blower (with a 20 horsepower motor),
- A moisture separator (50-gallon knockout tank with sight glass, level switch, and safety interlock to shutdown blower for high water level),
- Four granular activated carbon (GAC) vessels (each containing 2,000 lbs of vapor phase GAC) in a series-parallel arrangement, and
- A dilution air valve and recirculation air valve to regulate vacuum and flow.

Other accessories include a flow meter for measuring flow, magnehelic gauges and U-tube manometers to measure vacuum and vacuum responses, a field flame ionization detector (FID), and vapor sampling equipment.

VOCs are removed from the soil by the vacuum blower and then passed through the moisture separator, in-line filter, and air mixing valve before entering the GAC vessels for treatment. The treated vapor is discharged to the atmosphere. The maximum flow rate of extracted soil vapor and ambient air combined is 500 cubic feet per minute (cfm). A schematic diagram of the SVE system is shown on Figure 3-2.

3.2 SVE Operational Summary

A SVE pilot study was initiated at VE-01 in April 1998 and conducted through June 1998. Based on the results of the initial pilot study, operation of the SVE system was continued from November 1998 to September 1999, from April 2000 to August 2000, and from January 2001 to May 2001. The SVE system was re-started at extraction well VE-01 in December 2001 and continued through June 2002 as part of an extended pilot study. Following finalization of the ROD (NASA, 2002), the SVE system began operation on a rotation program (i.e., treatment at different wells using a rotating approach with mobile equipment). The SVE system was operated at each of the four wells for approximately 6 months per well.

Since January 8, 2001, the SVE system has operated effectively, achieving a relatively high runtime efficiency, design flow rates, and effective radius of influence (ROI), and removing approximately 60 lbs of VOCs. Table 3-2 summarizes key operational parameters at each well and the following subsections describe operation at each well. Figure 3-3 is a graph showing cumulative VOC mass removal.

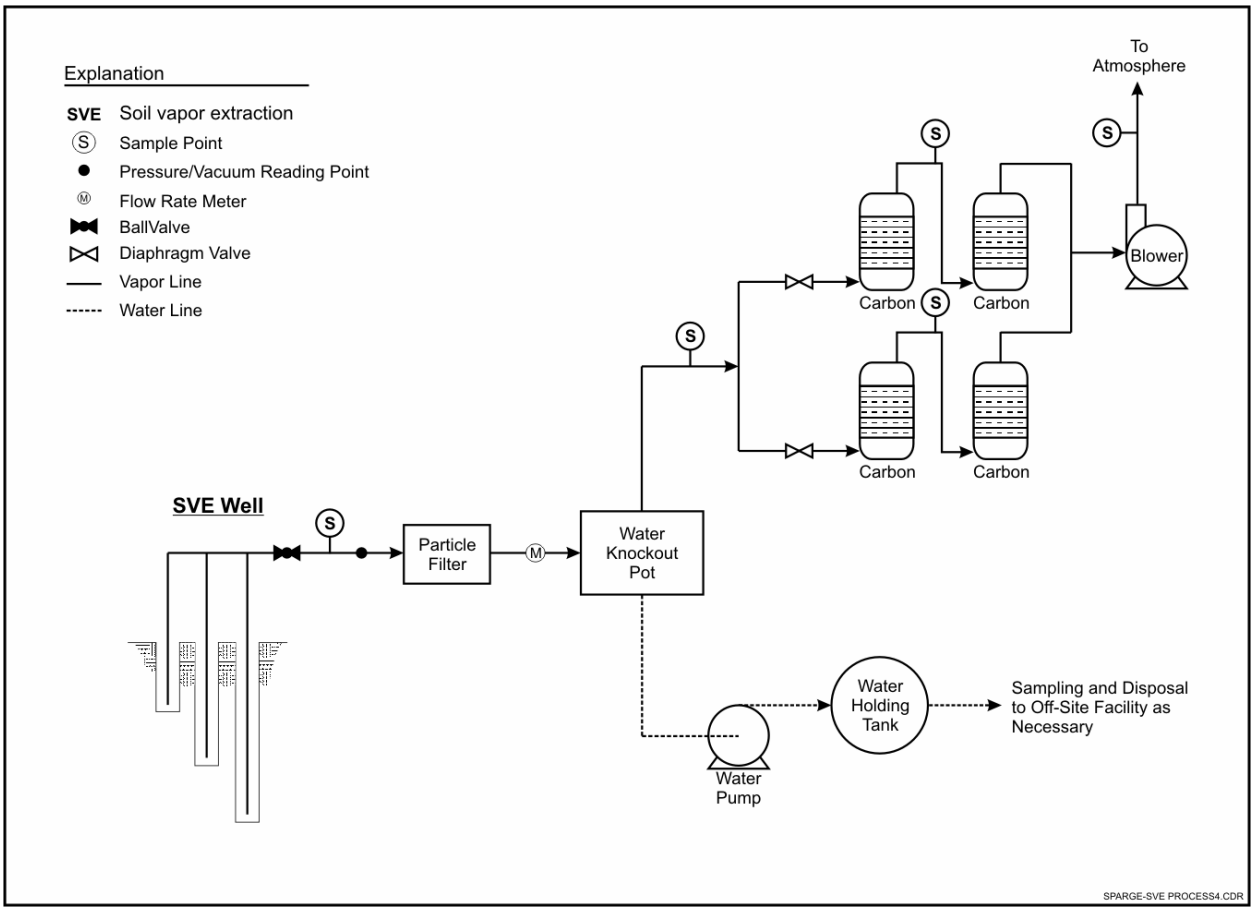

Figure 3-2: SVE Process Flow Diagram

Table 3-2. Summary of Key Operational Parameters

Extraction Well	Start Date	End Date	Runtime	Flow Rate/ Vacuum (cfm/in. water)	Influent VOC Concentrations (ppmv)	Effective Radius of Influence (ft)
VE-01	January 8, 2001	May 24, 2001	95%	300/70	0.47 to 2.13	350
	December 18, 2001	June 30, 2002	99%	450/50	0.48 – 1.14	350
VE-02	April 20, 2004	October 20, 2004	99%	340/50	1.139 to 3.169	350
VE-03	October 30, 2002	April 30, 2003	95%	370/60	0.072 to 1.806	400
VE-04	May 28, 2003	December 4, 2003	95%	300/50	0.486 to 3.243	450

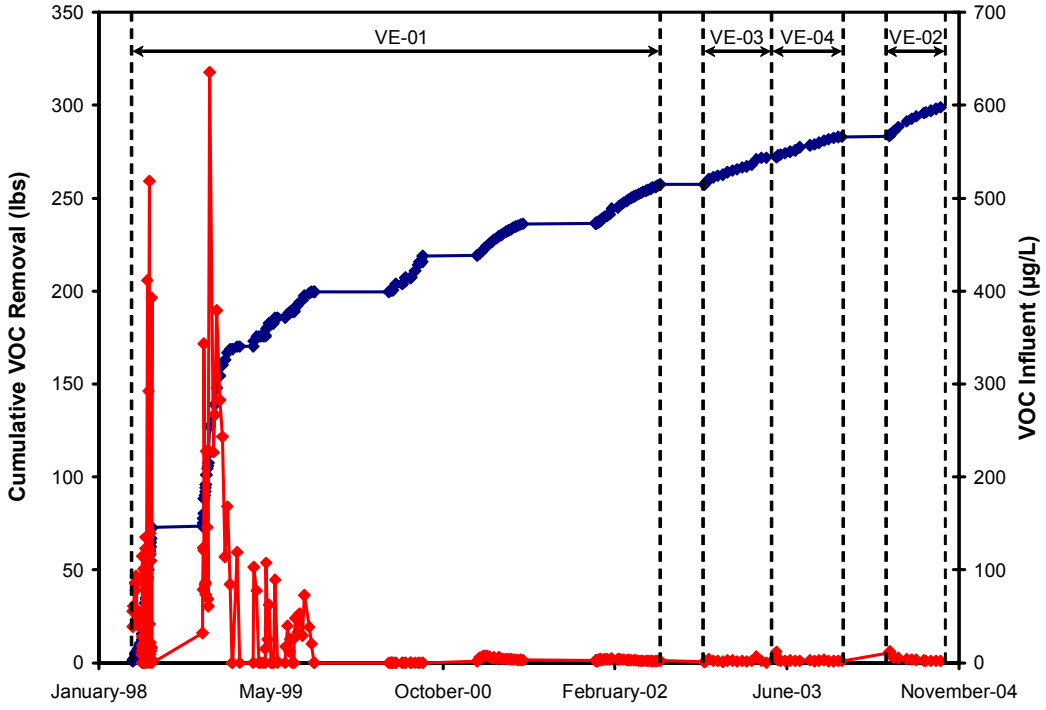

Figure 3-3: Cumulative VOC Mass Removal and Influent VOC Concentrations

3.2.1 Vapor Extraction Well VE-01. The SVE system was operated at VE-01 from January 8, 2001 through May 24, 2001, and from December 18, 2001 through June 30, 2002. The SVE system operated with two screened intervals (VE-01-B and VE-01-C) for the initial operating period from January 8 through May 24, 2001. Screened interval VE-01-A was initially taken off-line due to relatively low concentrations of VOCs in the extracted vapors from this zone (Geofon, 2001). During the first three weeks of the second operating period, vapor was extracted from each screened interval separately for a period of one week to measure VOC concentrations at the individual intervals. Screened intervals VE-01-B and VE-01-C were operated from January 4 through January 20, 2002. Screened interval VE-01-A was not operated during this time due to the presence of relatively large quantities of water in the influent. On January 21, 2002, screened interval VE-01-A was brought back on-line at a reduced vacuum and the SVE system operated with all three screened intervals until the system was shut down at the end of June 2002 (Geofon, 2002a).

The SVE system yielded an average runtime of approximately 95% during the first operating period, and 99% during the second operating period. The flow rate averaged approximately 300 cfm (first period) and 450 cfm (second period), as measured by the flow meter at an average applied wellhead vacuum of 70 and 50 inches (due to operation of different screen intervals) of water, respectively (Geofon, 2001 and Geofon, 2002a).

During the operation of VE-01, laboratory analytical results indicated that the SVE system influent VOC concentrations ranged from 0.47 to 2.13 parts per million by volume (ppmv). During the first operating period the influent VOC concentrations initially rebounded following start-up for the first five weeks, but decreased significantly from the sixth week onward (Geofon, 2001). During the second operating period, the influent VOC concentrations increased the first eight weeks, then decreased gradually from the ninth week onward (Geofon, 2002a) (see Figure 3-3).

The effective radius of influence (ROI) was calculated using measurements collected during operation of VE-01. The effective ROI is defined as the distance from the test well where the vacuum in the soil is equal to 5% of the wellhead vacuum. Therefore, the effective ROI is the distance from the well at which the vacuum in the soil was 3.5 and 2.5 inches of water for the first and second operating periods, respectively. An effective ROI was estimated to be 350 ft (Geofon, 2001 and Geofon, 2002a).

