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Multi-Phase Extraction: State-of-the-Practice

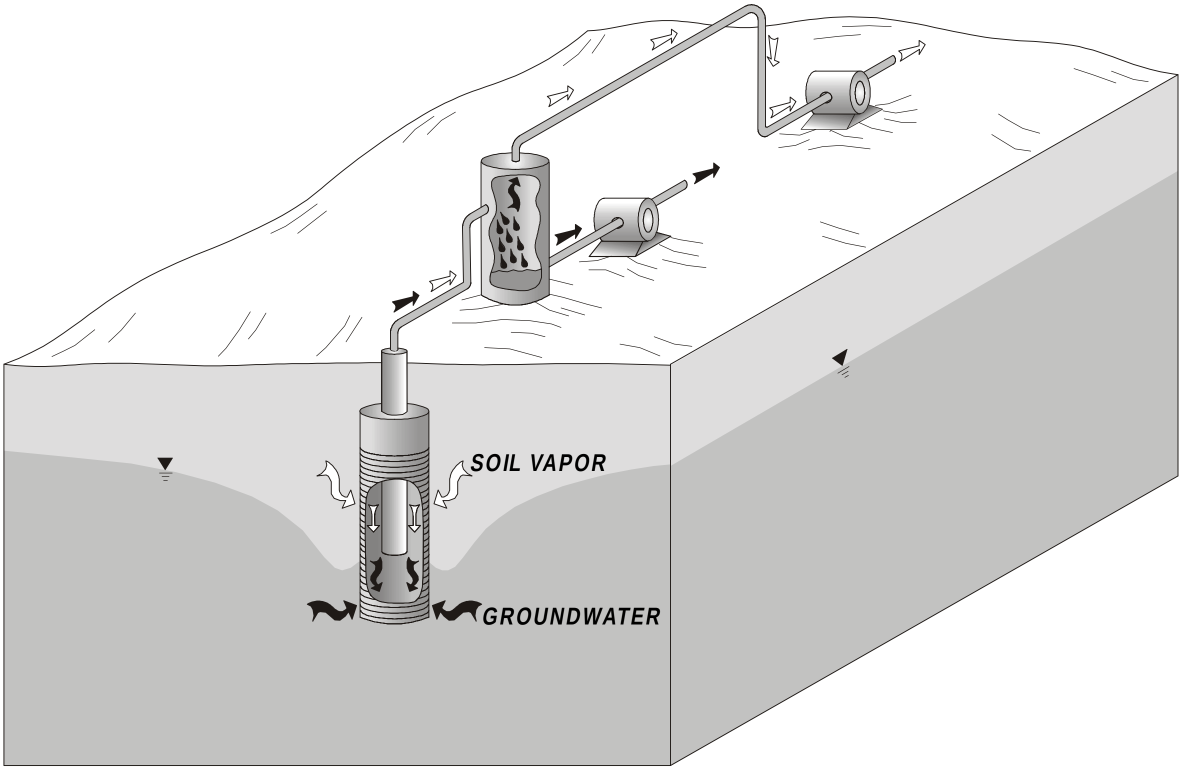

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TABLE OF CONTENTS

Page

TABLE OF CONTENTS
(continued)

Page

LIST OF FIGURES

LIST OF TABLES

Page

FOREWORD

This report describes the state-of-the-practice for multi-phase extraction (MPE) of contaminated soil and groundwater, focusing primarily on the application and use of MPE at sites with halogenated volatile organic compounds (VOCs). MPE is an innovative technology that has the potential to be more cost-effective and to remediate sites more quickly than with use of conventional technologies. Thousands of sites in the United States are contaminated with VOCs, including sites under Superfund, RCRA Corrective Action, RCRA Underground Storage Tank, Department of Defense, Department of Energy, and civilian federal agency and state programs.

MPE technology is described in this report, including the various configurations used for the technology, the types of site conditions to which MPE would be applicable, and the advantages and potential limitations of using MPE at these types of sites. In addition, the report summarizes information about vendors of MPE, including identifying sites where the vendors have applied their technologies. Detailed case studies summarizing the cost and performance of using MPE are provided for three sites. These sites include a military base, an industrial manufacturing facility, and a federal Superfund site all of which were contaminated with chlorinated VOCs in soil and groundwater.

This report is intended to assist federal and state project managers, permit writers, technology users, and contractors that may be considering the applicability of this technology, and in screening the feasibility of this technology early in the remedy selection process. It is not intended to revise or update EPA policy or guidance on how to clean up sites with contaminated soil and groundwater.

1 INTRODUCTION

EPA has estimated that more than 200,000 sites remain to be remediated in the United States, including Superfund, RCRA Corrective Action, Underground Storage Tank, Department of Defense (DoD), Department of Energy (DOE), civilian federal agency, and state sites. About 70 percent of Superfund, RCRA, DoD, and DOE sites have contaminated soil or groundwater, or both (EPA, 1997a). Volatile organic compounds (VOCs), including chlorinated solvents, are a frequently-occurring type of contaminant at these sites.

This report provides an overview of the state-of-the-practice for multi-phase extraction (MPE). MPE involves simultaneous extraction of soil vapor and groundwater to remediate both types of contaminated media. MPE has seen an increase in use at Superfund and other sites for cleanup of soil and groundwater impacted with halogenated VOCs, and also has been used frequently for cleanup of petroleum-hydrocarbon sites. This report focuses primarily on the applicability and use of MPE at sites with halogenated VOCs.

Section 2 of this report provides a description of MPE technology, including the various configurations used for this technology. Section 3 describes the types of site conditions to which MPE would be applicable, and discusses the advantages and disadvantages of using MPE at these types of sites. Section 4 summarizes information about attributes of MPE vendors and examples of sites where these vendors have applied their technologies. Information about these vendors was obtained from EPA REACH IT, an extensive database of information about characterization and treatment technologies. EPA REACH IT is available on the Internet at <*http://www.epareachit.org*>. Detailed case studies of sites where MPE has been used are summarized in Section 5 (for the Defense Supply Center, Richmond, VA; 328 Site, Santa Clara, CA; and Tinkham's Garage Superfund Site, Londonderry, NH), and referenced throughout the report. The references used during preparation of this report are listed in Section 6, and are cited in this report using parentheses.

2 TECHNOLOGY DESCRIPTION

Multi-phase extraction (MPE) is a generic term for technologies that extract VOCs in soil vapor and groundwater, simultaneously (OSWER Directive No. 9335.0-68FS). This section discusses MPE as the coupling of soil vapor extraction and groundwater pump-and-treat by applying a vacuum on a sealed recovery well. Reasons for implementing MPE are covered and typical configurations of MPE examined.

2.1 SOIL VAPOR AND GROUNDWATER EXTRACTION

Soil vapor extraction (SVE) is the extraction of soil vapor from the semi-saturated subsurface, or vadose zone. SVE induces subsurface air flow by a vacuum applied to a sealed well screened in the zone of interest. The technology is employed to facilitate mass removal of residual and vapor phase VOCs located in the vadose zone. Volatilization, with subsequent air advection, is the primary removal mechanism of these subsurface constituents. SVE is beneficial for soil remediation and provides an alternative to traditional excavation approaches for site remediation. SVE systems are useful in a variety of soil settings but are most advantageous in low to moderate permeability formations. Subsurface air flow may be short circuited in high permeability settings and may be inadequate in very low permeability formations that lack secondary flow paths (Suthersan, 1997; EPA, 1997b; EPA, 1996; API, 1996).

Groundwater pump-and-treat involves the extraction of groundwater from pumping wells and the subsequent ex-situ treatment and disposal. Groundwater flow to the well is induced by depressing the water table surface by pumping and creating a hydraulic gradient. Groundwater extraction seeks to reduce the mass of dissolved and non-aqueous phase constituents and to reduce mobility of contaminant plumes by hydraulic containment. The primary removal mechanism is groundwater advection and dissolution of constituents located in the saturated subsurface. Groundwater extraction can be employed in a wide variety of hydrogeologic settings ranging from high to low permeability. The effectiveness of the technology becomes limited as permeability decreases and becomes more heterogeneous.

Limitations manifest as low recovery rates, high drawdown, and rapid, steep gradients providing limited capture (EPA, 1996).

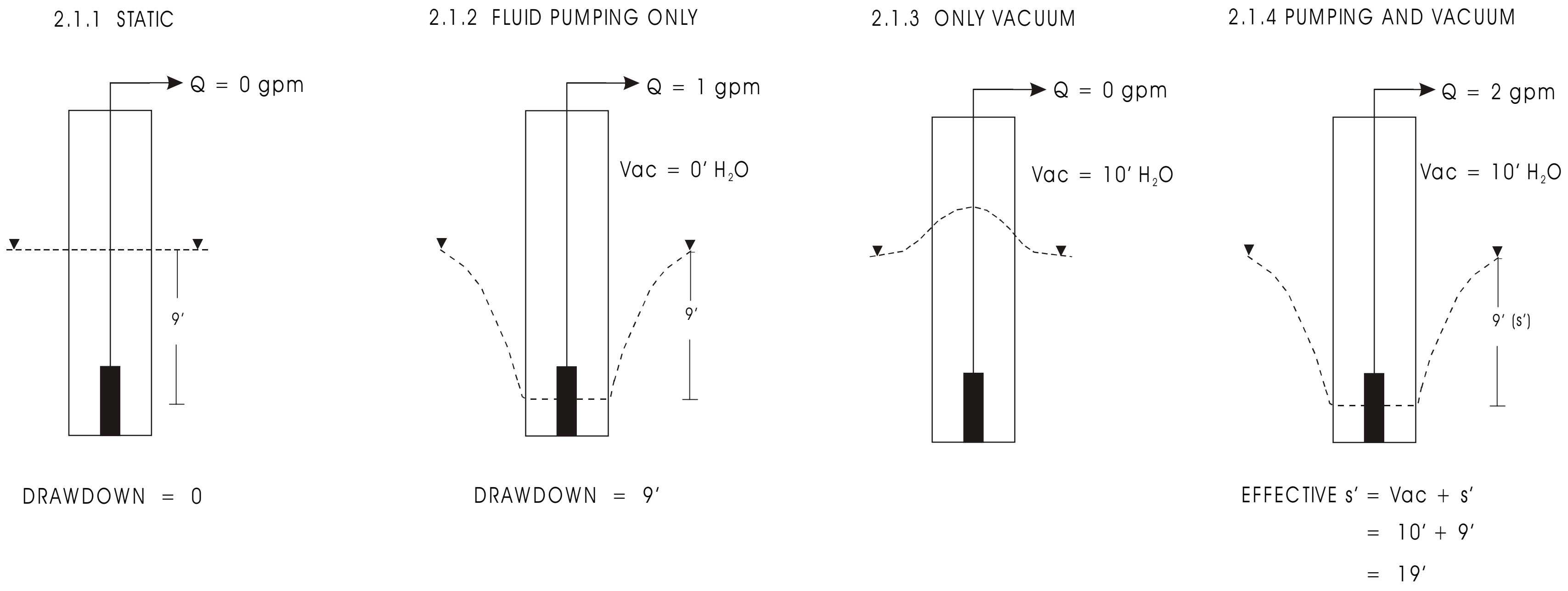
2.2 MPE TECHNOLOGY DESCRIPTION

MPE is typically applied in recovery wells with some portion of the well screen extending above the water table into the vadose zone. Groundwater recovery is achieved by pumping at or below the water table. The applied vacuum extracts soil vapor and enhances groundwater recovery. Liquid flow rates are increased due to the increased pressure gradient applied on the system. In some configurations, the vacuum increases the effective drawdown locally near the pumped well without significantly lowering the water table surface away from the pumped well.