PneuLog® testing was performed at VE-01 on January 22, 2002 to obtain vertical flow profiles, estimate the thickness of the mobile and immobile soil intervals, and to evaluate if VOC-producing soil layers have been adequately targeted. Based on the PneuLog® flow results, the more highly permeable zones are located at 54 to 64 and 69 to 72 ft bgs in the shallow screened interval; from 94 to 97, 99 to 102, 115 to 118, and 124 to 129 ft bgs in the middle screened interval; and from 154 to 178 ft bgs in the deep screened interval.

3.2.2 Vapor Extraction Well VE-02. The SVE system was started at VE-02 on April 20, 2004 for continuous operation. Because the screened interval VE-02-D casing collapsed and was not usable, the SVE system was operated with screened intervals VE-02-A, VE-02-B, and VE-02-C from April 30, 2004 to October 20, 2004. Since VE-02 was started in April, the SVE system yielded an average runtime of approximately 99%. The flow rate averaged approximately 340 cfm, as measured by the flow meter at an average applied wellhead vacuum of 50 inches of water (Geofon, 2004a).

Through the end of September, laboratory analytical results indicated that the SVE system influent VOC concentrations ranged from 1.139 to 3.169 ppmv in response to different applied well vacuums to VE-02. The influent total VOC concentrations remained steady following start-up of the SVE system at VE-02 for the first two weeks, and then began to decrease gradually from the third week onward (Geofon 2004a) (see Figure 3-3).

The effective ROI was calculated using measurements collected during operation of VE-02. The effective ROI is defined as the distance from the test well where the vacuum in the soil is equal to 5% of the wellhead vacuum. The average vacuum applied to the test well was 50 inches of water; therefore, the effective ROI is the distance from the well at which the vacuum in the soil was 2.5 inches of water. An effective ROI was estimated to be 350 feet (Geofon, 2004a).

PneuLog® testing was performed at VE-02 on April 20, 20004 to obtain vertical flow profiles, estimate the thickness of the mobile and immobile soil intervals, and to evaluate if VOC-producing soil layers have been adequately targeted. Based on the PneuLog® flow results, the more highly permeable zones are located at 20 to 43 ft bgs in the shallow screened interval; from 88 to 98 and 115 to 125 ft bgs in the middle screened interval; and from 155 to 162 ft bgs in the deep screened interval (Praxis, 2004).

3.2.3 Vapor Extraction Well VE-03. The SVE system was started at VE-03 on October 30, 2002 for continuous operation. The SVE system operated with two screened intervals (VE-03-A and VE-03-B) at extraction well VE-03 through April 30, 2003. The system was shutdown form January 10 through January 20, 2003 for replacement of carbon in the GAC vessels, installation of a new flow meter, and blower overhauling. Normal operation of the SVE system began on January 21, 2003 without further shutdowns. After VE-03 was restarted, the SVE system yielded an average runtime of approximately 95%. The flow rate averaged approximately 370 cfm, as measured by the flow meter at an average applied wellhead vacuum of 60 inches of water (Geofon, 2003).

During the operation of VE-03, laboratory analytical results indicated that the SVE system influent VOC concentrations ranged from 0.072 to 1.806 ppmv in response to different applied well vacuums. The influent total VOC concentrations initially increased slightly following start-up of the SVE system at VE-

03 for the first five days, and then began to decrease gradually from the second week onward (Geofon, 2003) (see Figure 3-3).

The effective ROI was calculated using measurements collected during operation of VE-03. The effective ROI is defined as the distance from the test well where the vacuum in the soil is equal to 5% of the wellhead vacuum. The average vacuum applied to the test well was 60 inches of water; therefore, the effective ROI is the distance from the well at which the vacuum in the soil was 3 inches of water. An effective ROI was estimated to be 400 feet (Geofon, 2003).

PneuLog® testing was performed at VE-03 on October 30, 2002 to obtain vertical flow profiles, estimate the thickness of the mobile and immobile soil intervals, and to evaluate if VOC-producing soil layers have been adequately targeted. Based on the PneuLog® flow results, the more highly permeable zones are located at 25 to 35 ft bgs in the shallow screened interval; and from 98 to 100, 110 to 118, and 129 to 136 ft bgs in the deep screened interval (Praxis, 2003).

3.2.4 Vapor Extraction Well VE-04. The SVE system was started at VE-04 on May 28, 2003 for continuous operation. The SVE system operated with all three screened intervals (VE-04-A, VE-04-B, and VE-04-C) at extraction well VE-04 through December 4, 2003. The system was shutdown form August 18 through August 31, 2003 during the fifteenth periodic soil vapor monitoring event. After completion of soil vapor monitoring activities, normal operation of the SVE system began on September 1, 2003 without further shutdowns. Since VE-04 was restarted, the SVE system yielded an average runtime of approximately 95%. The flow rate averaged approximately 300 cfm, as measured by the flow meter at an average applied wellhead vacuum of 50 inches of water (Geofon, 2004b).

During the operation of VE-04, laboratory analytical results indicated that the SVE system influent VOC concentrations ranged from 0.486 to 3.243 ppmv in response to different applied well vacuums. A gradual decrease of influent total VOC concentrations was noted from the second day onward flowing SVE operation at VE-04 (Geofon, 2004b) (see Figure 3-3).

The effective ROI was calculated using measurements collected during operation of VE-04. The effective ROI is defined as the distance from the test well where the vacuum in the soil is equal to 5% of the wellhead vacuum. The average vacuum applied to the test well was 50 inches of water; therefore, the effective ROI is the distance from the well at which the vacuum in the soil was 2.5 inches of water. An effective ROI was estimated to be 450 feet (Geofon, 2004b).

PneuLog® testing was performed at VE-04 on May 28, 2003 to obtain vertical flow profiles, estimate the thickness of the mobile and immobile soil intervals, and to evaluate if VOC-producing soil layers have been adequately targeted. Based on the PneuLog® flow results, the more highly permeable zones are located at 12 to 13, 41 to 43, and 48 to 51 ft bgs in the shallow screened interval; and from 76 to 76.5 and 85 to 103 ft bgs in the middle screened interval (Praxis, 2002b).

3.2.5 Permit and Performance Monitoring. SVE system influent and effluent (stack) vapor samples were collected in accordance with the South Coast Air Quality Management District (SCAQMD) permit conditions. All samples were analyzed for VOCs using an FID calibrated to hexane, as required by the SCAQMD. In addition, the SVE system influent, effluent, and individual screened interval vapor samples were collected for laboratory analyses once every week during operation of VE-01, and once every two weeks during operation of VE-02, VE-03, and VE-04. The SVE system achieved greater than 99% removal efficiencies for CCl_4 and TCE and all emission rates were within the permit requirements set by the SCAQMD (Geofon 2001, 2002a, 2003, 2004a and 2004b).

A remedial approach was documented in the ROD (NASA, 2002) that consisted of SVE operation, performance monitoring, optimization, and an exit strategy (see Figure 4-1).

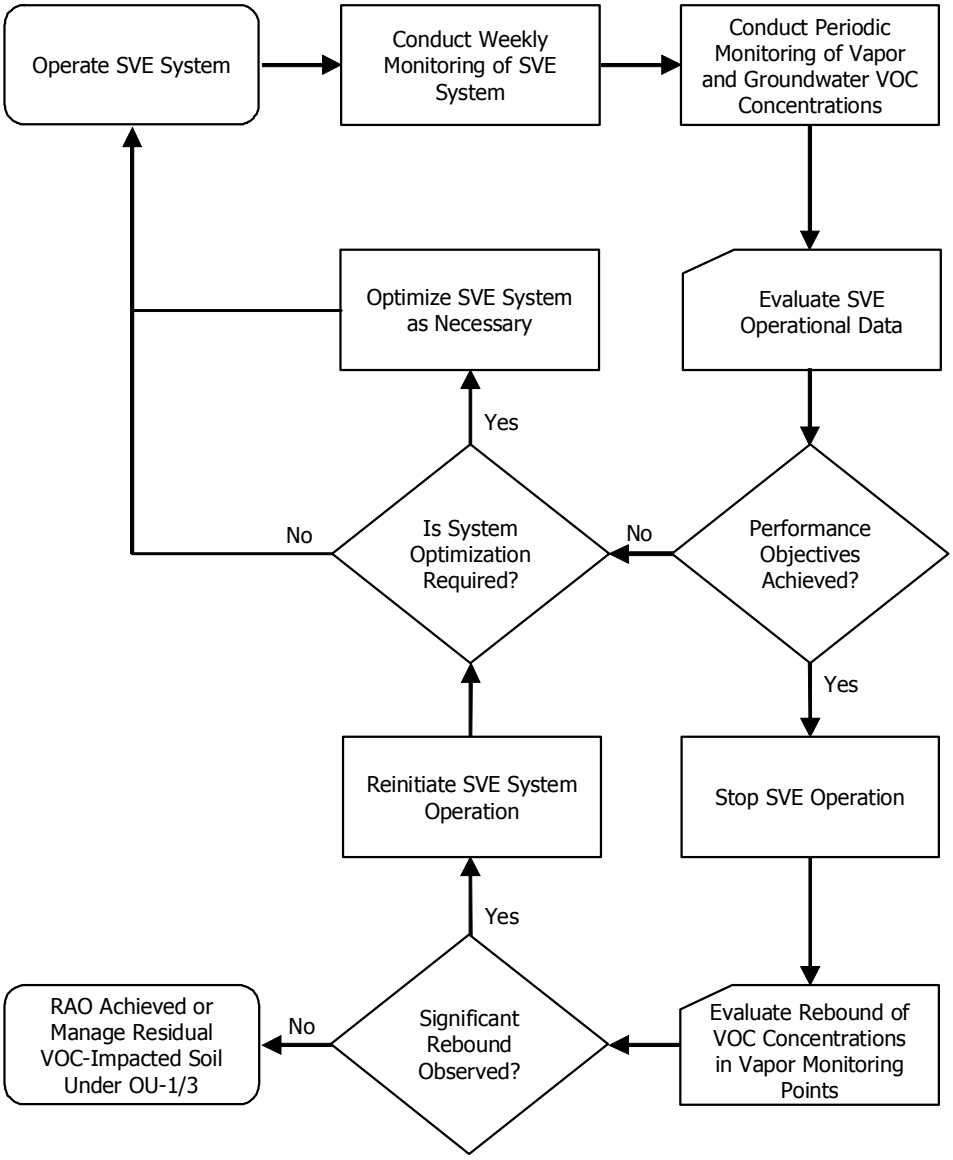

Figure 4-1. Remedial Approach Flowchart

As part of the remedial approach, the SVE system will be operated and optimized until performance objectives have been achieved. The performance objectives include the following:

- Reduction of overall VOC concentrations at the vapor monitoring points and extraction wells compared to baseline levels. This includes fate and transport modeling to evaluate

leaching to groundwater (using Regional Water Quality Control Board [RWQCB] guidance [RWQCB, 1996] and/or VLEACH™) and groundwater mixing.

- Asymptotic mass removal achieved after temporary shutdown periods and appropriate optimization of the SVE system. Asymptotic conditions will have been reached at a given SVE well when the upper limb of the cumulative mass removal curve is substantially linear and the slope of the curve approaches zero. In addition, rebound of chemical concentrations will be evaluated during the temporary shutdown periods. A general asymptotic decreasing trend in rebound of chemical concentrations in the soil vapor monitoring points will be demonstrated. Time series plots of VOC concentrations at each soil gas monitoring point will be prepared to assist in evaluation of rebound.