Figure 2.1 illustrates the effect of an applied vacuum on a pumping well. The drawdown in a pumping well without vacuum influence will be equal to the difference in the static water level (shown in 2.1.1) and dynamic water level in the pumping well (shown in 2.1.2). This drawdown will result in a flow rate. A well under the influence of a vacuum only results in a water table rise equal to the applied vacuum (shown in 2.1.3). Vacuum is negative gauge pressure (i.e., less than atmospheric) and creates a negative gradient towards the well. In MPE the pumping and vacuum scenarios are superimposed such that the effective drawdown is the sum of the drawdown produced by the vacuum and water table depression (shown in 2.1.4). Because the drawdown is increased, an increase in the well yield (extraction rate) is realized (Suthersan, 1997).

Applying a vacuum to an extraction well enhances the hydraulic gradient. The hydraulic gradient is defined as the difference in hydraulic head between two points divided by the length of the flow path. From Darcy’s Law, it is known that the rate of flow through the aquifer is directly proportional to the hydraulic gradient. When drawdown is maximized, the head difference cannot be increased by lowering the water level. However, the effective head difference can be increased by applying negative pressure (a vacuum) to the extraction well. Thus, the hydraulic gradient is increased and a resulting increase in the rate of groundwater extraction is realized (Suthersan, 1997).

Figure 2.1. Effect of a vacuum on pumping level (Suthersan, 1997).



2.3 MPE AS A REMEDIATION ALTERNATIVE

MPE addresses contamination in both the saturated and vadose zones, remediating dissolved, vapor, residual, and non-aqueous phases of contamination. MPE affects mass removal by volatilization, dissolution, and advective transport. In general, if both SVE and groundwater pump-and-treat are potential applicable technologies, then MPE may be considered as a remedial alternative. The following list highlights the capabilities of MPE and thus the primary factors for considering MPE as a remediation alternative.

- Increase in groundwater recovery rates, compared to conventional pumping practices in equivalent settings (EPA, 1997b)

- Increase in radius of influence of individual groundwater recovery wells (Suthersan, 1997)

- Recovery of shallow layer of floating, free product (EPA, 1996)

- Remediation of the capillary fringe and smear zone (EPA, 1997b; EPA, 1996; EPA, 1997c)

- Remediation of volatile, residual phase contaminants located above and below the water table (EPA, 1996; EPA, 1997c)

- Simultaneous remediation of soil and groundwater

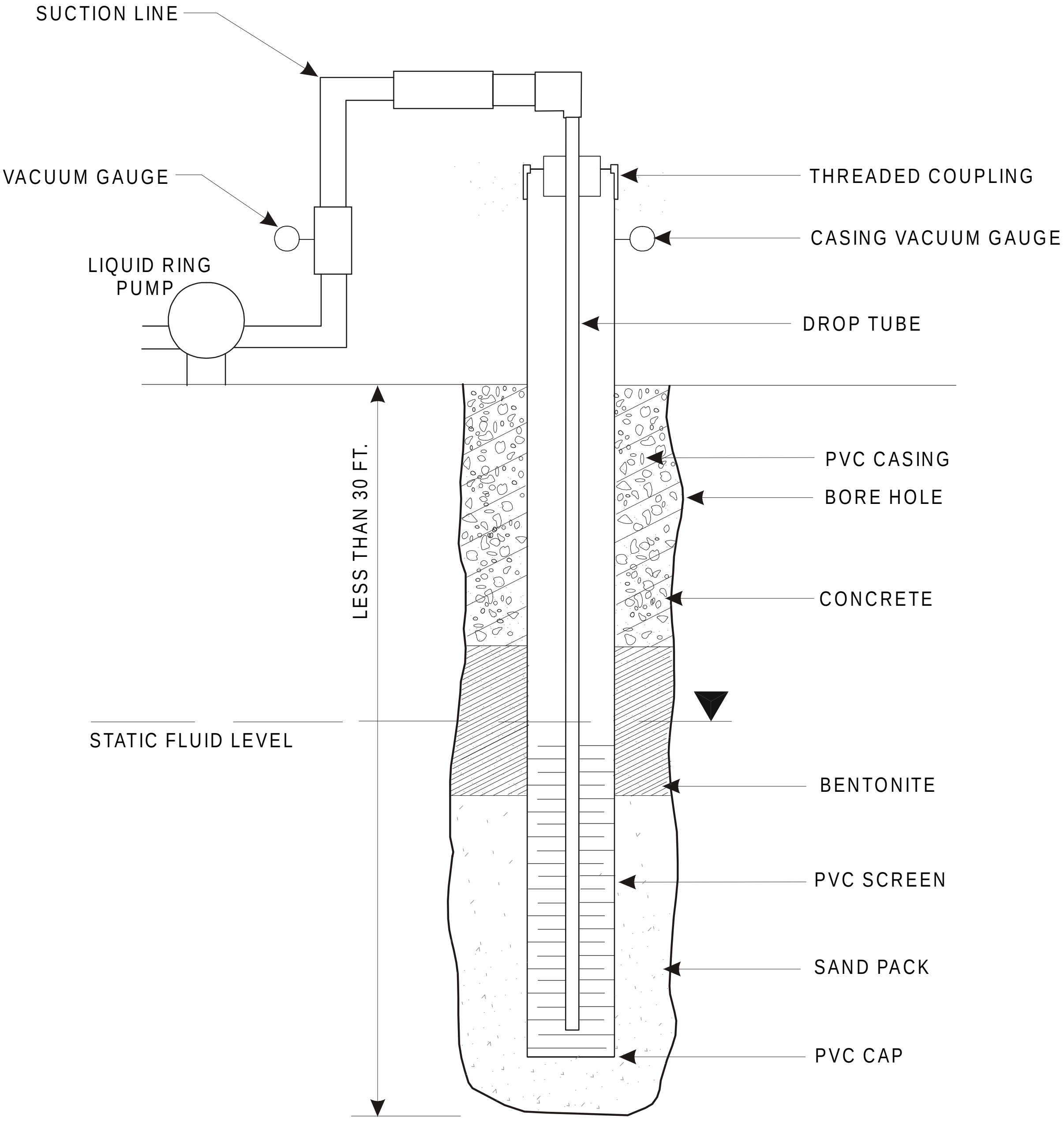
2.4 TECHNOLOGY CONFIGURATIONS

MPE can be designed and implemented in a variety of configurations. The three main forms of MPE are the single and two pump configurations and bioslurping. The latter is essentially a minor variation of the single pump configuration used to recover free product. Each is described in the following sections.

2.4.1 SINGLE PUMP CONFIGURATION

In the single pump configuration, as shown in Figure 2.2, a single drop tube is employed to extract both liquid and vapor from a single well. The vacuum and liquid suction lift is achieved by one vacuum pump (liquid-ring pumps, jet pumps, and blowers are typical).

Figure 2.2. Single pump MPE well schematic (Suthersan, 1997).



This configuration is limited to depths of about 30 feet below ground surface (bgs). A complete vacuum would be achieved at an equal and opposite value of the atmospheric pressure, or -14.7 psi, which equates to 34 feet of water column.[1] In theory, a vacuum lift pump can only lift water a height equal to the atmospheric pressure. As such, single pump configurations are used for shallow (less than 30 feet) water-table remediation (Suthersan, 1997; EPA, 1996).

2.4.2 TWO-PUMP CONFIGURATION

Depth limitations can be overcome with the second configuration, the two-pump MPE system shown in Figure 2.3. This system utilizes a submersible pump for groundwater recovery in conjunction with a separate vacuum applied at the sealed wellhead. In this configuration, liquid and vapor streams are separate from one another. Conductivity type level sensors can be utilized for pump control. Level control may be necessary to prevent the vacuum from causing the pump to lose positive suction head and cavitate. Depending on the application, two-pump systems can utilize electric or pneumatic submersible pumps for groundwater recovery and liquid ring pumps or blowers to induce vacuum. Applications for the recovery of a free product, or light, non-aqueous phase liquid (LNAPL), typically employ pneumatic submersible pumps for liquid recovery (Suthersan, 1997; EPA, 1996; Peargin, 1995).

2.4.3 BIOSLURPING

The last MPE configuration is often referred to as bioslurping (Kittel et al, 1994). This configuration is the same as the single pump MPE scheme, however, the drop tube in a bioslurping application is set at, or just below, the liquid-air interface. This configuration has shown to be effective at free product recovery (Suthersan, 1997; Kittel et al, 1994) and is primarily used for that purpose. The bioslurping system extracts water, LNAPL, and air from a single 1-inch drop tube in a 2-inch diameter well (Kittel et al, 1994). The extraction point alternates from recovering liquid to air, emanating a slurping sound. A secondary goal of

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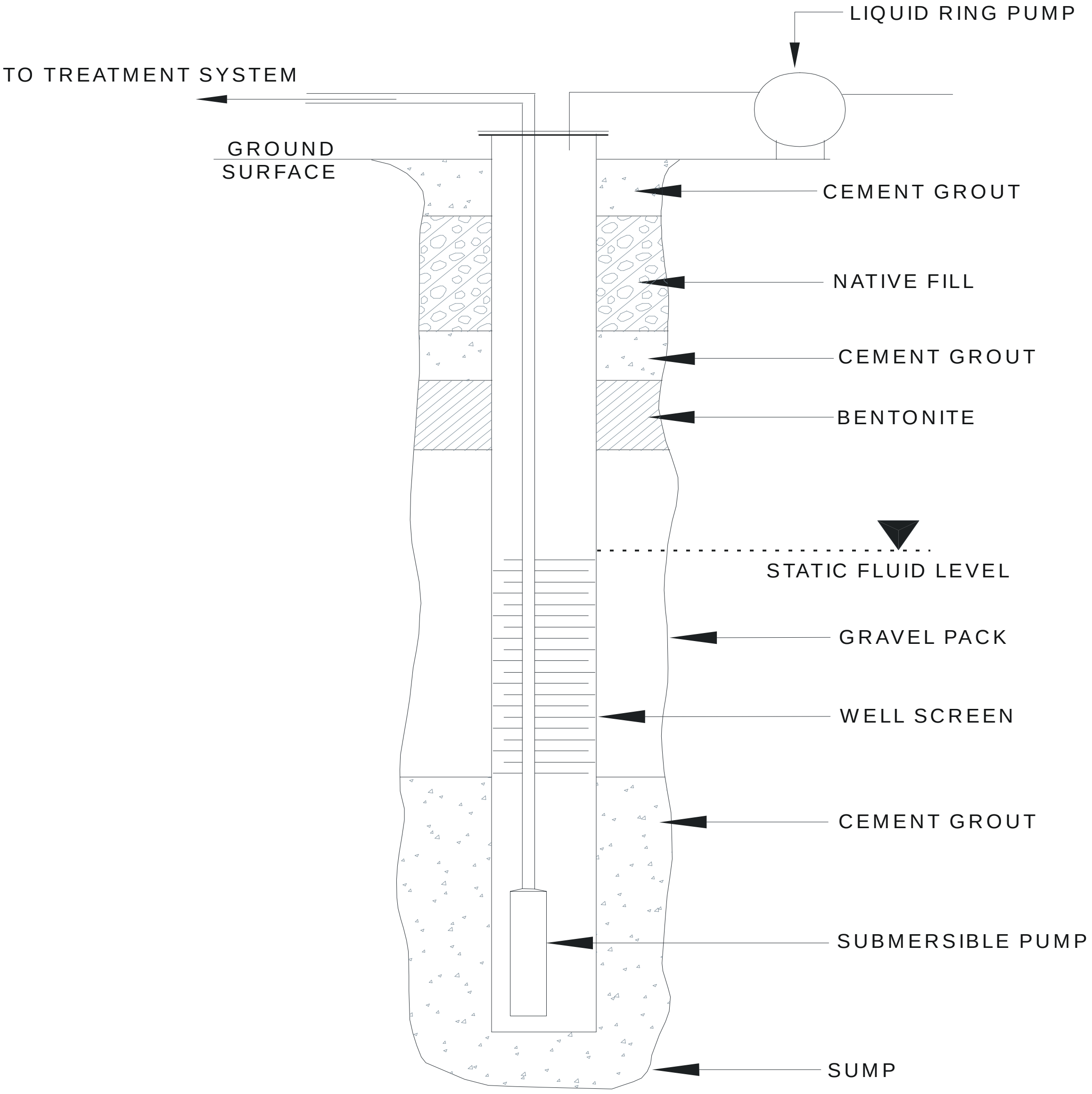
[1] $-14.7 \text{ psi} \times 2.311 \frac{\text{ft } H_2O}{\text{psi}} = 33.95 \text{ ft } H_2O$

Figure 2.3. Two-pump MPE schematic (Modified from Suthersan, 1997).



bioslurping is the enhancement of in-situ aerobic biodegradation of aromatic hydrocarbons as a result of increased airflow. Figure 2.4 illustrates a typical bioslurping configuration.