- Operate only as long as cost-effective. The SVE system will no longer be cost-effective when operating costs per unit of VOC mass removed from the vadose zone indicate that the additional cost of continuing to operate the SVE system is not warranted and/or when shutdown of the SVE system is not anticipated to significantly increase the cost of the groundwater remedy or significantly prolong the time to achieve groundwater cleanup.

Each performance objective is evaluated in the following subsections.

4.1 VOC Concentration Reduction

The first remedial performance objective for the SVE system is reduction of overall VOC concentrations compared to baseline levels and to concentrations protective of chemical leaching to groundwater. To identify the remaining chemicals of interest at the facility, data from the last one year of soil vapor monitoring (August 2003 to July 2004) was compared to soil vapor screening levels (VSLs) calculated from the RWQCB 1996 Interim Site Assessment and Cleanup Guidebook (RWQCB, 1996). This initial screening indicates that soil vapor concentrations exceed the screening values at 8 monitoring points (including 11 depth intervals) for CCl_4, at 2 monitoring points (including 4 depth intervals) for TCE, and at one monitoring point and depth interval for benzene. Table 4-1 presents a summary of the exceedances, and a complete table of the screening results is provided in Appendix B. Exceedances of the benzene screening level occurred in August 2003 and April 2004; however, the most recent sampling result from July 2004 was below the screening level. Also, the detection of benzene in MP-17 is collocated with a CCl_4 exceedance. Based on this evaluation, CCl_4 and TCE have been identified as the primary chemicals of interest; therefore, the additional data analysis in this report will focus on these two VOCs.

An alternate method for predicting the potential for VOC mass remaining in the vadose zone to migrate to the groundwater was used to evaluate the recent soil vapor data. The VLEACH™ model uses a computer code for estimating the impact due to the mobilization and migration of sorbed organic chemicals located in the vadose zone on the underlying groundwater resource. It is important to note that the model does not incorporate groundwater mixing, but rather only evaluates the impact to groundwater directly beneath a source area.

A VLEACH™ model was set up using site specific hydrogeology and recent CCl_4 and TCE soil vapor data. The model was used to estimate mass loading and potential concentrations in groundwater near areas where soil vapor concentrations of CCl_4 and TCE concentrations exceed VSLs. Four CCl_4 source areas and three TCE source areas were defined and are shown on Figure 4-2. Assumptions and parameters used for the VLEACH™ modeling are provided in Table 4-2. Results of the VLEACH™ model simulations are summarized in Table 4-3.

Table 4-1. Summary of Soil Vapor Screening Results

Soil Vapor Well Number	Depth (ft bgs)	Date	Concentration (µg/L)	Leaching Depth (ft)	VSL (µg/L)
Carbon Tetrachloride					
3	29	08/19/03	2.9	19	0.19
3	40	08/19/03	2.9	8	0.10
5	9	08/19/03	1.7	32	0.30
17	36	04/06/04	5.9	165	3.65
25	180	08/22/03	1.4	55.4	0.83
27	180	08/25/03	2.7	74.6	1.40
32	180	08/20/03	3.3	56	0.84
32	195	08/20/03	2.3	41	0.40
33	105	08/21/03	7	130.4	3.07
33	140	08/21/03	11	95.4	2.02
33	140	08/21/03	8.8	95.4	2.02
39	100	08/28/03	2.1	71	1.29
39	100	04/08/04	2.3	71	1.29
Trichloroethene					
4	20	08/19/03	26	104.4	8.52
4	20	08/19/03	28	104.4	8.52
4	20	02/02/04	21	104.4	8.52
4	20	04/06/04	24	104.4	8.52
4	20	07/14/04	33	104.4	8.52
4	56	02/02/04	14	68.4	4.51
4	56	02/02/04	12	68.4	4.51
4	56	04/06/04	14	68.4	4.51
4	56	07/14/04	6.9	68.4	4.51
39	100	08/28/03	5.2	71	4.80
39	130	08/28/03	8.2	41	1.47
Benzene					
17	36	08/20/03	110	165	39.57
17	36	08/20/03	90	165	39.57
17	36	04/06/04	76	165	39.57

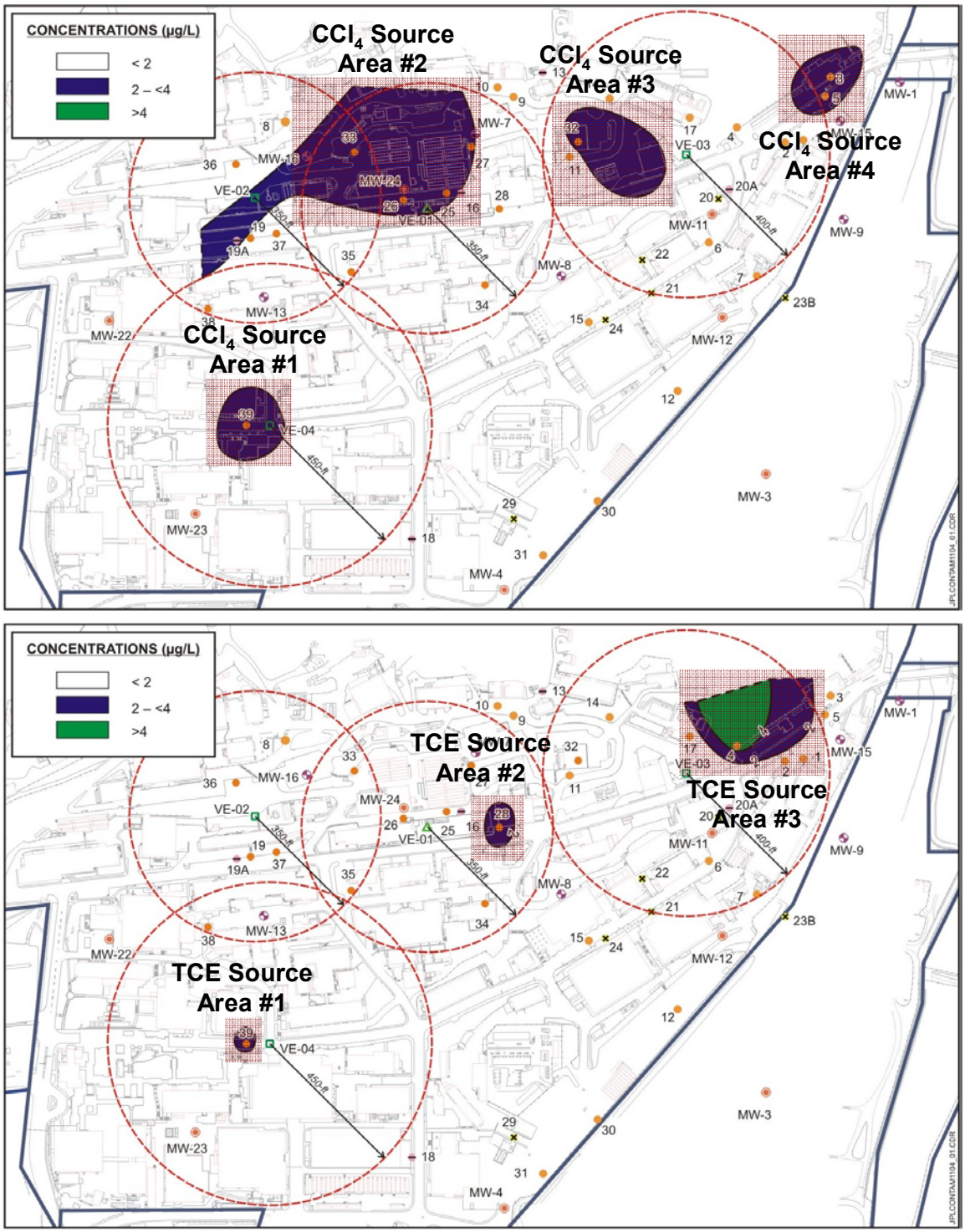

Figure 4-2. VLEACH™ Modeling Source Areas

Table 4-2. Summary of VLEACH™ Input Parameters

Parameter	CCl_4 Source Areas				TCE Source Areas		
	No.1	No. 2	No. 3	No. 4	No.1	No. 2	No. 3
Area (ft^2)	40,000	200,000	60,000	30,000	2,500	15,000	70,000
Net Recharge Rate (ft/yr)	10	10	10	10	10	10	10
Dry Bulk Density (g/cm^3)	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Effective Porosity	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Organic Carbon Content	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Organic Carbon Distribution Coefficient (ml/g)	436	436	436	436	125.9	125.9	125.9
Henry's Constant	0.81	0.81	0.81	0.81	0.373	0.373	0.373
Water Solubility (mg/L)	800	800	800	800	1100	1100	1100
Free Air Distribution Coefficient	0.674	0.674	0.674	0.674	0.7435	0.7435	0.7435

Table 4-3. VLEACH™ Modeling Results

Source Area	Estimated Maximum CCl_4 Concentration in Groundwater (µg/L)	Estimated Maximum TCE Concentration in Groundwater (µg/L)
CCl_4 No. 1	0.16	NA
CCl_4 No. 2	0.15	NA
CCl_4 No. 3	4.2	NA
CCl_4 No. 4	0.12	NA
TCE No. 1	NA	2.4
TCE No. 2	NA	0.96
TCE No. 3	NA	11.4

Based on the VLEACH™ model results, the potential mass loading from the source areas (as identified by exceedances of the RWQCB VSLs) will result in groundwater concentrations exceeding the groundwater maximum contaminant levels (MCLs) at only two locations, near MP-34 for TCE and near MP-32 for CCl_4.