2.5 MPE TERMINOLOGY

Multi-phase extraction is referred to by many other names in the literature. Table 2.1 lists some of the terms used to refer to MPE. The environmental remediation industry, as a whole, has not become unified or consistent with MPE terminology. Some organizations within the industry have created trademarked names. The majority of the trademarked names will utilize one of the three main configurations presented in this section. A partial list of trademarked names and trade names of MPE are presented in Section 4.

Figure 2.4. Bioslurping schematic (Kittel, et al., 1994).

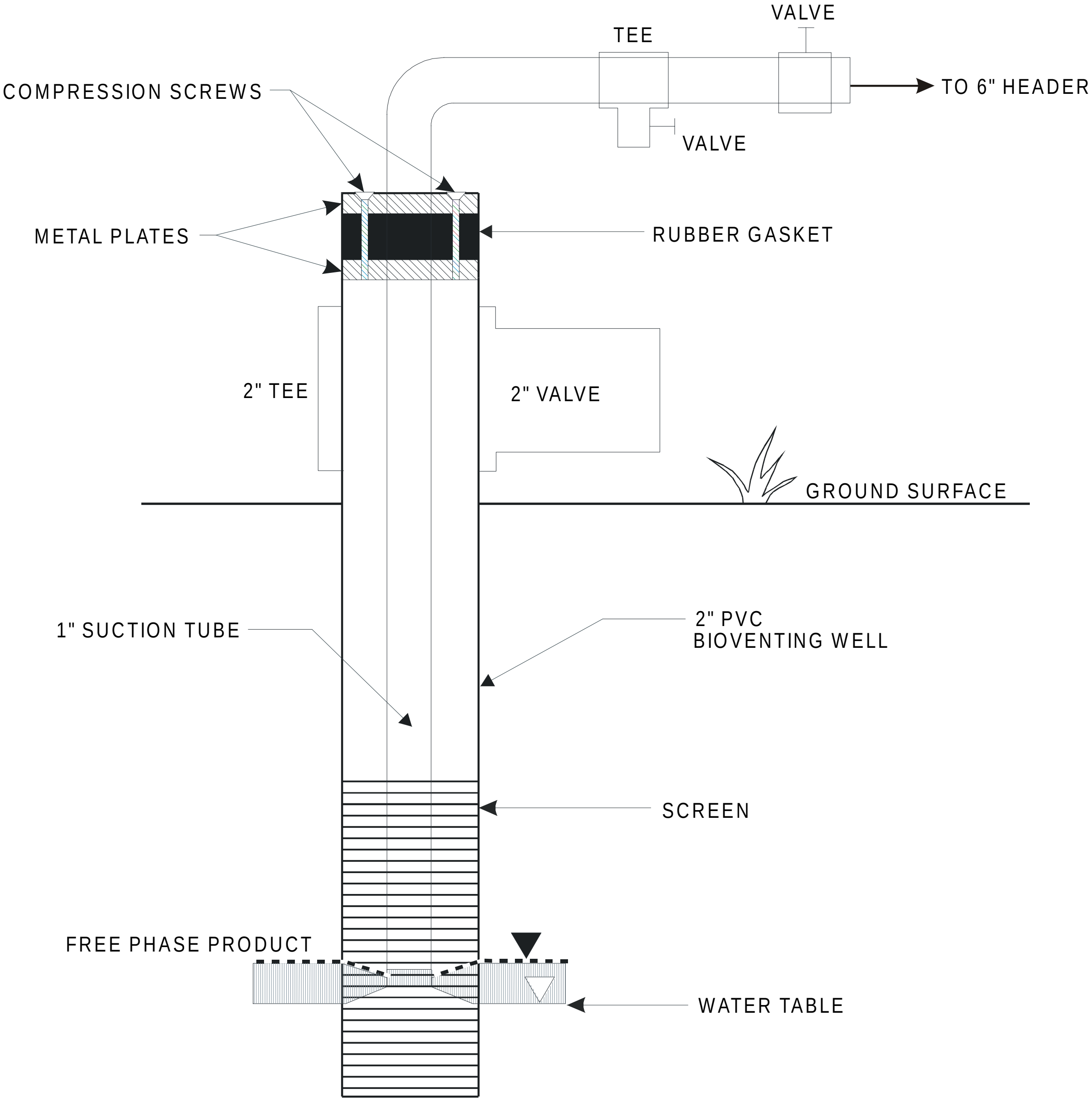


Table 2.1. Terms referring to multi-phase extraction and their configurations.

Term	Configuration	Source
Dual-Phase Extraction (DPE)	Non-specific MPE term	1
Drop-Tube Entrainment Extraction	Single pump configuration	1
Well-Screen Entrainment Extraction	Extraction of vapor and groundwater from a sealed well with induced vacuum. Groundwater is aspirated into the vapor stream at the well screen.	1
High-Vacuum Dual Phase Extraction (HVDPE)	Two pump configuration with a submersible pump for groundwater recovery. High vacuum application (18 to 26 in Hg)	2
Low-Vacuum Dual Phase Extraction (LVDPE)	Two pump configuration with a submersible pump for groundwater recovery. Low vacuum application (2 to 12 in Hg)	2
Two-Phase Extraction (TPE)	Single pump configuration with high vacuum application (18 to 26 in Hg)	2
Bioslurping	Single pump configuration with drop tube set at, or just below, the air-liquid interface	3
VE/GE (“Veggie”); Downhole-Pump Extraction	Two pump configuration with a submersible pump for groundwater recovery	4,5
Vacuum Enhanced Pumping (VEP)	Non-specific MPE term	4
Vacuum Enhanced Recovery (VER)	Non-specific MPE term	6

Sources:

1. EPA, 1997b
2. EPA, 1997c
3. Kittel et al, 1994
4. EPA, 1996
5. Peargin, 1995
6. Suthersan, 1997

3 APPLICABILITY OF MPE

3.1 APPLICABILITY

The use of MPE can be highly beneficial to site remediation provided that the technology is applied within the appropriate range of hydrogeologic settings and contaminant properties. If applied outside of the appropriate conditions, MPE may be ineffective in remediating the problem and may not be cost effective (Suthersan, 1997). The applicability of MPE is governed, primarily, by media properties and, to a lesser extent, contaminant properties. Once groundwater extraction wells have been utilized, and concentrations have reached an asymptote (leveled off), conversion of these wells to MPE wells may be cost effective, leading to increased contaminant mass recovery. The applicability of MPE is summarized in Table 3.1.

Hydraulic conductivity (K) is the media parameter of greatest interest because it characterizes the ability of a formation to transmit water. MPE is most applicable to fine-grained formations in the fine sand to silty sand range (hydraulic conductivity, $K = 10^{-3}$ to 10^{-5} cm/s) (EPA, 1996). Application of systems to lower conductivity (less than 10^{-6} cm/s) may be possible if some secondary permeability exists (Suthersan, 1997). MPE applicability can also be determined from the product of the saturated thickness and hydraulic conductivity, known as the transmissivity. Low transmissivity formations of less than 500 gpd/ft (gallons per day per foot) are normally considered to be applicable to MPE (Suthersan, 1997). A typical result of pumping in low conductivity and transmissivity formations is increased, and sometimes rapid, drawdown with steep gradients. This condition limits the influence of the conventional pumping well. MPE overcomes this limiting factor with the application of a vacuum (as discussed in Section 2.4).

Low permeability formations also tend to possess thick capillary zones (up to several feet). Fluid in the capillary zone is held in the pore spaces by capillary forces at less than atmospheric pressure. The vacuum enhancement of MPE overcomes these capillary forces and removes the fluid from the capillary zone. This poses a particular advantage to LNAPL recovery. LNAPL tends to accumulate in the capillary zone at the air-water interface. The

Table 3.1. Applicability of MPE.

Parameter	Applicable Range or Characteristic for MPE	Source
Hydraulic Conductivity	• Moderate to Low (K = 10^{-3} to 10^{-5} cm/s)	1
Transmissivity	• Low ($\leq$ 500 gpd/ft)	2
Geologic Setting	• Sands to Clays	3
Vadose Zone Soil Permeability to Air	• Moderate to Low (k < 1 darcy)[a]	3
Formation Characteristics	• Low permeability, fractured systems • Interbedded sand and clay stringers • Limited saturated thickness • Shallow water table • Thick capillary zone (up to several feet) • Perched NAPL or groundwater layers	1,2
Drawdown/Recovery Rate	• Conditions producing steep or high drawdown in wells • Low groundwater recovery rates achieved with conventional pumping	1
Contaminant Location	• Vadose, saturated, and capillary zones	1,3
Contaminants	• Halogenated VOCs • Aromatic VOCs and/or total petroleum hydrocarbons (TPH) • Floating, free product (LNAPL)	1,3
Contaminant Vapor Pressure	• > 1 mm Hg at 20°C	3
Contaminant Volatility	• > 0.01 at 20°C[b] • >2 x 10^{-4} atm m^3/mol at 20°C[c]	3

[a] 1 darcy $\approx 10^{-8}$ cm^2

[b] Expressed as dimensionless Henry's Law Constant: Concentration in gas phase/concentration in liquid phase

[c] Henry's Law Constant: Computed from (b) using method of Mills et al. (1982) as shown in Tetra Tech, 1983.

Sources:

1. EPA, 1996
2. Suthersan, 1997
3. EPA, 1997c

imposed vacuum of an MPE system facilitates recovery of the LNAPL by reducing the effect of capillary and interface forces (EPA, 1996).

The applicability of MPE is also governed by the volatility or vapor pressure of the contaminants. The primary removal mechanism of the SVE portion of MPE is volatilization followed by advective transport to the recovery well (Peargin, 1995). Therefore, MPE is most applicable to VOCs such as petroleum hydrocarbons (e.g., benzene, toluene, ethylbenzene, and xylenes) and chlorinated and nonchlorinated solvents and degreasing agents (e.g., tetrachloroethylene and trichloroethylene) (EPA, 1997b). Others state that MPE is applicable to nonvolatile contaminants provided that the increased airflow and subsequent introduction of oxygen stimulate biodegradation (EPA, 1997b; EPA, 1996; Kittel et al, 1994).

3.2 ADVANTAGES AND POTENTIAL LIMITATIONS OF MPE COMPARED TO CONVENTIONAL PUMPING

MPE provides a number of advantages and benefits over conventional pumping approaches. A summary of the advantages and potential limitations of MPE is provided in Table 3.2. The foremost of these is the ability of MPE to effectively function in moderate to low permeability soils (Suthersan, 1997; EPA, 1996). MPE can provide contaminant source removal in lower permeability settings that may only be served otherwise by excavation of the source area (Suthersan, 1997). MPE is versatile in that it can be employed to remediate multiple phases of contamination, including the vapor, residual, dissolved, and non-aqueous phases of contamination, while conventional pumping addresses only the latter two phases (EPA, 1996). MPE can potentially create a large radius of influence affecting greater capture of the contaminant plume. Conventional recovery approaches in low permeability formations tend to realize low flow rates with steep drawdown and limited capture. This forces the use of a greater number of recovery wells to affect mass removal and plume containment. MPE requires significantly fewer wells due to its ability to maximize fluid recovery at the wellhead (EPA, 1997b; Suthersan, 1997; EPA, 1996). MPE also reduces the drawdown necessary to obtain a given flow rate. This is especially beneficial to settings requiring free product recovery. Conventional pumping approaches tend to smear free product along the face of the drawdown curve and have limited success in removing NAPL trapped in the capillary fringe.

Table 3.2. Summary of the advantages and potential limitations of MPE.

Advantages	Potential Limitations
• Effective on moderate to low permeability soils (Suthersan, 1997; EPA, 1996) • Effective source removal at low permeability sites where the only other viable remedial option may be excavation (Suthersan, 1997) • Effective for simultaneous remediation of dissolved, vapor, residual, and non-aqueous phases of contamination (EPA, 1996) • Creates potentially large radius of influence and increased capture zone (Suthersan, 1997; EPA, 1996) • Increase total fluids recovery, minimize drawdown and free product smearing, and maximize aquifer transmissivity at the wellhead (EPA, 1997b; Suthersan, 1997; EPA, 1996) • Reduces number of recovery wells required (Suthersan, 1997) • Effective for capillary zone remediation (EPA, 1997b; EPA, 1996) • Reduces duration of remediation compared to conventional pumping approaches (Suthersan, 1997; EPA, 1996)	• Requires vacuum pump or blower (EPA, 1996) • Potentially greater treatment requirements as a result of NAPL emulsions and VOC-laden vapors (i.e., liquid-phase separation and vapor treatment) (EPA, 1996) • Initial startup and adjustment periods may be longer compared to conventional pumping approaches (EPA, 1996) • Potentially higher capital costs compared to conventional pumping approaches (EPA, 1996) • Depth limitations apply to some MPE configurations (EPA, 1996; EPA, 1997c)

Smearing of free product is minimized by MPE since the aquifer transmissivity is maintained at the well. The induced vacuum of MPE also removes NAPL from the capillary fringe by overcoming the capillary forces (EPA, 1997b; EPA, 1996). Perhaps the most significant advantage of MPE is its ability to expedite remediation resulting in a cost savings when compared to conventional pumping (Suthersan, 1997; EPA, 1996).

However, compared to conventional pumping approaches, MPE has increased equipment and appurtenance requirements that can increase costs. This includes the vacuum pump or blower along with the various instrumentation and valving that support the vacuum manifold. In addition, implementing MPE may result in increased treatment requirements over conventional pumping. For example, vapor phase treatment, either by activated carbon or thermal/catalytic destruction, may be necessary to treat the recovered soil vapor. Because some vacuum pumps may emulsify NAPLs in the liquid stream, the emulsified product must be separated from the liquid stream by gravimetric separation or other means to protect other treatment processes (HSI GeoTrans, 1998). Initial startup and adjustment periods may be longer due to the need to optimize flow rates, vacuum pressures, and drawdown throughout the recovery network and for monitoring requirements. The most significant technical limitation of MPE is depth for configurations, such as bioslurping, that are to be used for LNAPL recovery. As mentioned before, vacuum lift is limited to a depth of approximately 30 feet. Other configurations, such as VE/GE or the two pump system, can be employed to overcome depth limitations since submersible pumps are used to provide fluid lift and recovery.

4 VENDORS OF MPE

EPA's Technology Innovation Office (TIO) has an ongoing effort to update and maintain a database of vendors of characterization and remediation technologies, known as EPA REACH IT (<*http://www.epareachit.org*>). This database is used by site owners, technology providers, and other environmental professionals to better understand the types of technologies currently available and sites where technologies are being used.

EPA REACH IT combines information from three established EPA databases, the Vendor Information System for Innovative Treatment Technologies (VISITT), the Vendor Field Analytical and Characterization Technologies System (Vendor FACTS), and the Innovative Treatment Technologies (ITT), to give users access to comprehensive information about treatment and characterization technologies and their applications. It combines information submitted by technology service providers about remediation and characterization technologies with information from EPA, the U.S. Department of Defense (DoD), the U.S. Department of Energy (DOE), and state project managers about sites at which innovative technologies are being deployed. As of early 1999, EPA REACH IT included information about more than 750 service providers that offer almost 1,300 remediation technologies and more than 150 characterization technologies.

A search of the EPA REACH IT database was conducted to find vendors that offer multi-phase extraction. Table 4.1 lists the vendors and provides a summary description of the technology they offer. The vendors also provided information on specific sites where the technologies were applied, as shown on Table 4.2. It is important to note that information reported in Tables 4.1 and 4.2 are claims provided by the technology vendors in EPA REACH IT. Information was not modified or verified for this report.

Many of the vendors listed possess patents on their repsective MPE systems. Using a patented MPE process may require the user to obtain design and/or construction services directly from the patent holder or purchase a license to provide the technology to others. Interested parties should contact the individual vendors to discuss licensing terms and patent provisions.

Table 4.1. MPE vendors listed in EPA REACH IT[1].

Vendor	Technology	Aspects of Configuration	# of Units			Vendor Points of Contact	List of Performance Claims	Patented Applications
			Pilot	Design	Full-Scale			
Billings & Associates, Inc. www.aristotle.com	Subsurface Volatilization and Ventilation System™	• Air injection using positive pressure. • Vapor withdrawal using negative pressure to remove volatiles. • Stimulation of existing microbial community.	0	100	60	Rick Billings Vice President Ph:(505) 345-1116 Fx:(505)345-1756 rickbillings@aristotle.com	• Rapid installation. • Uses air to avoid water treatment. • Able to manipulate air flows and pressures. • Able to direct air to select areas of a site.	Registered trademark. Patent pending.
Dames & Moore www.dames.com	Two-phase vacuum extraction	• Recovery of contaminated soil vapor and groundwater in same borehole. • VOCs are stripped from groundwater. • Air is injected below water table.	26	0	28	Joseph M. Tarsavage, P.E., Senior Chemical Engineer Ph: (215)657-5000X2010 Fx: (215) 657-5454 phljmt@dames.com	• Up to 85 to 99% of contaminants are volatilized/ stripped from groundwater. • Groundwater extraction rates are up to 10 times greater than through conventional pumping methods.	• Non-registered trademark. • Two phase extraction process is patented. • Priming methods for vacuum extraction well is a patented process.
IT Corporation www.itcorporation.com	Vacuum enhanced pumping	• Passive air lift techniques and either vacuum blower or pump to extract fluids.	4	16	19	John Mastroianni Project Manager Ph: (713)996-4400 Fx: (713)3299163 jmastroianni@itcrp.com	• Successfully used to lift groundwater from depths up to 60 to 70 feet bgs. • Accelerates the remediation process.	Patent pending

Table 4.1. MPE vendors listed in EPA REACH IT (continued).

Vendor	Technology	Aspects of Configuration	# of Units			Vendor Points of Contact	List of Performance Claims	Patented Applications
			Pilot	Design	Full-Scale			
KAP & SEPA, Ltd. www.kap.cz	SVE combined with LNAPL vacuum extraction. No trade name specified.	• ½-inch pipe extracts LNAPL from 4-inch SVE well.	0	0	7	Peter Kohout (KAP) & Vladimir Kinkor (SEPA) Czech Republic Ph: +4202 24313630 Fx :+4202 57211255 pkohout@prg.kap.cz	• Capable of treating halogenated or nonhalogenated VOC contaminated soils nonhalogenated volatile. • Does not require expensive equipment or numerous personnel to operate.	Patent information unknown.
Radian International, LLC www.radian.com	Xerox Two-Phase High Vacuum Extraction™	• High vacuum oil sealed pump draws vapors and liquid through extraction straw.	36	2	21	Joe Fitzgerald Site Manager Ph: (315) 456-3671 Fx:(315) 456-6844 joe_fitzgerald@radian.com	• Significant advantages over conventional dual phase systems.	Registered trademark. Patented process by Xerox. Radian is first full licensee.
Terra Vac, Inc. www.terravac.com	Dual Extraction™ Entrainment Extraction™	• Water table is lowered by vacuum tube. • Common blower draws vacuum on both liquid and vapor.	70	115	250	Tony Vinici Operations Manager Ph: (609) 371-0070 Fx: (609) 371-9446	• Considerably more efficient than a P&T system. • Substantial savings in cost.	Non-registered trademark. Patented.

Table 4.1. MPE vendors listed in EPA REACH IT (continued).

Vendor	Technology	Aspects of Configuration	# of Units			Vendor Points of Contact	List of Performance Claims	Patented Applications
			Pilot	Design	Full-Scale			
ARS Technology, Inc. www.arstechnologies.com	Pneumatic Fracturing Extraction (PFE)™	• High burst injection of air at several discrete intervals. • Used in conjunction with dual phase extraction and other technologies.	36	1	11	John Liskowitz President Ph: (732)296-6620 Fx: (732)296-6625	• Capital costs and operating costs are reduced compared with other technologies. • Number of wells required is decreased. • Speeds up the rate of mass removal. • Reduces time required for remediation.	Registered trademark. Patented.

[1] Information given in this table, including aspects of configuration, number of units, points of contact, list of performance claims, and patented applications, was extracted from EPA REACH IT (<*http://www.epareachit.org*>) in December 1998. Information is shown as provided by technology vendors in EPA REACH IT, and was not modified for this report.

Table 4.2. Representative MPE sites for vendors listed in EPA REACH IT[1].

Site Name/ Location	Media	NAPL	Contaminant Untreated Concentration Range[2]	Contaminant Treated Concentration Range[2]	Volume/ Quantity Treated	Depth Treated	Date Contracted	Current Status	Project Reference
Billings & Associates, Inc. Subsurface Volatilization and Ventilization System™									
Confidential	Soil Groundwater	DNAPL LNAPL	Benzene: 10 ppm Ethylbenzene: >10 ppm Toluene: >10 ppm Xylene: >10 ppm	Benzene: 0.01 ppm Ethylbenzene: <5.0 ppm Toluene: <5.0 ppm Xylene: <5.0 ppm	1,500 ft^3	40 feet	March 1991	Completed - October 1993	James Bearzi NMED-USTB P.O. Box 26110 Santa Fe, NM 87502
Electro-Voice Site Buchanan, MI USA	Soil Sediments Groundwater	Not reported	1,1,1 - Trichloroethane(TCA): 18 ppm Ethylbenzene: 1,400 ppm PCE: 240 ppm Toluene: 4,300 ppm TCE: 23 ppm Xylene: 6,600 ppm	Not Available	169,500 ft^3	66 feet	March 1992	Ongoing	Tim Mayotte Brown & Root Environmental, Inc. 4641 Willoughby Road, Hold Michigan Ph: (517) 694-6200
Super Valu Site Albuquerque, NM USA	Soil Sediments Groundwater	Not reported	Benzene: 25 ppm Ethylbenzene: 25 ppm Toluene: 25 ppm Xylene: 25 ppm	Benzene: 0.01 ppm Ethylbenzene: <1.0 ppm Toluene: <1.0 ppm Xylene: <1.0 ppm	21,600 ft^3	45 feet	March 1992	Completed - December 1993	Keith Fox NMED, USTB 4131 Montgomery Blvd. N.E. Albuquerque, NM 87109 (505) 841-9478
Dames & Moore Two-Phase Vacuum Extraction™									
Indiana Gasoline Station Clarkesville, IN USA	Soil Groundwater	LNAPL	Benzene: 21 ppm Ethylbenzene: 1.1 ppm Toluene: 14 ppm Xylene: 5.8 ppm	Not Available	169,760 ft^3	10 to 20 feet	October 1992	Ongoing	Not Available
Machine Shop Trenton, NJ USA	Soil Groundwater	LNAPL	TCA: ND-5.1 ppm 1,1-Dichloroethane: ND - 2.8 ppm VOC's: ND - 12.14 ppm	TCA: ND 1,1-Dichloroethane: ND VOC's: ND - 0.020 ppm	2,660 yd^3	10 feet	May 1993	Ongoing	Not Available
IT Corporation Vacuum enhanced pumping									
Gasoline Service Station Houston, Texas USA	Soil Groundwater	LNAPL	Not Available	Not Available	59,850 ft^3	10 to 30 feet	1992	1993	Not Available

Table 4.2. Representative MPE sites for vendors listed in EPA REACH IT[1] (continued).