Figures 4-3A/B and 4-4A/B show the CCl_4 and TCE concentrations prior to operation of the SVE system and at the latest facility-wide monitoring event conducted in August 2003. These figures illustrate that the overall extent of soil vapor contamination has significantly decreased since operation of the SVE system began. However, during the last several sampling events some of the vapor monitoring probes were plugged and samples could not be collected. CCl_4 and/or TCE were detected

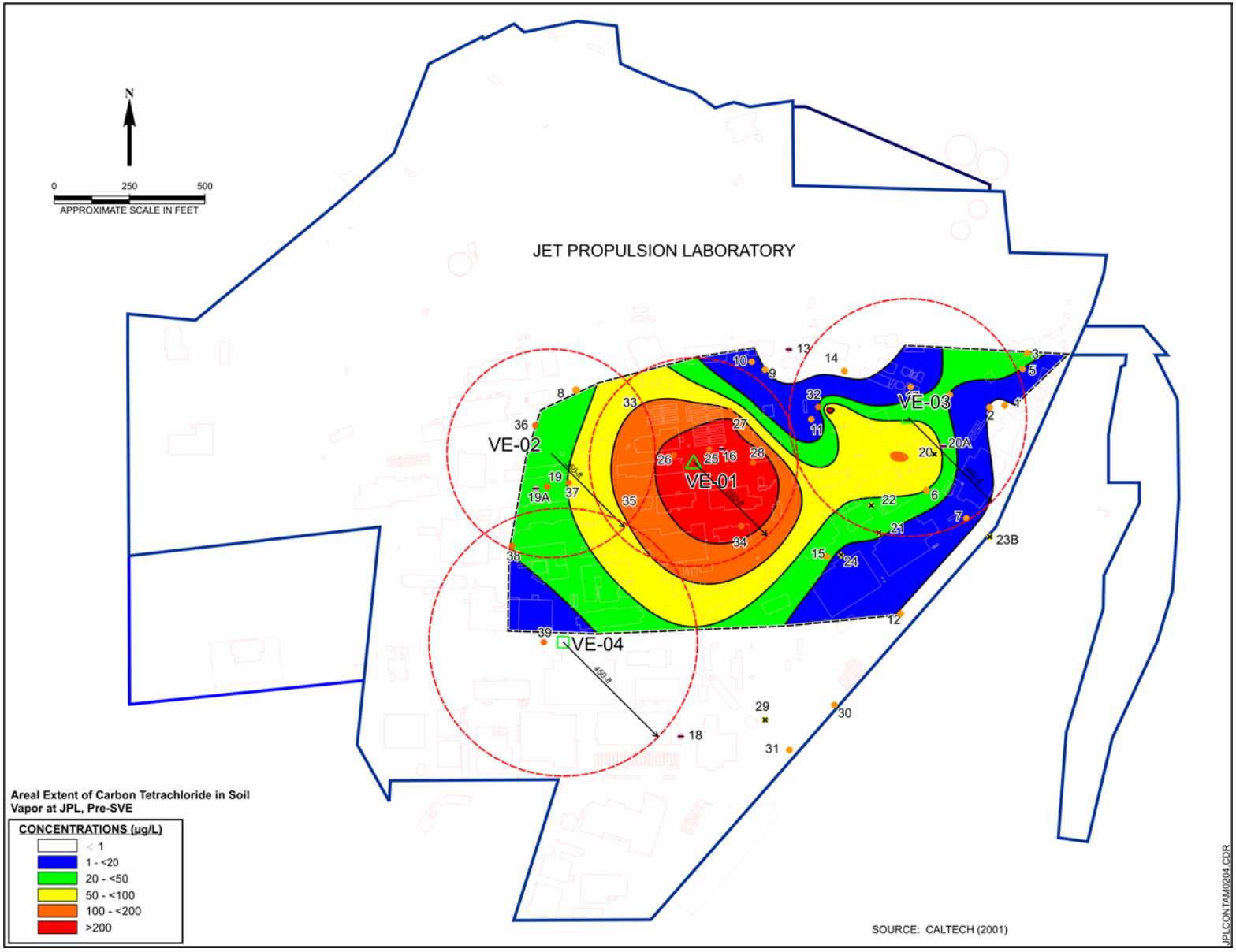

Figure 4-3A. Carbon Tetrachloride Concentrations (Pre-SVE)

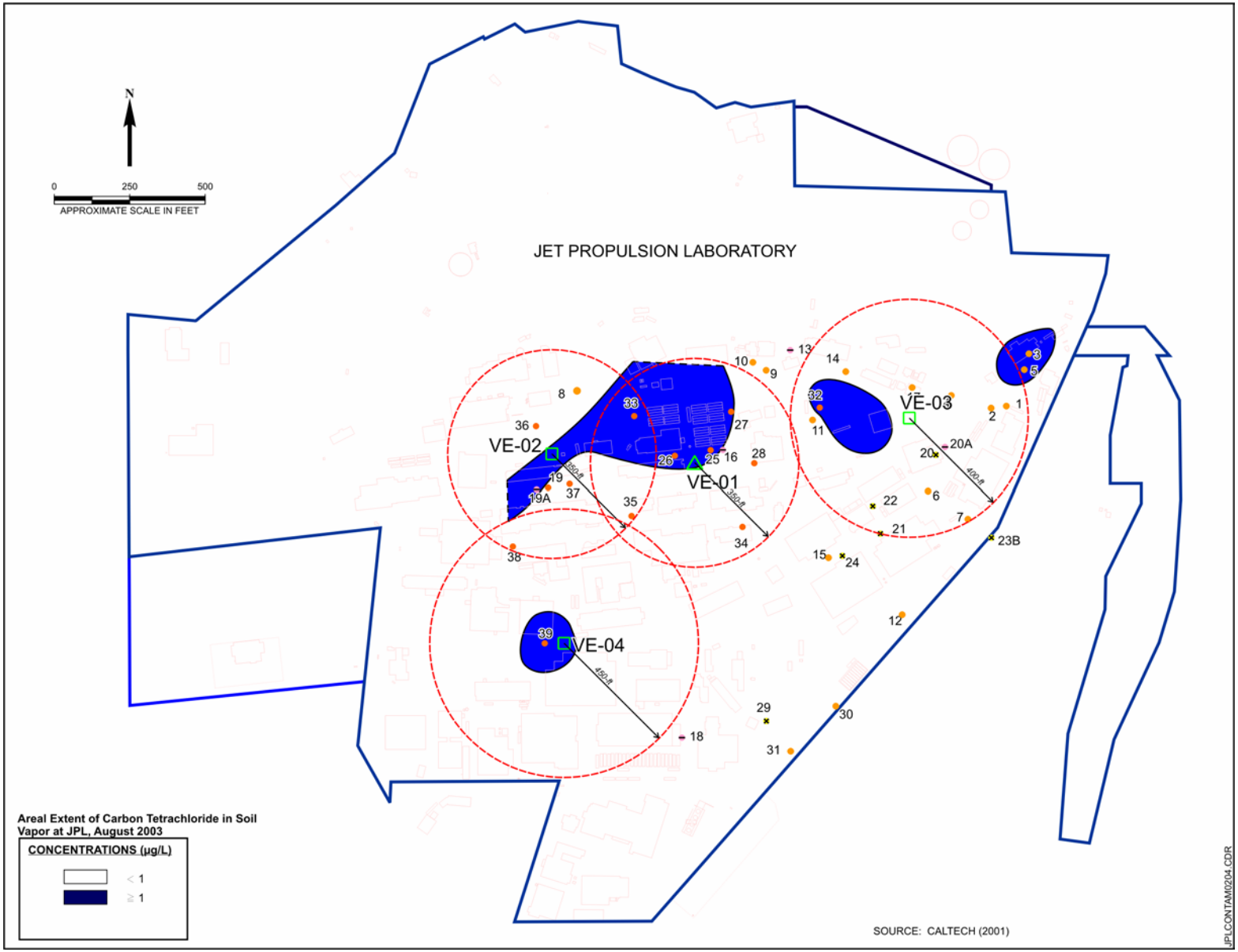

Figure 4-3B. Carbon Tetrachloride Concentrations (August 2003)

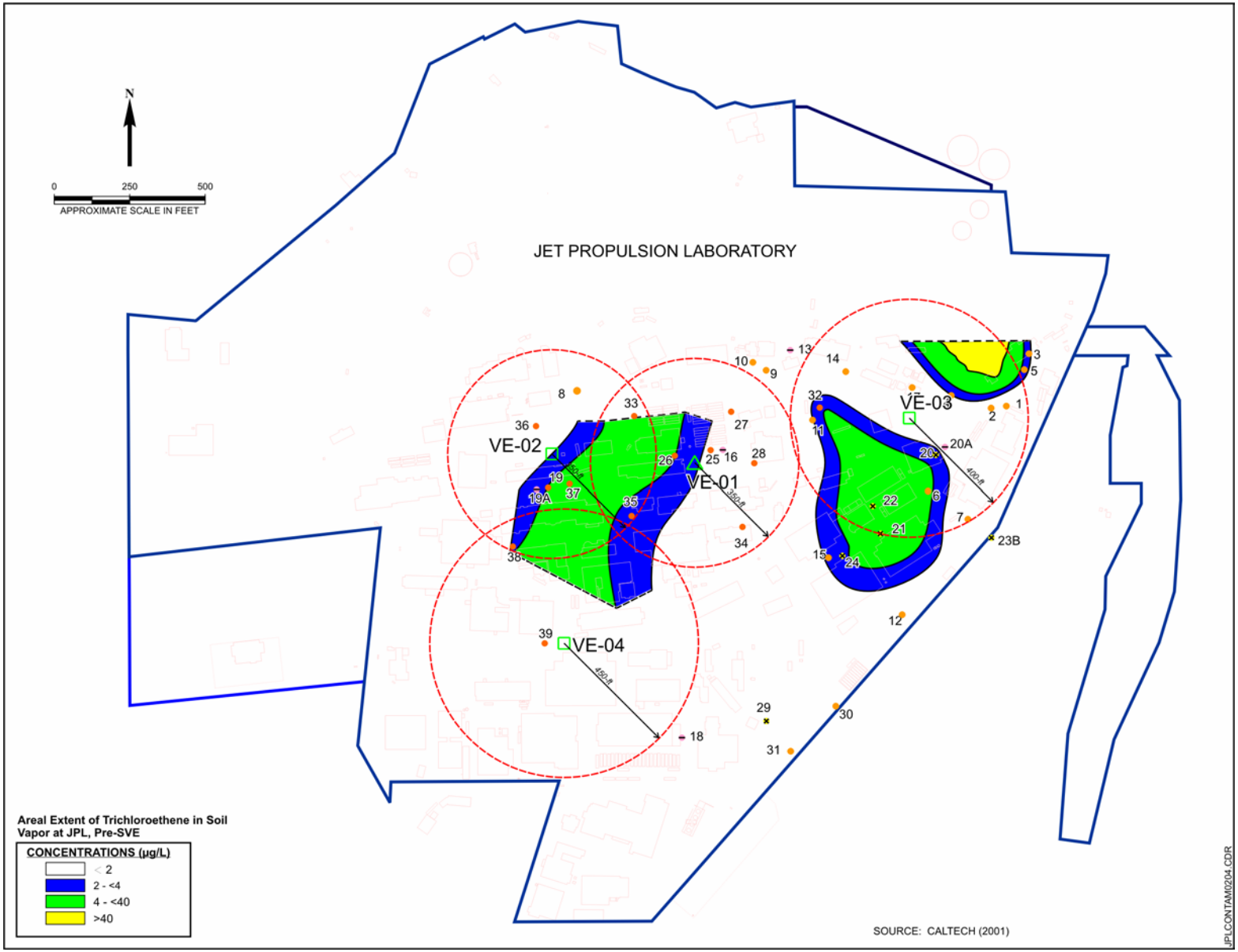

Figure 4-4A: Trichloroethene Concentrations (Pre-SVE)