Site Name/ Location	Media	NAPL	Contaminant Untreated Concentration Range[2]	Contaminant Treated Concentration Range[2]	Volume/ Quantity Treated	Depth Treated	Date Contracted	Current Status	Project Reference
KAP & SEPA, Ltd.									
Ralsko Airbase Ralsko, Czech Republic	Soil Groundwater	LNAPL	Kerosene: 0.1 - 0.4 ppm PCE: 0.1 - 0.4 ppm	Kerosene: 0.1 - 0.4 ppm PCE: 0.1 - 0.4 ppm	22,030 lbs.	26 feet	March 1993	Ongoing	Ing. Kroova, Director of Department of Environmental Damages Vrsovicka 65, 100 10 Praha 10, Czech Rep +4202 6712078
Radian International LLC Xerox 2-Phase High Vacuum Extraction™									
Xerox Corporation Mississauga, Ontario Canada	Soil Groundwater	Not reported	Dichloroethylene: >500 ppm (soil)	Dichloroethylene: 1.3 ppm (soil)	3,000 lbs.	25 feet	NA	Completed - December 1995	Scott Huber Xerox Corporation Ontario (716) 422-0779
McClellan Air Force Base Sacramento, CA USA	Soil Groundwater	Not reported	TCE: 7,000 ppm	Not Available	6,000 lbs.	115 feet	August 1994	Ongoing	Kevin Wong McClellan AFB (916) 643-0830
Terra Vac, Inc.™ Dual Extraction, Entrainment Extraction™									
Gasoline Service Station Los Angeles, CA USA	Soil Sediments Groundwater	LNAPL	Benzene: free product - gasoline	Benzene: ND - 0.05 ppm (soil)	Approx. 500,000 ft^3	25 feet	September 1990	Completed - October 1991	Not Available
Rental Car Facility Los Angeles, CA USA	Soil Sediments Groundwater	LNAPL	BTEX: >100 ppm TPH: >1000 ppm	BTEX: ND TPH: ND -470 ppm	Not Available	Not Available	June 1990	Completed - February 1991	Not Available
Tinkhams Garage Londonderry, NH USA	Soil Sediments Groundwater	LNAPL	PCE: .003-190 ppm (soil) Toluene: ND-300 ppm (soil) TCE: ND - 10 ppm (soil) VOC's: ND-0.8 ppm (soil) Xylene: ND-0.3 ppm (soil)	NA	81,000 ft^3	18 feet	1989	Ongoing	Mike Walters Cannons Site Group Technical Committee 1265 Main Street Waltham, MA 02254

Table 4.2. Representative MPE sites for vendors listed in EPA REACH IT[1] (continued).

Site Name/ Location	Media	NAPL	Contaminant Untreated Concentration Range[2]	Contaminant Treated Concentration Range[2]	Volume/ Quantity Treated	Depth Treated	Date Contracted	Current Status	Project Reference
ARS Technology, Inc. Pneumatic Fracturing Extraction (PFE)™									
Electroplating Industrial Site Somerville, NJ USA	Soil Groundwater	DNAPL LNAPL	Benzene: 0.5328 lbs/day PCE: 0.6048 lbs/day TCE: 0.2448 lbs/day	Benzene: 0.00048 lbs/day PCE: 0.00072 lbs/day TCE: 0.00936 lbs/day	Approx. 19,000 ft^3	9 to 17 feet	June 1992	Completed - December 1993	Herb Skrovronek SAIC 411 Hackensack Ave. Hackensack, NJ 07652 Ph: (201) 489-5200
Industrial Facility Santa Clara, CA USA	Soil Groundwater	DNAPL LNAPL	TCE: 7 - 20 ppm	TCE: 0.46 - 0.88 ppm	4,500 ft^3	3.5 to 13 feet	August 1993	Completed - December 1993	Trevor King McLaren/Hart Environmental Eng. 25 Independence Blvd. Warren, NJ 07059 Ph: (908) 647-8111
Military Base Oklahoma City, OK USA	Soil Groundwater	LNAPL	Fuel Oil: 8.6 gal/day	Fuel Oil: 1.2 gal/day	Approx: 5,000,000 ft^3	25 to 31 feet	June 1993	Ongoing	Dan Hunt TAFB OC-ALC/EMR 7701 Second Street, Ste. 20 Midwest City, OK 73145-9100
Petroleum Refinery Marcus Hook, PA USA	Soil Groundwater	LNAPL	BTEX: Not Available	BTEX: Not Available	3,500 ft^3	2 to 7 feet	November 1991	Completed - December 1996	John Schuring NJIT-HSMRC 138 Warren Street Newark, NJ 07102 Ph: (201) 596-5849
Former Manufacturing Facility Highland Park, NJ USA	Soil Groundwater	DNAPL LNAPL	TCE: 8.43 - 56.2 lbs/day	TCE: 0.23 - 2.40 lbs/day	Approx. 784,080 ft^3	10 to 17 feet	May 1994	Ongoing	Tom Nunno ChemCycle Corporation 129 South Street Boston, MA 02111-2820 Ph: (617) 451-0922
Confidential Manufacturing Site Western NY State USA	Soil Groundwater	LNAPL	Benzene: 2,400 - 2,500 ppm	Benzene: 10 - 13 ppm	5,400 ft^3	0 to 17 feet	July 1995	Completed - August 1995	Not Available

1 Information given in this table, including media treated, NAPL presence, untreated and treated contaminant concentrations, volume treated/quantity of contaminant extracted, depth treated, and date contracted, was extracted from EPA REACH IT (<*http://www.epareachit.org*>) in December 1998. Information is shown as provided by the technology vendors in EPA REACH IT, and was not modified for this report.

2 Concentration units given in mass loading rates (e.g. lbs/day) are of the extraction system prior to and after implementing MPE. Otherwise untreated and treated media concentrations are given (e.g. ppm).

Contaminant Abbreviations: Benzene, Toluene, Ethylbenzene and Xylene (BTEX) Total Petroleum Hydrocarbons (TPH) Trichloroethene (TCE) Tetrachloroethene (PCE)

5 CASE STUDIES

This section summarizes three case studies of MPE technology. MPE was used at the Defense Supply Center in Richmond, VA, the 328 Site in Santa Clara, CA, and the Tinkham's Garage Superfund Site in Londonderry, NH. All of these case studies review the site history, setting, contaminant source, and the performance of the MPE system employed. A summary of identifying information for case study sites is provided in Table 5.1. References used in preparation of the case studies are listed at the end of each case study.

Table 5.1. Summary of identifying information for case study sites.

	Defense Supply Center, Richmond, VA	**328 Site, Santa Clara, CA**	**Tinkhams's Garage, Londonderry, NH**
Vendor	Law Engineering and Environmental Services, Inc.	HSI-GeoTrans, Inc. Terra Vac, Inc.	Terra Vac, Inc.
Technology Configuration	Two-pump MPE	Single Pump MPE with Pneumatic Fracturing	Single Pump MPE
Technology Scale	Field demonstration (Treatability study)	Full scale	Full scale
Media/Matrix Treated	Soil and groundwater	Soil and groundwater	Soil (primary target media)
Contaminants Targeted	TCE, PCE, 1,2-DCE	TCE	PCE, TCE
Total VOC Mass Removed	117 lb from soil 28 lb from groundwater	782 lb from soil 382 lb from groundwater	48 lb from soil 5 lb from groundwater
Period of Operation	July 1997 - July 1998	November 1996 - December 1998	November 1994- September 1995

5.1 DEFENSE SUPPLY CENTER, RICHMOND, VA

A treatability study using dual-phase extraction (DPE) technology was conducted at the U.S. Defense Supply Center Richmond (DSCR) Acid Neutralization Pit (ANP) site. The one-year treatability study (July 1997 - July 1998) focused on deriving conclusions with respect to effectiveness of DPE and to make recommendations as to the use of this technology for full-scale remediation. The results indicated that DPE was effective in removing chlorinated and aromatic VOC contamination from the vadose zone and groundwater. The preliminary results also suggested that the DPE system would likely be adequate for groundwater remediation without additional expansion. This case study addresses the results of the one-year treatability study and the performance of DPE technology.

5.1.1 SUMMARY INFORMATION

The 640-acre DSCR is a military support, service, and storage facility located approximately 11 miles south of the City of Richmond, VA and 16 miles north of the City of Petersburg, VA. Land use in the area is predominantly residential and wooded, with the James River located approximately one mile east of the site. Since 1942, DSCR has been furnishing and managing general military supplies to the Armed Forces and several federal civilian agencies. Historical and current industrial operations at the DSCR have included repair of small equipment, engine rebuilding, and refurbishment of combat helmets and compressed gas cylinders. Historical and current operational areas consist of indoor and outdoor material storage areas, a motor pool facility, a National Guard training area, fire training areas, and a wastewater treatment system.

The ANP site is located in the northern section of the DSCR in an area used for warehouse storage and light industrial operations. Approximately one-quarter mile east and southeast of the ANP site is an off-base residential area. The ANP site consists of two former concrete settling basins that received wastewater from metal cleaning operations conducted at one of the warehouse buildings. Both tanks were approximately 6.5 feet in depth with the primary tank capacity of 14,600 gallons and a secondary tank capacity of 3,000 gallons. Metal cleaning operations were active from 1958 into the early 1980s. The operations focused on paint and rust removal and repainting of combat helmets and compressed gas cylinders. The cleaning process utilized inorganic acid and base baths. Spent metal cleaning solutions were dispensed to the tanks every one to two months. Wastewater was then discharged from the tanks to the storm sewer between 1958 and the late 1970s. After a secondary tank was added in the late 1970s, wastewater was discharged to the sanitary sewer. The settled solids in the tanks were periodically disposed of at a county landfill. The tanks were closed in 1985 by cleaning the bottoms and filling with clean earth. At the time of closing the sides of the tanks were observed to be cracked and broken. These cracks and holes were suspected migration routes of contaminants to the surrounding soil. The predominant contaminants detected in groundwater at the ANP site were chlorinated solvents, notably tetrachloroethylene (PCE) and trichloroethylene (TCE). Although site records did not indicate the use of solvents at the metal cleaning operations conducted at this portion of the site, it has been proposed that the solvents were transported from other locations at the DSCR and disposed of in the tanks at the ANP site.

5.1.1.1 GEOLOGIC AND HYDROGEOLOGIC SETTING

Impacted soil beneath the DSCR consists of the Eastover Formation extending from the surface to approximately 25 feet below ground surface (bgs). Grain size diameter appears to increase with depth in the Eastover Formation, grading from a silty clay and fine-grained sand into a coarse-grained sand with interlayered gravel. Specifically, the layers can be characterized as: (1) red-brown silty clay and clayey silt; (2) gray mottled, red/yellow interlayered sand and silty clay; (3) red-yellow clayey, fine-grained sand and sandy clay; and (4) light gray, mottled red-brown clayey, coarse-grained sand with gravel.