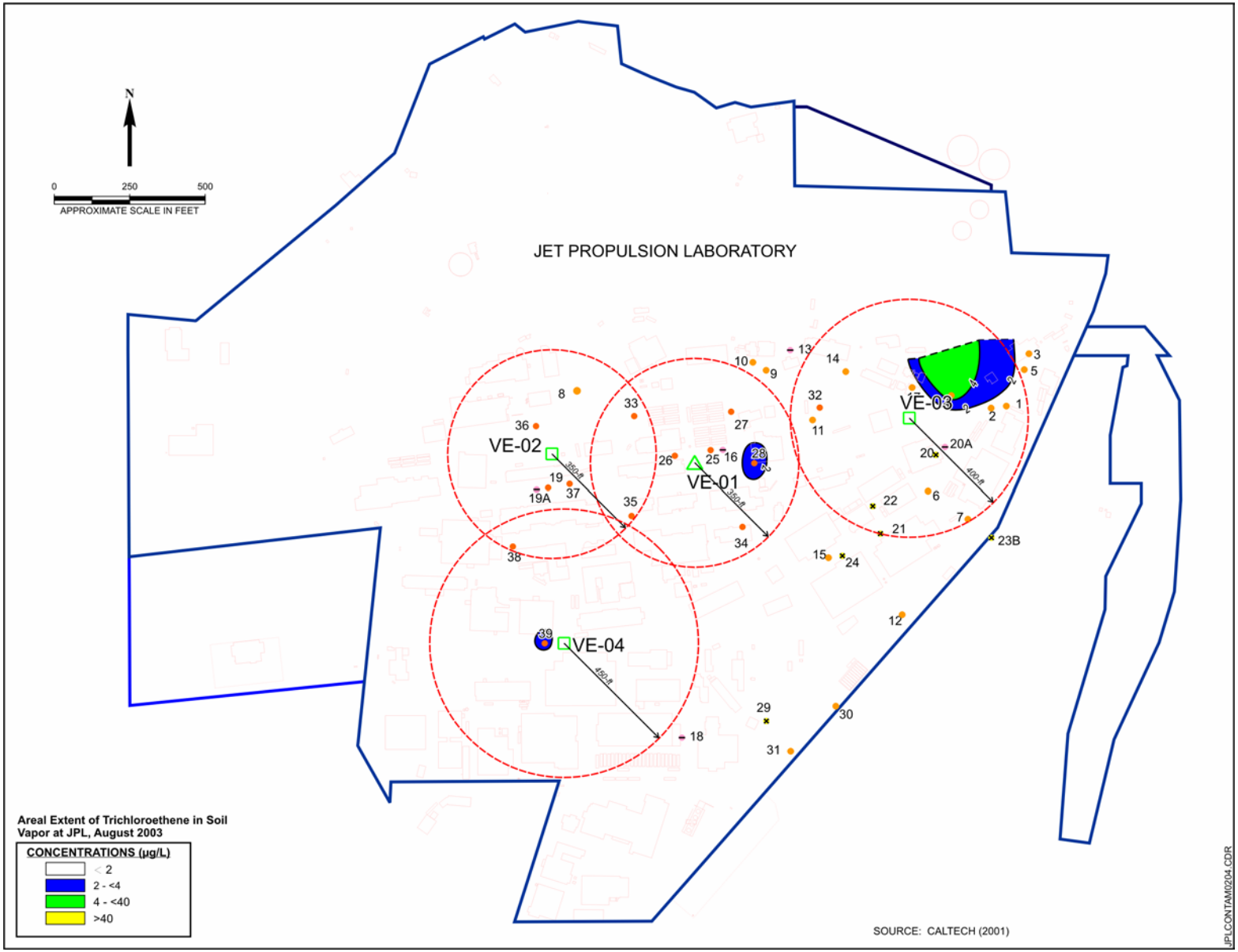

Figure 4-4B: Trichloroethene Concentrations (August 2003)

in the last sample collected before plugging occurred at vapor monitoring probes MP-25, MP-26, MP-27, MP-33, MP-34, MP-35, and MP-37, and recent data was not available to be evaluated as part of this optimization study.

A table of extracted vapor concentrations measured at each of the extraction well screen intervals during start-up of the wells is provided in Appendix C. In addition, PneuLog® testing was conducted at each extraction well prior to start-up in order to estimate the thickness of the mobile and immobile soil intervals, and to measure VOC concentrations in various depths along each screen interval. Table 4-4 presents a summary comparison of the start-up data, the PneuLog® data, and the vapor monitoring point data. In general, concentrations from the extraction well screens are lower than those measured at discrete depths from the monitoring points. This is expected due to the larger intervals covered by the extraction well screens as compared to the vapor monitoring probes.

Table 4-4. Comparison of Extraction Well Data and Vapor Monitoring Point Data

Extraction Well	Concentration Range from PneuLog® Testing[(a)] (µg/L)		Concentration Range from Extraction Well Screens at Start-up (µg/L)		Concentration Range from Corresponding Vapor Monitoring Points (µg/L)	
	CCl_4	TCE	CCl_4	TCE	CCl_4	TCE
VE-01A	360 – 650	ND	0.5 – 9.5	ND – 0.09	ND – 14	ND – 1.2
VE-01B	260 – 300	180 – 310	0.4 – 8.1	0.01 – 1.0	ND – 15	ND – 1.6
VE-01C	120 - 200	220 – 400	0.3 – 5.4	1.6 – 2.1	ND - 13	ND – 5.5
VE-02A	775 – 1634	2020 – 4092	20.3 – 5.6	1.6 – 12.4	ND – 2.4	ND – 11.0
VE-02B	379 – 615	938 – 1196	1.8– 3.8	0.4 – 5.4	ND	ND
VE-02C	202 - 951	299 - 850	0.6 – 1.0	0.1 – 1.5	ND	ND – 1.2
VE-03A	ND	ND	ND – 0.03	0.003 – 0.03	ND – 2.9	ND – 33
VE-03B	ND	ND	0.1 – 0.4	0.01 – 0.5	ND	ND
VE-04A	109 – 439	512 – 1271	0.05 – 0.1	0.02 – 1.2	ND	ND
VE-04B	404 - 1162	2256 - 2486	0.3 – 0.8	0.07 – 8.2	ND – 2.2	ND – 5.2
VE-04C	NS	NS	0.1 – 0.3	0.02 – 2.9	ND – 1.0	ND – 17

NS = Not Sampled
ND = Below Detection Limit

It is important to note that PneuLog® samples were analyzed by a field gas chromatograph, while samples from the extraction wells and vapor monitoring points were analyzed by a state-certified laboratory. During the PneuLog® testing for VE-03, data from the field gas chromatograph was compared to that from state-certified laboratory analysis, and the vapor concentrations were significantly higher using the field gas chromatograph. This is likely due to several unidentified compounds being quantified with the field gas chromatograph (Praxis, 2002b). Therefore, the data from the PneuLog® samples are not considered valid.

Figures 4-5 through 4-10 show CCl_4 and TCE concentration trends at vapor monitoring points where exceedances of the soil screening values were identified. These figures show an overall decreasing trend with time at most monitoring points; however, rebound of chemical concentrations to levels above the screening criteria is identified in monitoring points MP-4 and MP-39. Vapor monitoring point MP-4 is located within the radius of influence for VE-03, and TCE concentrations at this vapor monitoring point decreased during operation of VE-03. However, the concentrations have rebounded to pre-treatment levels since the system stopped operating at this location. Vapor monitoring point MP-39 is