An unconfined water table aquifer exists in the Eastover Formation beneath the DSCR site. The depth to the water table surface ranges from 10 to 15 feet bgs. The aquifer found in the Eastover Formation can be separated into an upper low permeability zone and a lower high permeability zone. The upper low permeability zone consists of the upper three layers of the Eastover Formation, with occasional localized areas having relatively higher permeabilities. The lower sand and gravel layer is considered the high permeability zone. Transmissivity values for the upper aquifer range from 374 to 504 feet square per day (ft^2/d).

The hydraulic gradient is essentially flat at 0.001 ft/ft to 0.002 ft/ft with flow to the northeast direction.

5.1.1.2 SITE CHARACTERIZATION SUMMARY

Soil and groundwater samples were collected and analyzed for the remedial investigation (RI) in 1987 and a supplemental RI in 1992. Soil and groundwater at the ANP site were divided into Operable Units 5 and 8, respectively. Constituents detected in soil consisted of low levels of volatile and semi-volatile organic compounds including PCE, phthalates, naphthalene, and phenanthrene. VOCs were detected at elevated levels in monitor wells screened in the upper aquifer. The highest concentrations of VOCs detected downgradient of the ANP area were 3300 micrograms per liter (μg/L) for PCE and 890 μg/L for TCE. Chlorinated VOCs were not detected in the lower aquifer. This information supported earlier conclusions that a clay confining interval between the upper and lower aquifers was preventing downward migration of contaminants into the lower aquifer. Based on the data collected during the investigations, the plume area was estimated to be 16,000 square feet. A summary of the ANP site information is provided in Table 5.2.

Table 5.2. DSCR-ANP site summary.

Parameter	Characteristics
Geologic Setting of Source Area	Upper Eastover Formation Silty Clay, Fine Sands, Course Sands and Interlayered Gravels 0 to 25 ft bgs
Geologic Setting of Impacted Aquifer	Upper Low Permeability Zone of Eastover Formation Silty Clay, Clayey Silt, Interlayered Sand and Silty Clay 10 to 25 ft bgs
Depth to Groundwater	10 to 15 ft bgs
Hydraulic Gradient	0.001 to 0.002 ft/ft NE
Aquifer Transmissivity	374 to 504 ft^2/d
Constituents of Concern	Tetrachloroethylene (PCE), Trichloroethylene (TCE), 1,2-Dichloroethylene (1,2-DCE)
Groundwater Concentrations Prior to DPE Treatability Study†	3300 μg/L PCE; 890 μg/L TCE; 26 μg/L 1,2-DCE
Plume Area Prior to DPE Treatability Study	Approximately 16,000 square feet

† Maximum detections from RI

5.1.1.3 REMEDIATION SUMMARY

The Record of Decision (ROD) for operable unit 5 (OU5) included the use of SVE to address soil contamination. An SVE pilot test was conducted in support of the remedial design for OU5. Results from the SVE test resulted in low air flow rates and minor recovery of VOCs. Analysis of samples from borings installed after the SVE test showed that soil VOC concentrations had decreased to below risk-based concentrations. An Explanation of Significant Differences (ESD) was submitted and recommended no further remediation for OU5.

The Feasibility Study (FS) identified dual phase extraction as a potentially viable remediation alternative for groundwater (OU8). Aquifer tests and a DPE pilot test were conducted to gather site-specific data including transmissivity, specific yield, groundwater recovery rates, hydrostatic responses, vadose zone vacuum distributions, intrinsic permeability, air extraction rates, and SVE mass removal rates. Overall the test supported the use of DPE for VOC recovery. The test data supported the design of a larger DPE system. The pilot test also showed the need to employ air injection to facilitate vadose zone air flow.

Several performance goals were established for remediation of groundwater by DPE at the ANP site. The first goal was to remove contaminated groundwater from the upper aquifer for ex-situ treatment by air stripping. In addition, DPE was to lower the groundwater table to increase the volume of semi-saturated soil through which air flow and volatilization of constituents would occur. Based on theory and practice, mass transfer of VOCs from the soil will continue to occur, provided drawdown is maintained. Moreover, DPE was sought to maintain a constant hydraulic gradient toward the DPE wells to prevent off-site migration.

The performance goals for DPE were set to evaluate its effectiveness in achieving remedial action objectives (RAOs) for the site. The RAOs are as follows:

- Reduction of the highest levels of contamination resulting in immediate risk reduction;
- Plume containment of contamination in excess of remedial goals;

- Achievement of remedial goals (PCE ≤ 5 μg/L, TCE ≤ 5 μg/L), or attainment of an asymptotic trend in contaminant of concern (COC) concentrations in groundwater (whichever occurs first).

It was proposed that DPE would achieve these goals in a more timely manner than could be accomplished by conventional groundwater pumping.

The purpose of the DPE treatability study at the ANP site was to evaluate the effectiveness of a full-scale system. The treatability study also sought to collect additional operational data that may refine system design parameters, if necessary. The study also evaluated the effectiveness of an air injection system to facilitate air flow through soils exposed by drawdown of the groundwater surface. Table 5.3 presents a timeline of remedial activities related to DPE at the ANP site beginning with the remedial investigation (RI) through the present.

Table 5.3. Timeline of remedial activities at DSCR-ANP site.

Activity	**Time of Performance**
Remedial Investigation (RI)	January 1987 - November 1988
Supplemental RI	September 1992 - December 1992
ROD for Soils (OU5)	1992
SVE Pilot-Test for Soil	December 1992
Feasibility Study (FS)	November 1994
Aquifer Test/DPE Pilot-Test for Groundwater (OU8)	June - July 1995
ESD† for OU5	September 1995
Work Task Proposal Issued for DPE	July 1996
DPE System Construction Begins	January 1997
Groundwater Extraction Begins	June 1997
SVE and Air Injection Begins	July 1997
12-Month DPE Treatability Study	July 1997 - July 1998
Treatability Study Report Issued/Continued DPE Operation	November 1998

† Explanation of Significant Differences (ESD) for soils at ANP site (OU5) indicated that soil contamination was below risk-based action levels. Recommendation was made to exclude OU5 from further remediation.

5.1.2 TECHNOLOGY DESCRIPTION AND SYSTEM DESIGN

The DPE system consists of 12 dual phase extraction wells and six air injection wells arranged in a rectangular grid. The DPE well configuration is the two pump MPE configuration as discussed in Section 2.4.2 and shown in Figure 2.3. Each DPE well consists of a sealed casing to maintain SVE vacuum and an electric, submersible (variable-frequency drive) pump for groundwater extraction. The DPE wells are 6-inch diameter polyvinyl chloride (PVC) screen and casing. Well screen was 0.020-inch factory slotted continuous for a depth of 10 feet. A solid cased sump of 2-feet in length was provided at the base of the well for the submersible recovery pump. The wells were installed to be fully penetrating, to depths ranging from 22 to 28 ft bgs. Wells were developed by surging and pumping techniques prior to use. Air injection is achieved by a low pressure rotary-lobe blower through injection wells. The air injection, in conjunction with the SVE portion of DPE, creates air movement through the soil to transfer VOCs. The VOC-laden vapors are extracted by the DPE wells. SVE vacuum is induced by a blower equipped with an air-water separator. Air extracted by the SVE blower is vented to the atmosphere. Extracted groundwater is pumped directly to a low-profile tray type air stripper to remove VOCs. Air stripper off-gas is released to the atmosphere. Effluent water is discharged to a storm sewer that flows to a nearby stream. To date, an exemption from a state administered discharge permit is active while a ROD is completed for the site.

5.1.3 TECHNOLOGY PERFORMANCE

The DPE treatability study was conducted for one year. During system operation, operational data were routinely collected. This information served as a means of monitoring the performance of system components. A summary of the performance data from the treatability study is provided in Table 5.4. Figure 5.1 and Table 5.5 illustrates the potentiometric surface of groundwater at various times of system operation. The areal extent of drawdown in the water table (radius of influence) during the study period was estimated to be 600 to 800 feet in a down gradient direction and 1,800 to 2,500 feet in an up gradient direction. Drawdown in surrounding monitoring wells ranged from 3.94 feet (400 feet from the nearest dual phase extraction well) to 10.88 feet (in a monitoring well within the

Table 5.4. Summary of DPE system performance data at DSCR.

Parameter	**Value**			
Treatability Study Duration	384 days			
DPE System Operation	7687 hours (320 days)			
SVE Vacuum at Blower	42 in WC, average			
SVE Air Flow Rate	314 cfm, average			
Groundwater Extraction Rate	37 gpm, average			
Cumulative Volume of Extracted Groundwater	17,000,000 gallons			
DPE Radius of Influence	600 to 800 ft, downgradient			
Maximum Drawdown Realized	3.94 ft at 400 ft distance			
Maximum Influent Total VOC Concentrations	1162 μg/L (first month) 90 μg/L (last month)			
Maximum Reduction in VOCs Concentrations in Groundwater	Constituent	Initial Conc.	Final Conc.	% Reduction
	PCE	1300 μg/L	< RAO[*]	99.6
	TCE	290 μg/L	< RAO	98.3
Soil VOC Mass Removal (Rate)	117 lb (0.37 lb/d), total 70 lb (0.22 lb/d), aromatic 47 lb (0.15 lb/d), chlorinated			
Groundwater VOC Mass Removal (Rate)	28 lb (0.09 lb/d), total 2 lb (<0.01 lb/d), aromatic 26 lb (0.08 lb/d), chlorinated			

Unit notes: in WC = inches of water column; cfm = cubic feet per minute; gpm = gallons per day; μg/L = micrograms per liter; lb = pounds; lb/d = pounds per day

* Remedial action objective (RAO) for groundwater was 5 μg/L for PCE and TCE

Figure 5.1. Comparison of baseline groundwater levels (Law Engineering and Environmental Services, 1998). (Best available copy)