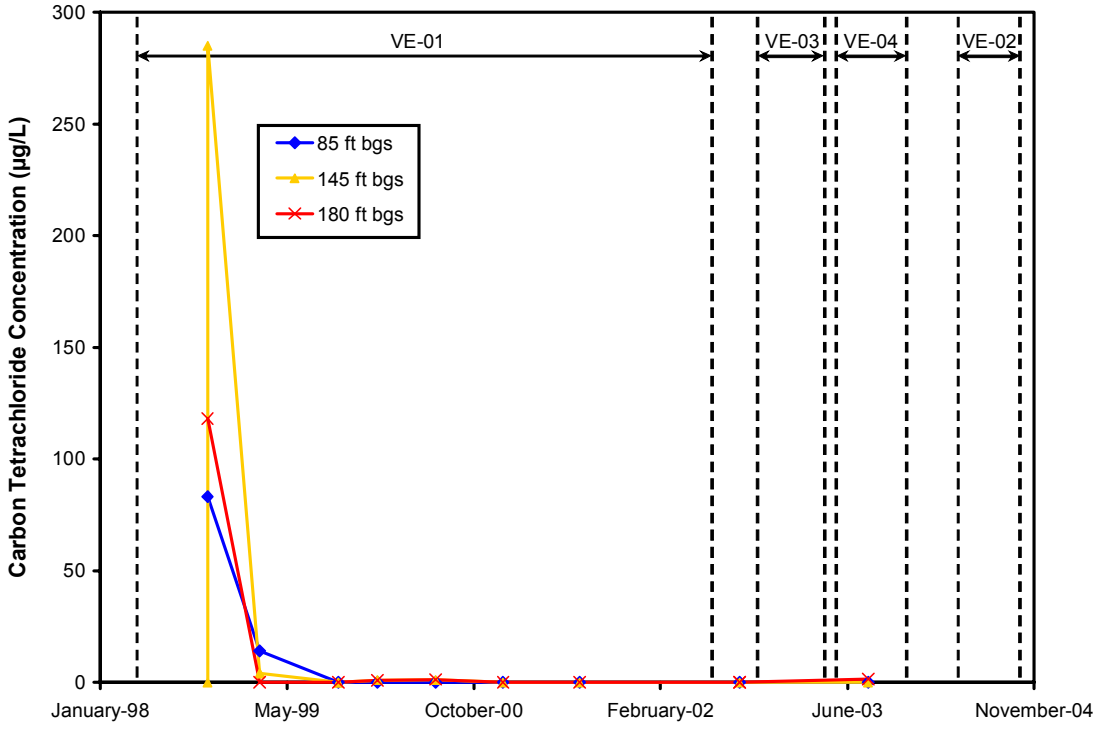

Figure 4-5. Carbon Tetrachloride Concentrations in MP-25

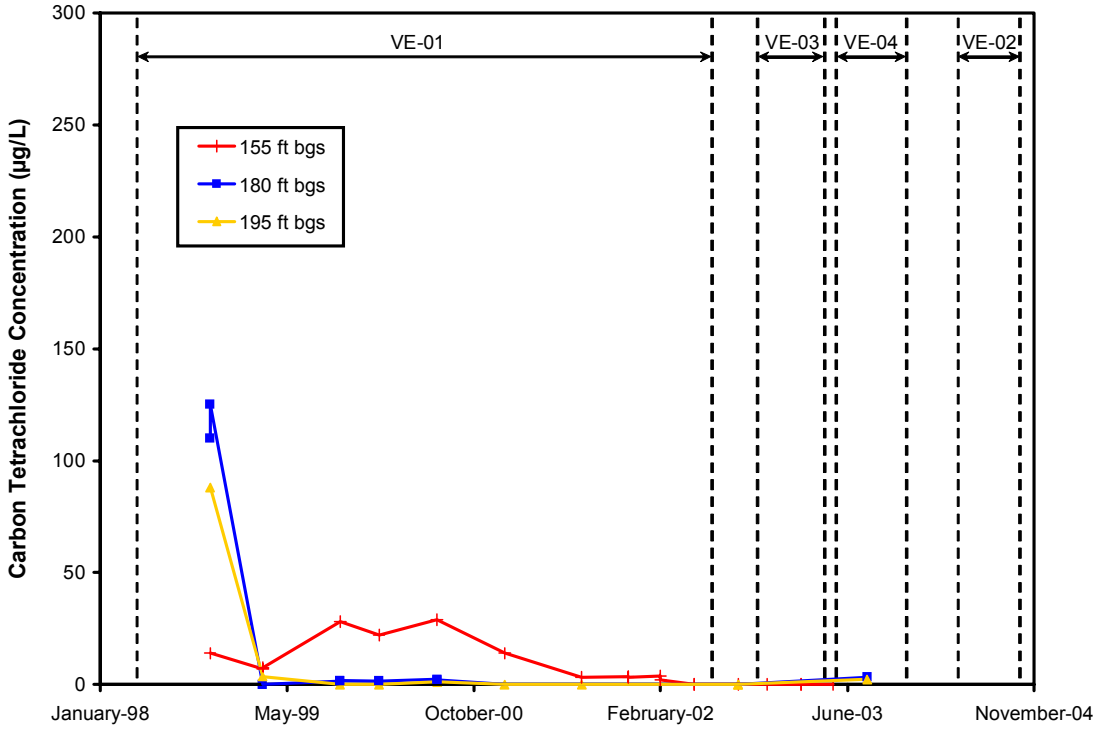

Figure 4-6. Carbon Tetrachloride Concentrations in MP-32

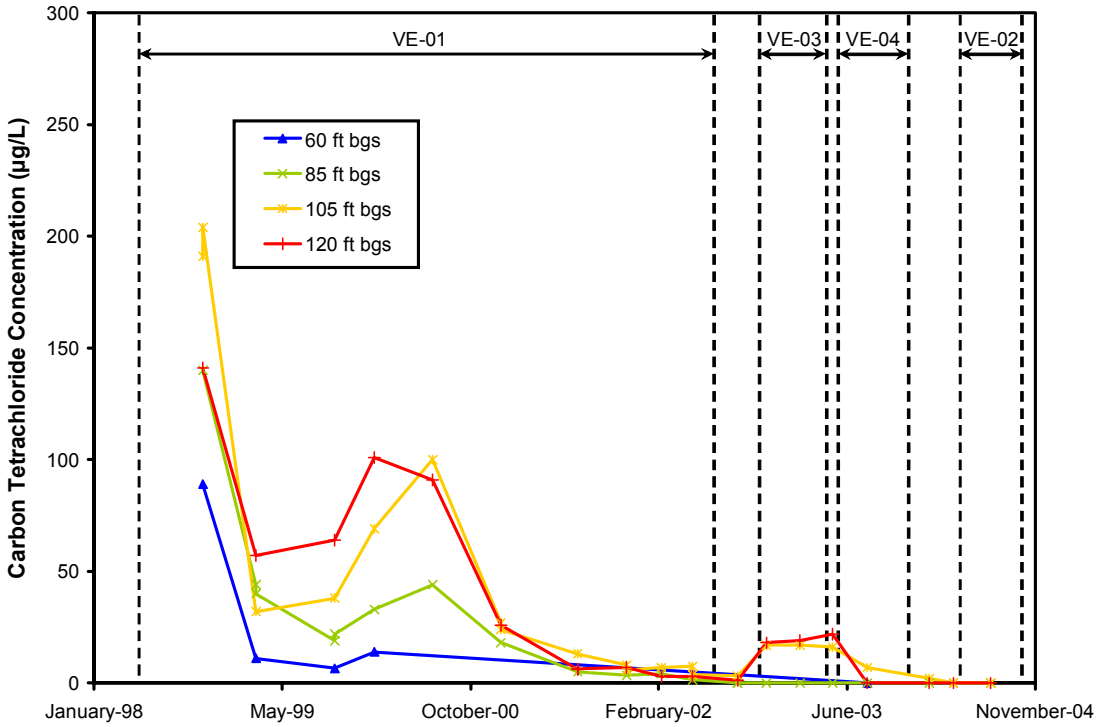

Figure 4-7. Carbon Tetrachloride Concentrations in MP-33

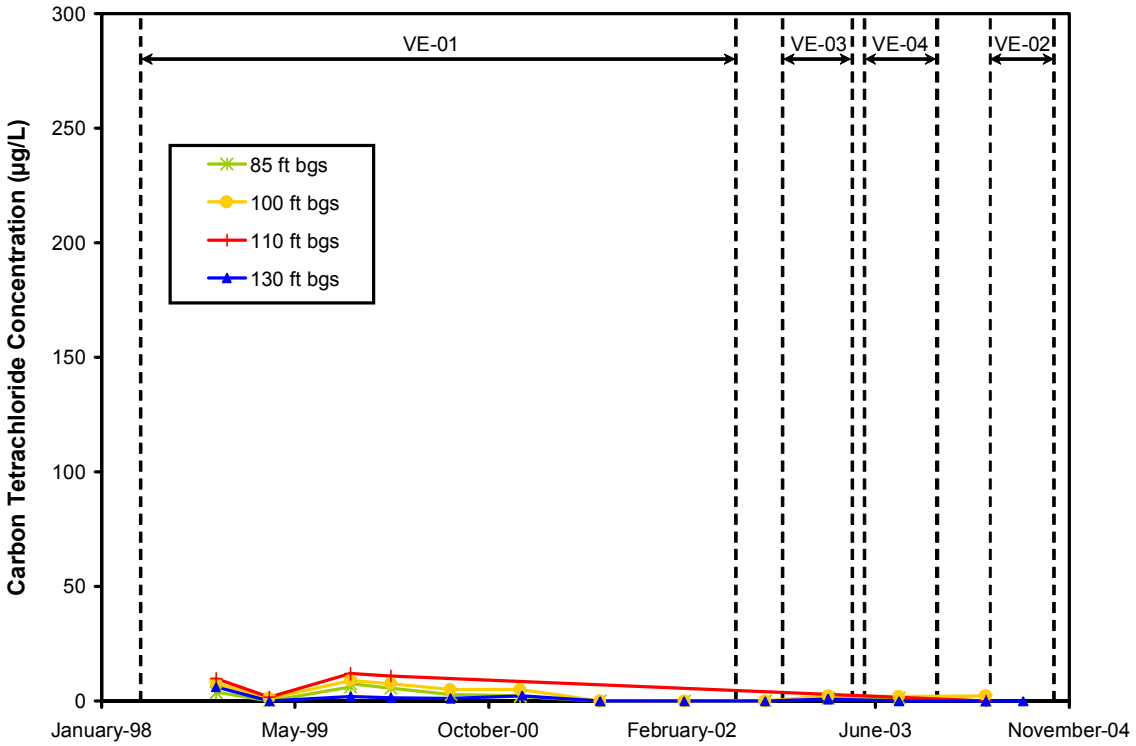

Figure 4-8. Carbon Tetrachloride Concentrations in MP-39

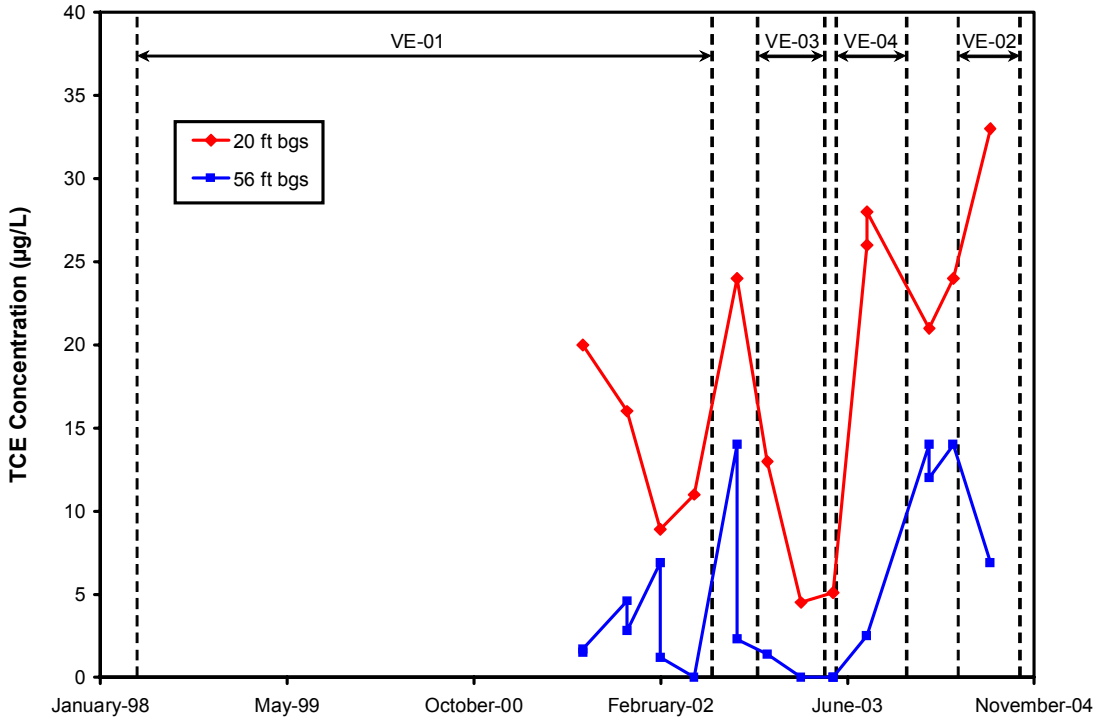

Figure 4-9. Trichloroethen Concentrations in MP-4

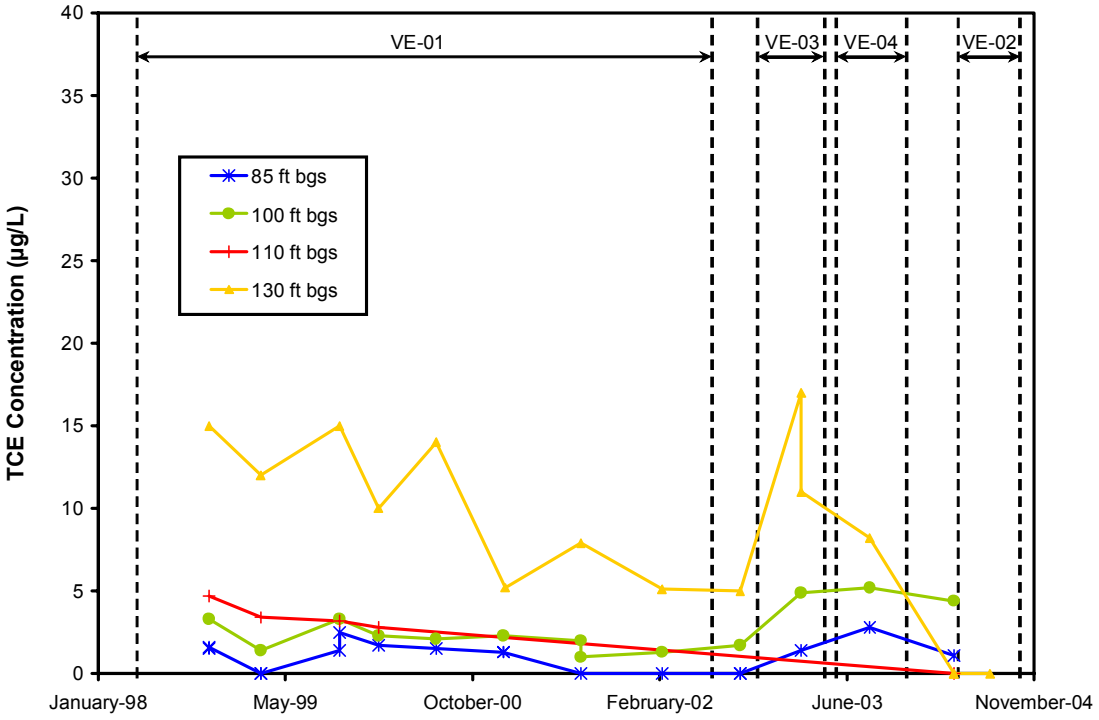

Figure 4-10. Trichloroethene Concentrations in MP-39

located within the radius of influence for VE-04. TCE concentrations increased after operation of VE-01 in some screen intervals; however, the concentrations decreased after operation of VE-04 in most screen intervals.