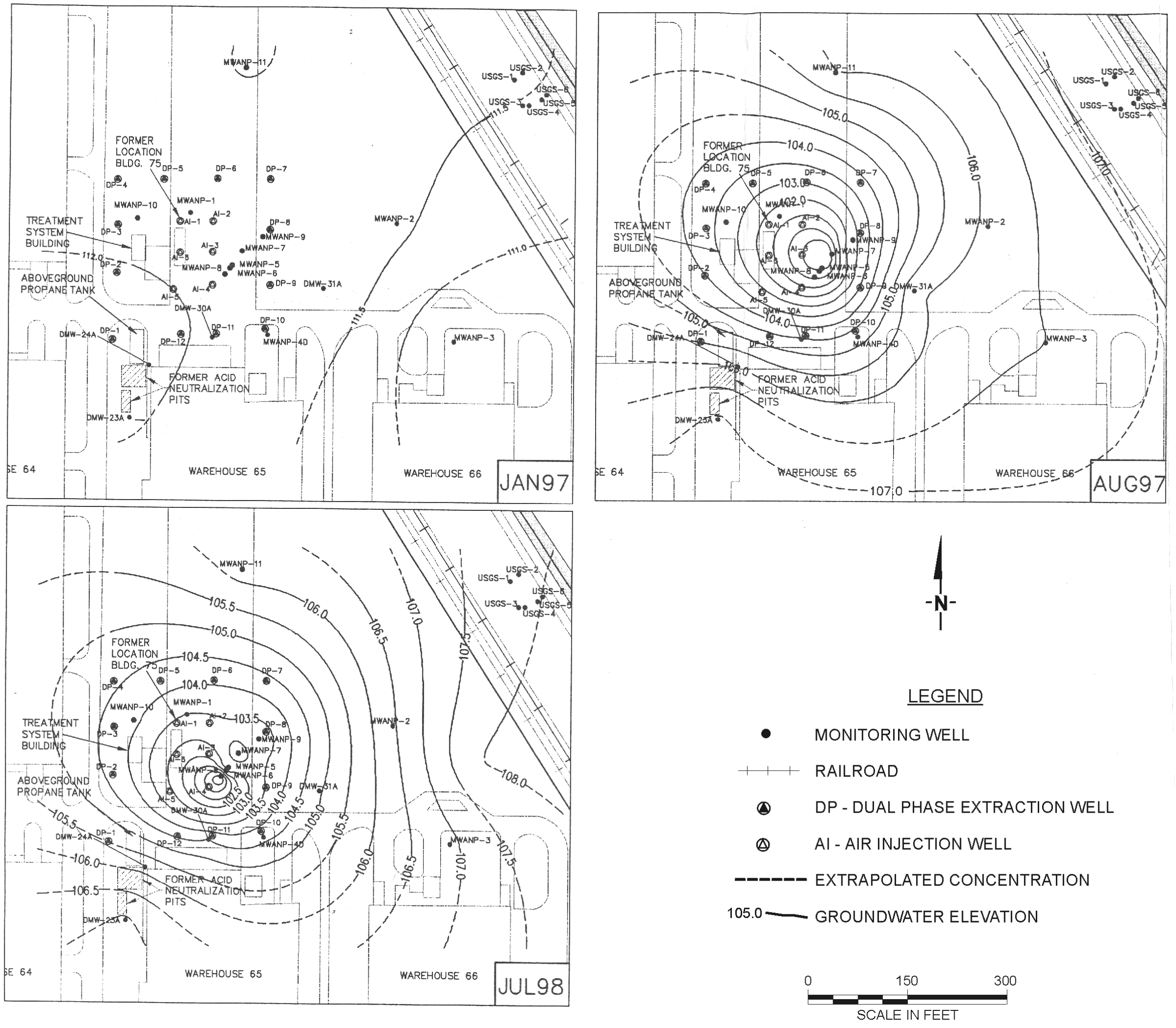


Table 5.5. Potentiometric surface elevations.

Well I.D.	Potentiometric Surface Elevation		
	January 1997	August 1997	July 1998
DMW-23A	112.04	107.07	107.08
DMW-24A	112.05	106.04	105.86
DMW-30A	111.97	104.55	104.50
DMW-31A	111.88	105.87	104.94
MWANP-1	111.91	102.30	103.50
MWANP-2	111.62	106.88	106.43
MWANP-3	110.51	106.49	106.87
MWANP-5	NA	100.14	103.15
MWANP-6	NA	100.76	103.62
MWANP-7	111.89	101.93	103.81
MWANP-8	NA	100.14	100.40
MWANP-9	NA	NA	103.00
MWANP-10	111.94	103.30	104.13
MWANP-11	111.47	106.03	106.23
USGS-2	NA	107.39	107.89
OS72-1	NA	NA	108.01
OS72-1	NA	NA	107.86

NA=Not Available

perimeter of the extraction wells). Groundwater was extracted at a rate between 22 to 53 gallons per minute (gpm), averaging 37 gpm for the study period.

SVE flow rates ranged from 150 to 378 cubic feet per minute (cfm) at 40 to 44 inches of water column (in WC). The average extraction air flow rate was 314 cfm with an average vacuum of 42 in WC. SVE emissions were routinely analyzed to support mass removal calculations. Chlorinated VOC concentrations in the extracted vapors increased an order of magnitude within the first 5 days of DPE system operation. This was followed by a steady decrease over the following two weeks. A discrete peak of aromatic VOCs was observed for one sampling event early in system operation. In general, total VOC concentrations in extracted soil vapor remained steady over the last 10 months of the treatability study. These static VOC levels in extracted vapor suggest that VOC removal rates through SVE approached asymptotic levels, or steady-state. Figure 5.2 plots the time variation of VOCs in SVE air emissions.

Groundwater samples were also analyzed at five events through the treatability study duration plus one, initial round to establish baseline conditions. These data (shown in

Figure 5.2. Plot of VOC concentrations in SVE emissions over time (Law Engineering and Environmental Services, Inc., 1998). (Best copy available)

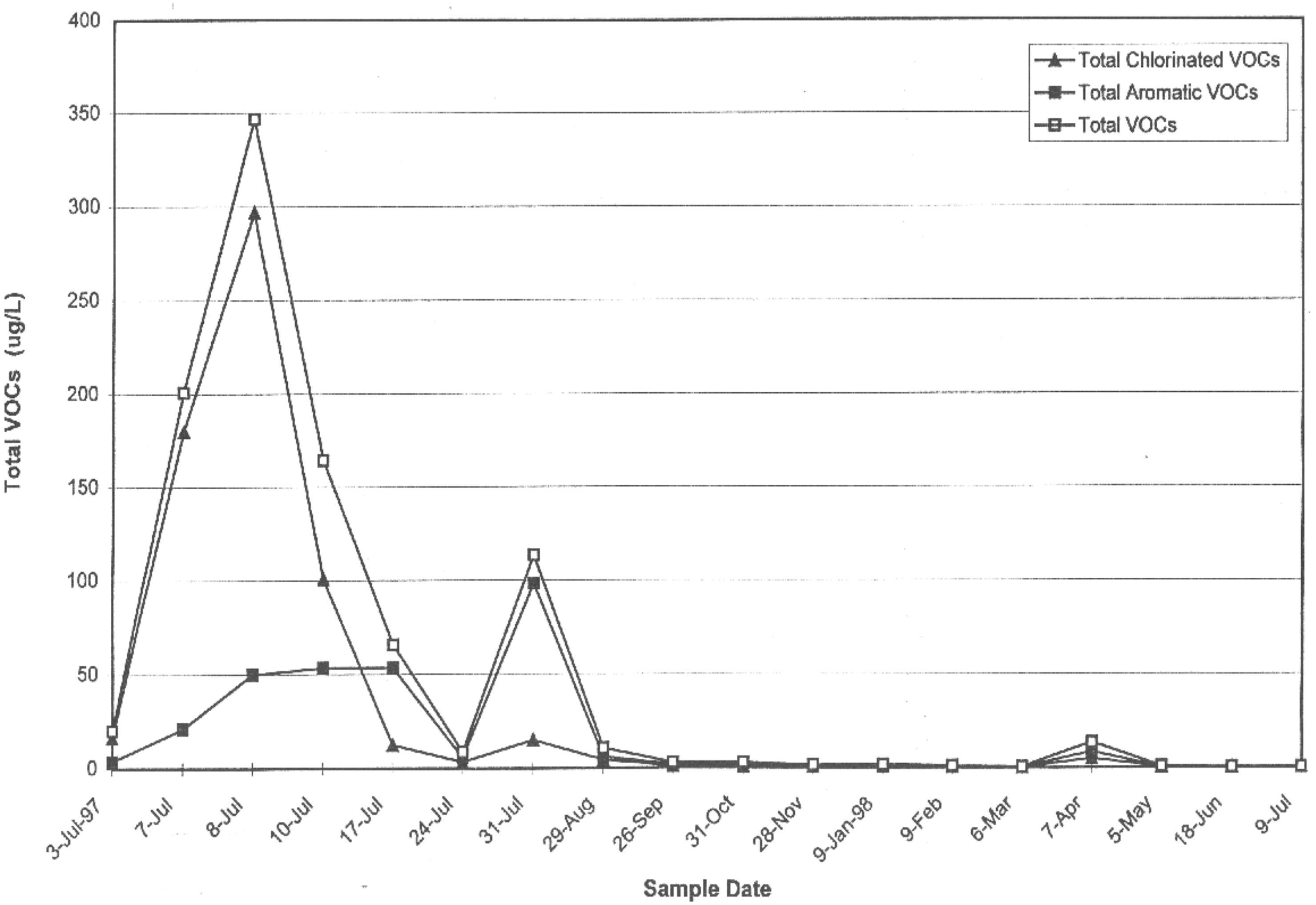


Table 5.6) were used to monitor and evaluate the change in VOC concentrations in groundwater affected by DPE. Figure 5.3 illustrates the VOC distribution in groundwater at several stages in the study time frame. Significant reductions in groundwater VOC concentrations were realized during DPE operation. Most notable were the reductions observed in the plume center where total VOCs were reduced from 1766 μg/L to 3.6 μg/L at one monitor well and from 1980 μg/L to 12 μg/L at another monitor well. Increasing concentrations of chlorinated VOCs were observed at two wells on the outer edge of the DPE influence. The source of this contamination is uncertain. At the conclusion of this study, several wells possessed PCE and TCE concentrations in excess of the remedial goals (<5 μg/L).

Table 5.6. Summary of groundwater VOC data.

Well I.D.	**Total Chlorinated VOCs (ug/L)**					
	January 1997	**August 1997**	**October 1997**	**January 1998**	**April 1998**	**July 1998**
DMW-23A	0.53	3.13	2.00	2.28	0.9	2.1
DMW-24A	41.56	18.11	2.26	4.73	5.2	3.6
DMW-30A	1980.5	637.20	21.52	25.28	71.1	11.9
DMW-31A	10.43	30.39	43.71	31.81	20.2	58.6
MWANP-1	21.78	12.63	1.02	1.11	0.6	0.70
MWANP-2	116.14	83.42	28.00	16.65*	25.6	20.5
MWANP-3	2.26	9.60	14.46	43.51	158.6	141
MWANP-7	1765.9	298.95	4.50	3.89	7.7	3.5
MWANP-10	860.7	5.43	ND	0.33	0.3	0.4
MWANP-11	142.74	177.84	15.14	23.30	130.1	55.6
USGS-2	12.78	1.29	18.00	8.27	1.1	0.5

ND = Not Detected
*Collected in February 1998

Mass removal rates were calculated based on analytical sampling and volumetric flow rates of SVE emissions and groundwater treatment system influent. In total, 145 pounds of VOCs were removed by DPE. SVE accounted for approximately 117 pounds (81 percent) and groundwater extraction for the remaining 28 pounds (19 percent). For SVE, aromatic VOC removal rates outweighed those for chlorinated VOCs through most of the study. Figures 5.4 and 5.5 plot the cumulative mass removal of VOCs by groundwater extraction and SVE, respectively.