4.2 Asymptotic Mass Removal

The second remedial performance objective for the SVE system is to achieve asymptotic mass removal after temporary shutdown periods and appropriate optimization of the system. Asymptotic conditions are reached at a given SVE well when the upper limb of the cumulative mass removal curve is substantially linear and the slope of the curve approaches zero.

Figure 4-11 presents the daily mass removal rates for the SVE system. Daily mass removal rates of CCl_4 and TCE were significantly higher for VE-01 (maximum of 14 lbs per day) compared to the other vapor extraction points which removed less than 0.35 lbs per day. Average daily mass extraction rates for extraction wells VE-01 through VE-04 were 0.83, 0.10, 0.01, and 0.04 lbs per day, respectively.

With the exception of VE-04, the daily mass removal rates were highest at each well during the first few weeks of operation, and gradually declined for the remaining operational period. Daily mass removal rates remained relatively constant throughout the operating period for VE-04. This would suggest that system operation has either achieved or is nearing asymptotic mass removal at wells VE-01, VE-02, and VE-03.

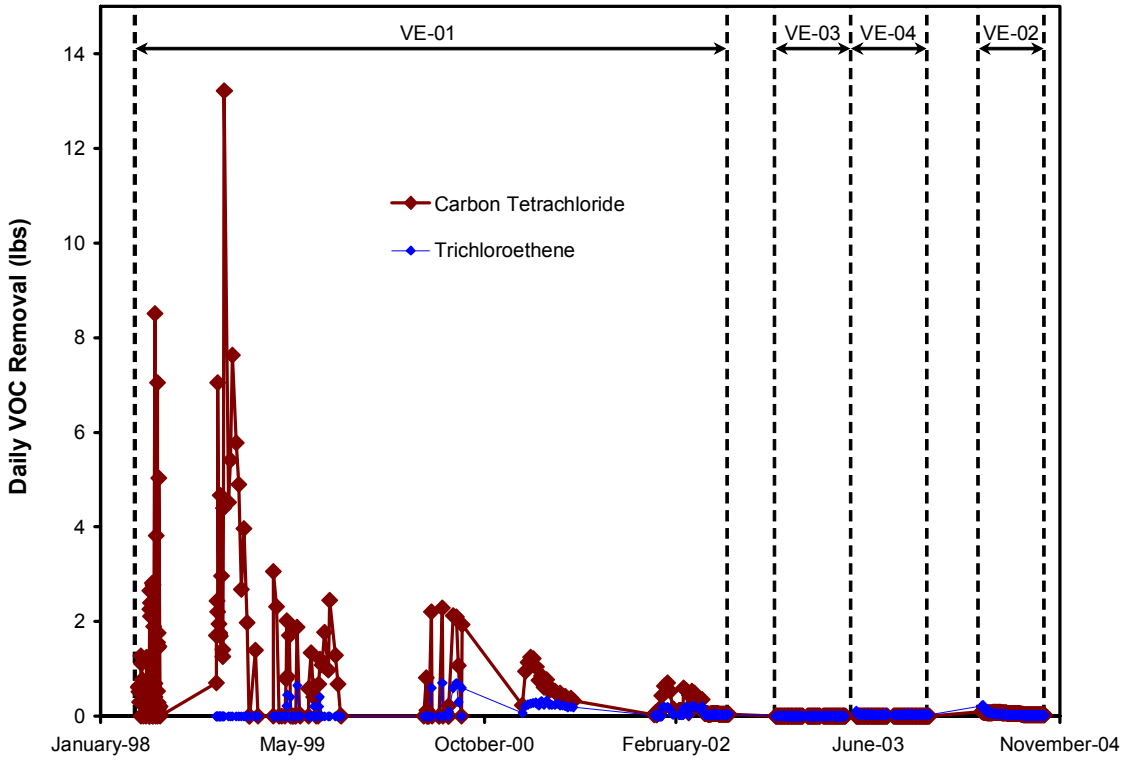

Figure 4-11. Daily Mass Removal Rates for the SVE System

Figures 4-12 and 4-13 present the cumulative CCl_4 and TCE mass recovered by the SVE system over time. The SVE system removed approximately 230 pounds of CCl_4 and 30 pounds of TCE since the pilot test began in April 1998. These figures indicate that asymptotic CCl_4 mass removal has been achieved in vapor extraction wells VE-03 and VE-04; however, asymptotic TCE mass removal has not been achieved within any of the vapor extraction wells after the first operation period in each well.

As discussed in Section 4.1.1, even though the system may not have completely reached asymptotic mass removal at all extraction wells, results of the VLEACH™ modeling suggest that only two source areas remain which require additional treatment to prevent additional VOC leaching to the groundwater which would result in concentrations exceeding groundwater MCLs. These two areas are located within the ROI for extraction well VE-03.

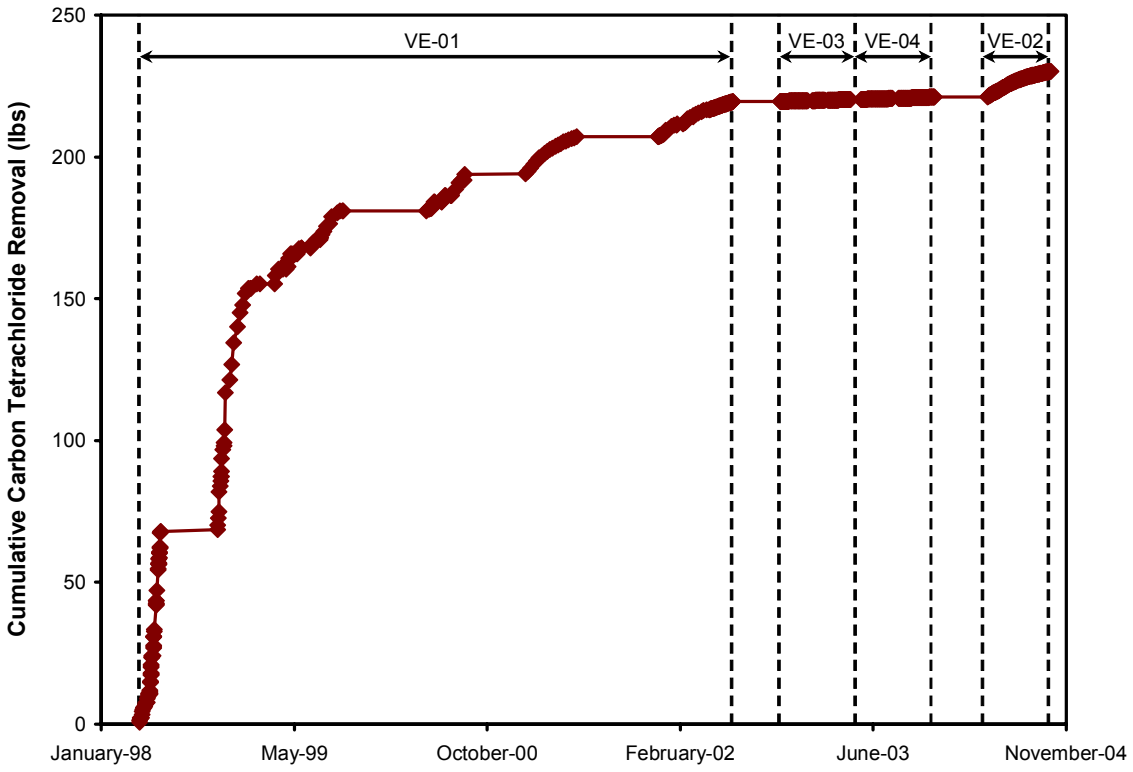

Figure 4-12. Cumulative Carbon Tetrachloride Mass Removal

4.3 Cost Effectiveness

The third and final remedial objective for the SVE system is to operate only as long as cost-effective. The SVE system will no longer be cost-effective when operating costs per unit of VOC mass removed from the vadose zone indicate that the additional cost of continuing to operate the SVE system is not warranted and/or when shutdown of the SVE system is not anticipated to significantly increase the cost of the groundwater remedy or significantly prolong the time to achieve groundwater cleanup.

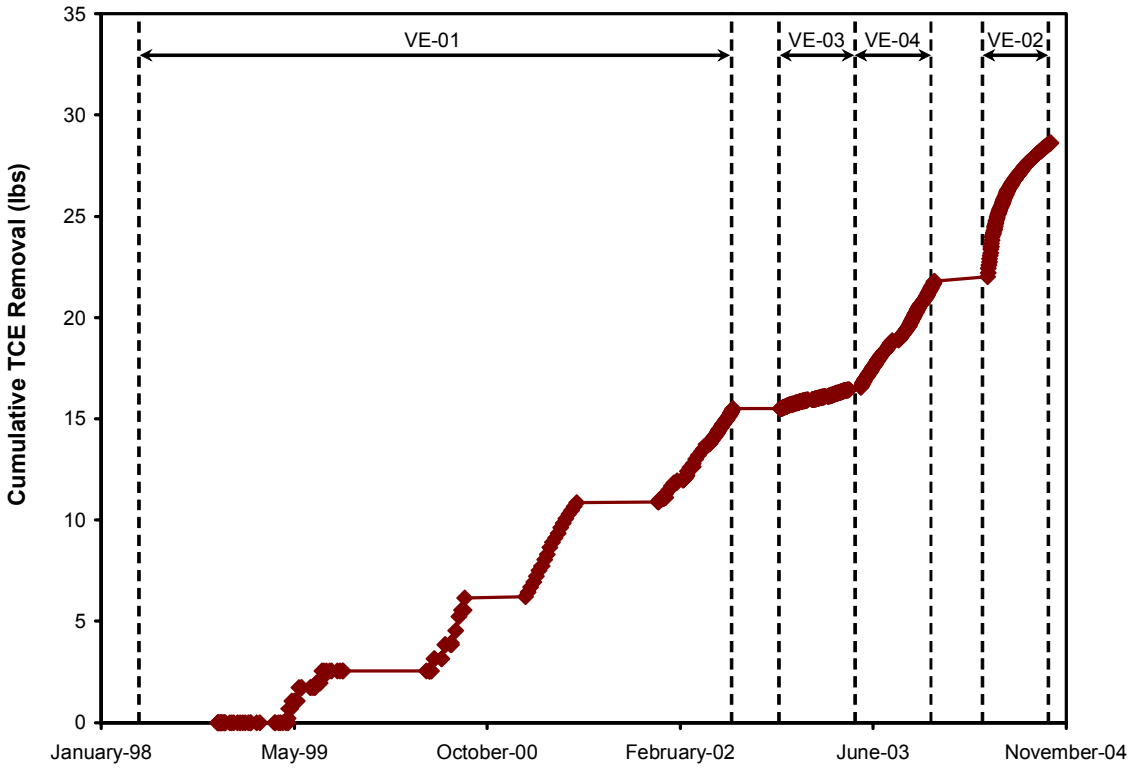

Figure 4-13. Cumulative Trichloroethene Mass Removal

Figure 4-14 presents the approximate cumulative costs versus cumulative mass recovered for the SVE system. This plot illustrates, by its increasing vertical slope, that operation of the system is becoming increasingly more costly. The increasing vertical slope of the cumulative costs coincides with the cumulative mass removal curve becoming more asymptotic over time (see Figures 4-12 and 4-13).

Figure 4-15 presents the cost per pound of VOC mass (sum of CCl_4 and TCE) removed by the SVE system. This plot indicates that VE-03 was the least cost effective extraction well to operate, while VE-01 and VE-02 were the most cost effective to operate. The average cost per pound of VOC mass removed by the SVE system at each well was approximately $10,000/lb at VE-01, $12,000/lb at VE-02, $100,000/lb at VE-03, and $37,000 at VE-04.

Alternatively, a groundwater recirculation system is currently being constructed to address VOC and perchlorate in the on-facility groundwater source area. The cost for treating VOC contamination with the GAC vessels in this system is estimated at approximately $250/lb. This cost is based on information provided by US Filter indicating that the cost per changout of a GAC vessel is $6,200, and approximately 26 lb of VOC will be removed by the carbon per changeout. However, the OU-1 system is expected to treat groundwater within the ROI of VE-01 and VE-02. The VLEACH™ modeling indicates that the remaining source areas are within the ROI for VE-03 and groundwater near VE-03 will not be captured by the OU-1 system.

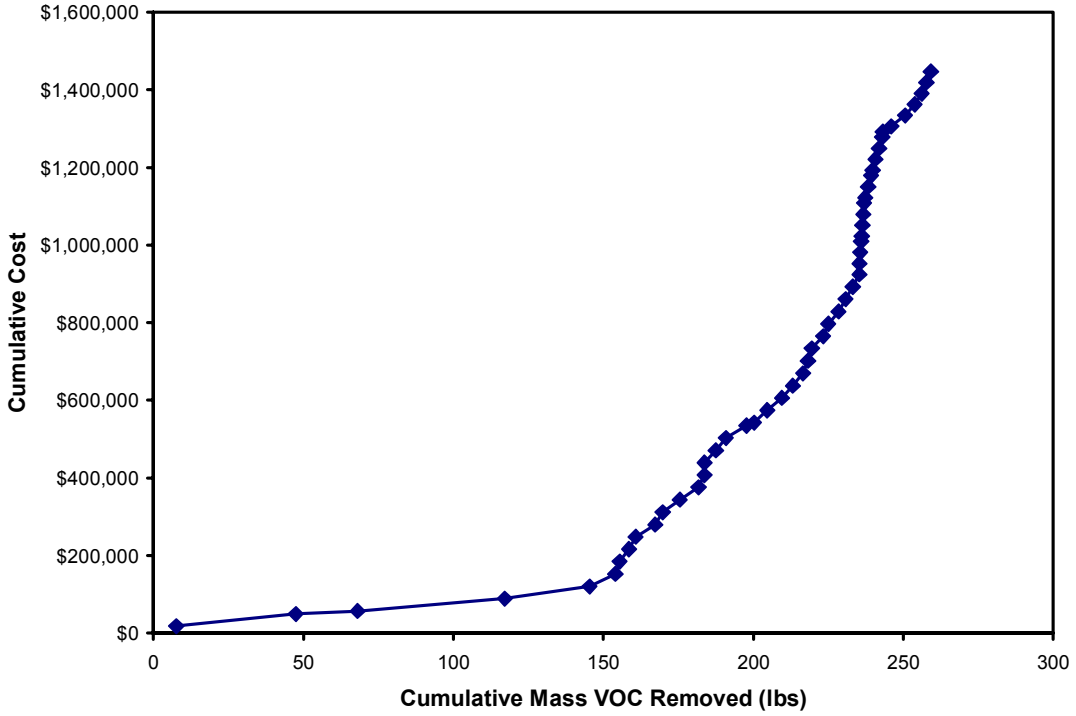

Figure 4-14. Cumulative Cost vs. Cumulative Mass of VOCs Removed

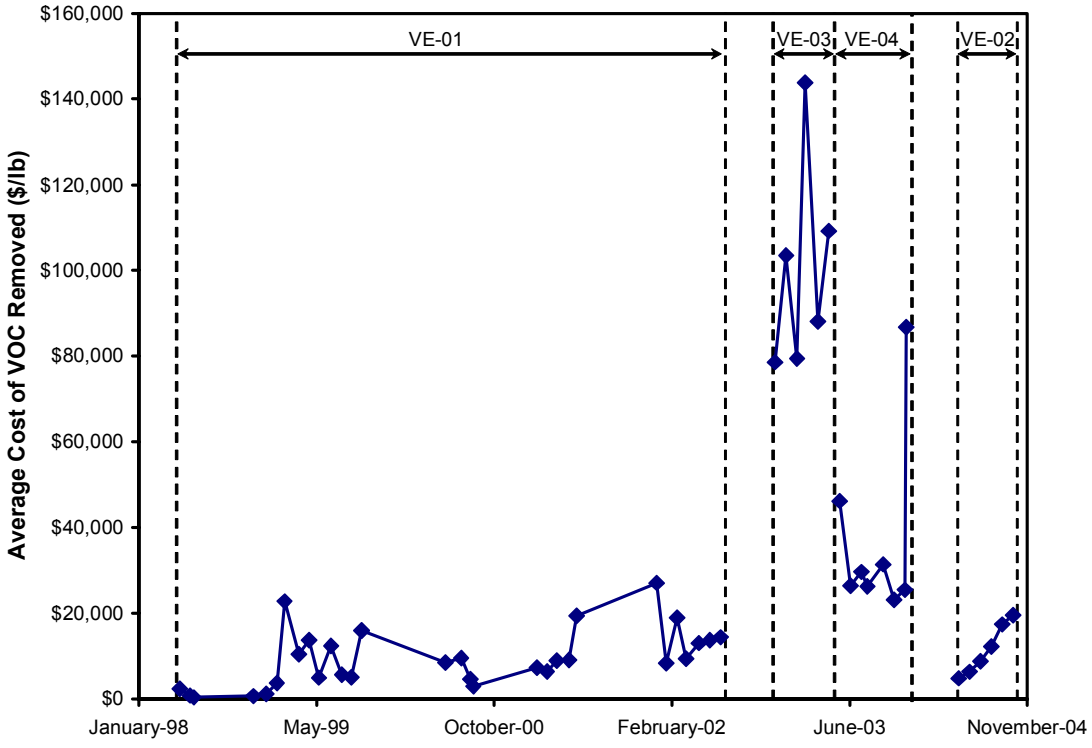

Figure 4-15. Operational Cost per Pound of VOC Removed

5.1 System Operation

Soil vapor concentrations exceed the RWQCB VSLs at 8 monitoring points (MP-3, MP-5, MP-17, MP-25, MP-27, MP-32, MP-33, and MP-39) for CCl_4, at 2 monitoring points (MP-4 and MP-39) for TCE. VLEACH™ modeling was then used to predict the potential impact to groundwater in areas where these exceedances were identified. Based on the VLEACH™ modeling, the potential mass loading from the areas exceeding RWQCB VSLs will result in groundwater concentrations exceeding the MCLs at two locations, near MP-34 for TCE and near MP-32 for CCl_4. Both of these monitoring points are located within the radius of influence for VE-03.

Mass removal rates from operation of VE-01 and VE-02 suggest that additional mass removal may be achieved with continued operation of these extraction wells. In addition, the mass estimates used for the VLEACH™ model may underestimate the actual mass present due to several plugged monitoring points located near VE-01 and VE-02.

Based on this information, it is recommended that over the next year additional operation of the SVE system target the vapor extraction wells VE-01, VE-02, and VE-03. Further, the screened intervals which coincide with the depths where exceedances have been identified should be targeted during further operation. Therefore, the zones which should be targeted for additional operation include VE-01-B, VE-01-C, VE-02-B, VE-03-A, and VE-03-B.

Due to the lack of data from several plugged monitoring points near VE-01 and VE-02, it is recommended that samples be collected for laboratory analysis from each of the well screens in these extraction wells. Results from this sampling should be evaluated using the RWQCB VSLs and the VLEACH™ modeling, and additional well screens may be operated if this evaluation indicates that remaining VOC mass may impact groundwater from screen intervals not already targeted for operation.

Based on the PneuLog® test results (presented in Section 3.3.1 through 3.3.4) and the data screening results presented in Table 4-2, all but two of the exceedances are located within high or moderately permeable zones in the vapor extraction wells. Therefore, additional operation of the appropriate extraction well screen intervals should result in continued mass removal and reduction in VOC concentrations.

The CCl_4 exceedance at MP-32 (180 ft bgs) lies within the effective radius of influence of VE-03, but the deepest screened interval of the extraction well only extends to 159 ft bgs. However, VE-03-B should be operated for an additional period to attempt further mass removal from this area by focusing extraction from the deeper screen. If operation of this well does not adequately reduce soil vapor concentrations, then alternative treatment options could be evaluated.

Exceedances of the CCl_4 screening levels at MP-25 and MP-27 (180 ft bgs) lie within a low permeability zone of VE-01-C. Based on results from the PneuLog® testing, the bottom 7 ft of the screen (178 – 185 ft bgs) produced no measurable flow (Praxis, 2002a). As discussed above, it is recommended that VE-01-C operate for an additional cycle to attempt to further reduce VOC mass in this area; however, given the low remaining concentrations (less than 2 times the vapor screening level) and the low permeability of this zone, it is unlikely that any remaining mass would adversely impact groundwater.

5.2 Soil Vapor Monitoring

Currently the vapor monitoring program includes 2 quarterly events, one semiannual event, and one annual event, which includes all sample ports which are not plugged. Some of the monitoring probes where VOC concentrations were previously detected are now plugged, and personnel are unable to collect samples from these ports. The plugged ports which are of potential concern include MP-25 (85 ft), MP-26 (80 ft), MP-28 (120 ft), MP-33 (160, 180 ft), MP-34 (35, 118 ft), MP-35 (95, 155), and MP-37 (120, 140 ft). These sample ports are also located within the effective ROI of VE-01 and VE-02, which are the two extraction wells that did not reach asymptotic mass removal during the first operating cycle and are recommended for continued operation. If possible, these monitoring points should be rehabilitated so that samples can be collected during the next monitoring event to confirm VOC mass estimates and VLEACH™ modeling.

Based on the evaluation of the vapor monitoring data presented in Section 4.1, it appears that the vapor monitoring points are providing reliable data, and continued monitoring of the soil vapor will aid in determining optimal operation of the SVE system.

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