Figure 5.3. Total VOC concentrations in groundwater (Law Engineering and Environmental Services, Inc., 1998). (Best available copy)

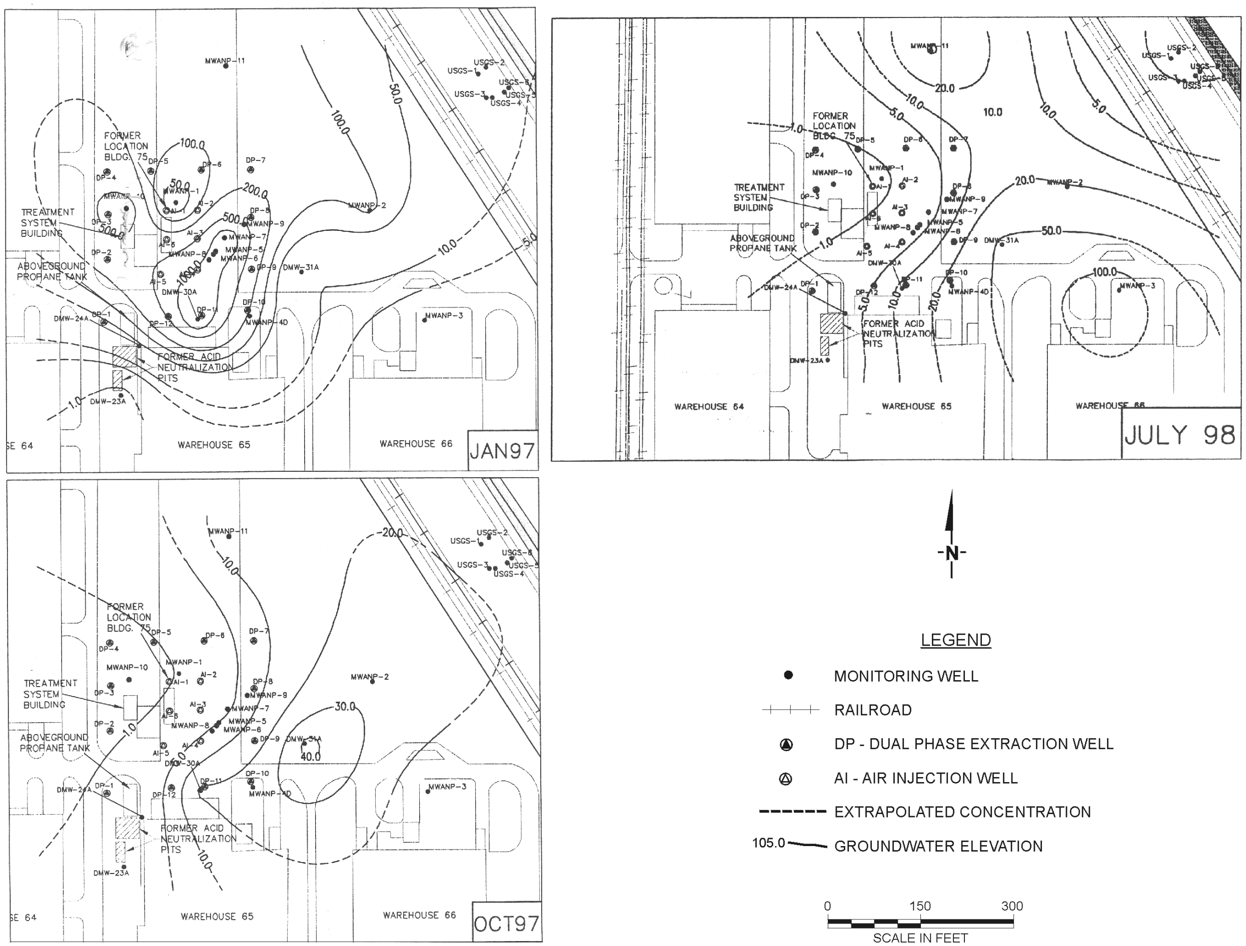


Figure 5.4. Cumulative mass of VOCs removed by groundwater extraction (Law Engineering and Environmental Services, 1998). (Best available copy)

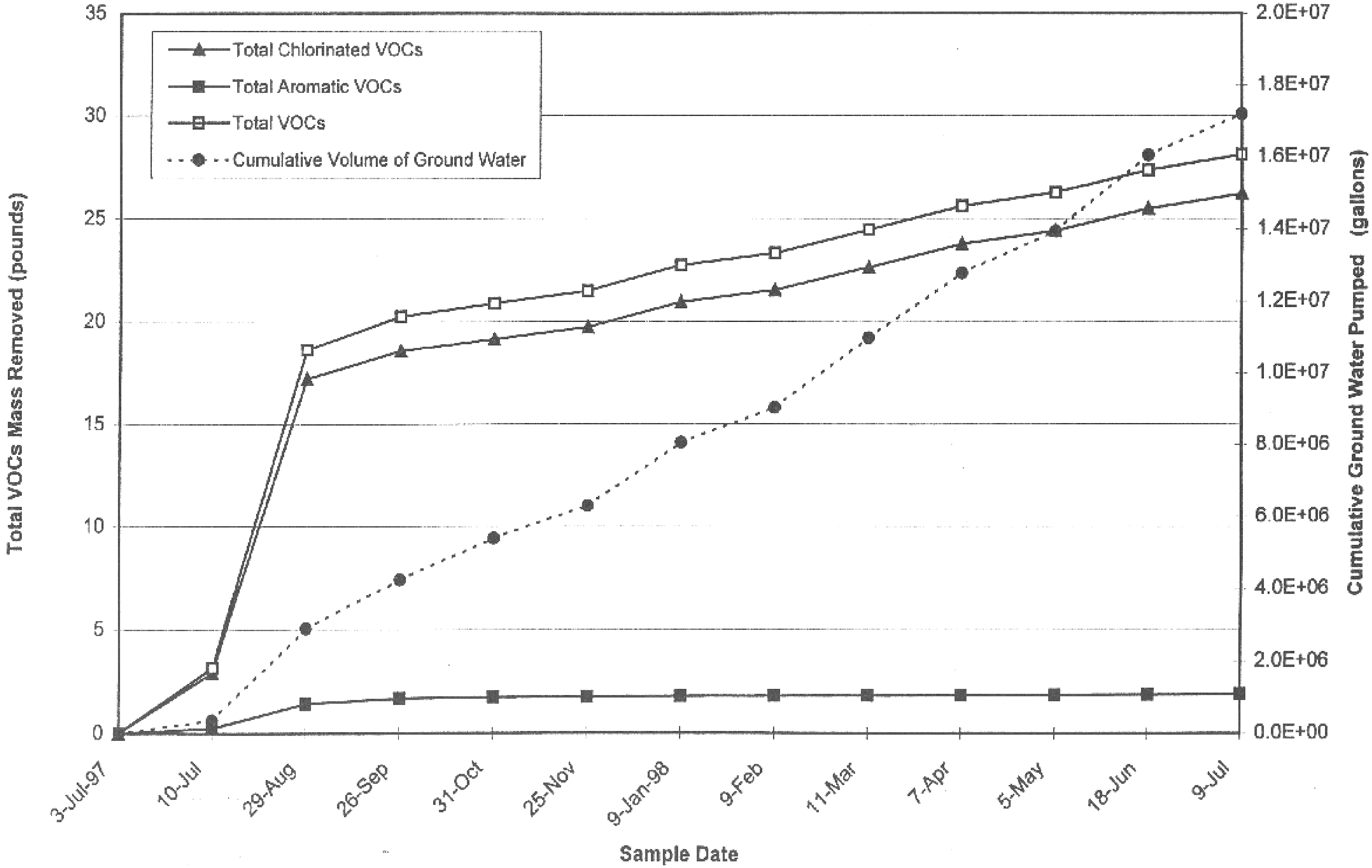
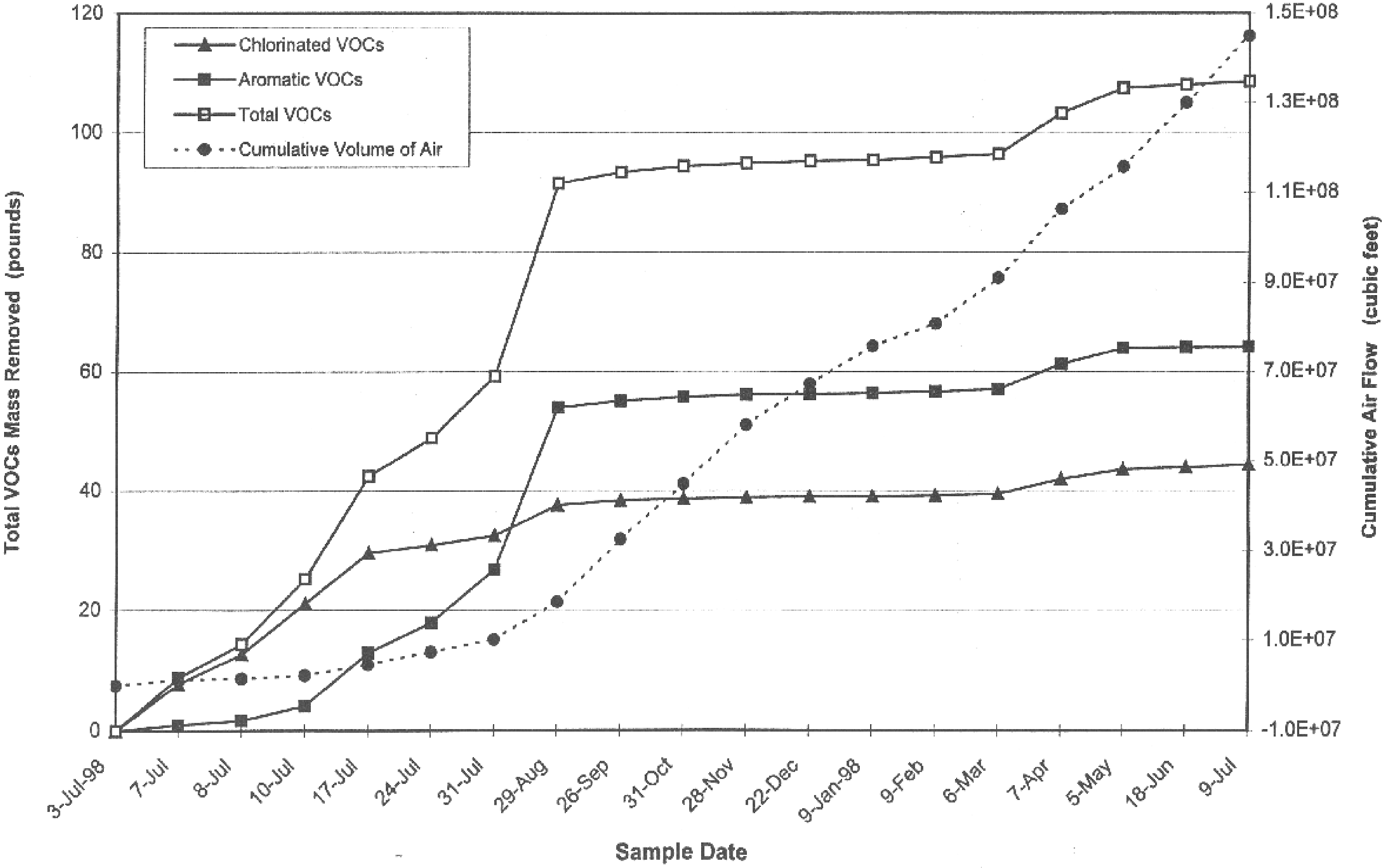


Figure 5.5. Cumulative mass of VOC's removed by SVE (Law Engineering and Environmental Services, 1998). (Best available copy)



5.1.4 TECHNOLOGY COST

The cost for pre-design investigations supporting DPE design, namely pilot and aquifer testing, was $134,092. Engineering design of the DPE system was $73,198. System construction costs (equipment only) were $205,743. Startup costs were $24,309 and the cost for one year of operation and maintenance was $101,148 and includes the cost of sample collection and analysis. Based on 17 million gallons of groundwater recovered during the project, the total cost per unit volume of groundwater recovered and treated is $0.03 per gallon.

5.1.5 SUMMARY OF OBSERVATIONS AND LESSONS LEARNED

The following conclusions and recommendations were identified by the Army's contractor (Law, 1998) on the performance of the DPE system during the treatability study period.

- Site conditions are favorable for dual phase extraction to be implemented for groundwater remediation.
- The reduction in VOC concentrations in the upper aquifer of the ANP site was affected by DPE and the existing system configuration appears to be adequate for remediating groundwater at OU8.
- Operation of the existing DPE system should be continued until remedial goals or asymptotic levels of contaminants of concern are achieved. If remedial goals are not achieved, then the system should be shut down to monitor VOC rebound. Remaining contamination above remedial goals, if present, should be evaluated and alternatives for remediation, including continued DPE operation and natural attenuation, be considered.
- Additional investigations are recommended to better define the capture zone of the DPE system; to determine the extent of discrete, elevated levels of contamination; and evaluate the ability of the existing DPE system to address contamination present in that area, if necessary.

5.1.6 CONTACT INFORMATION

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5.2 328 SITE, SANTA CLARA, CA

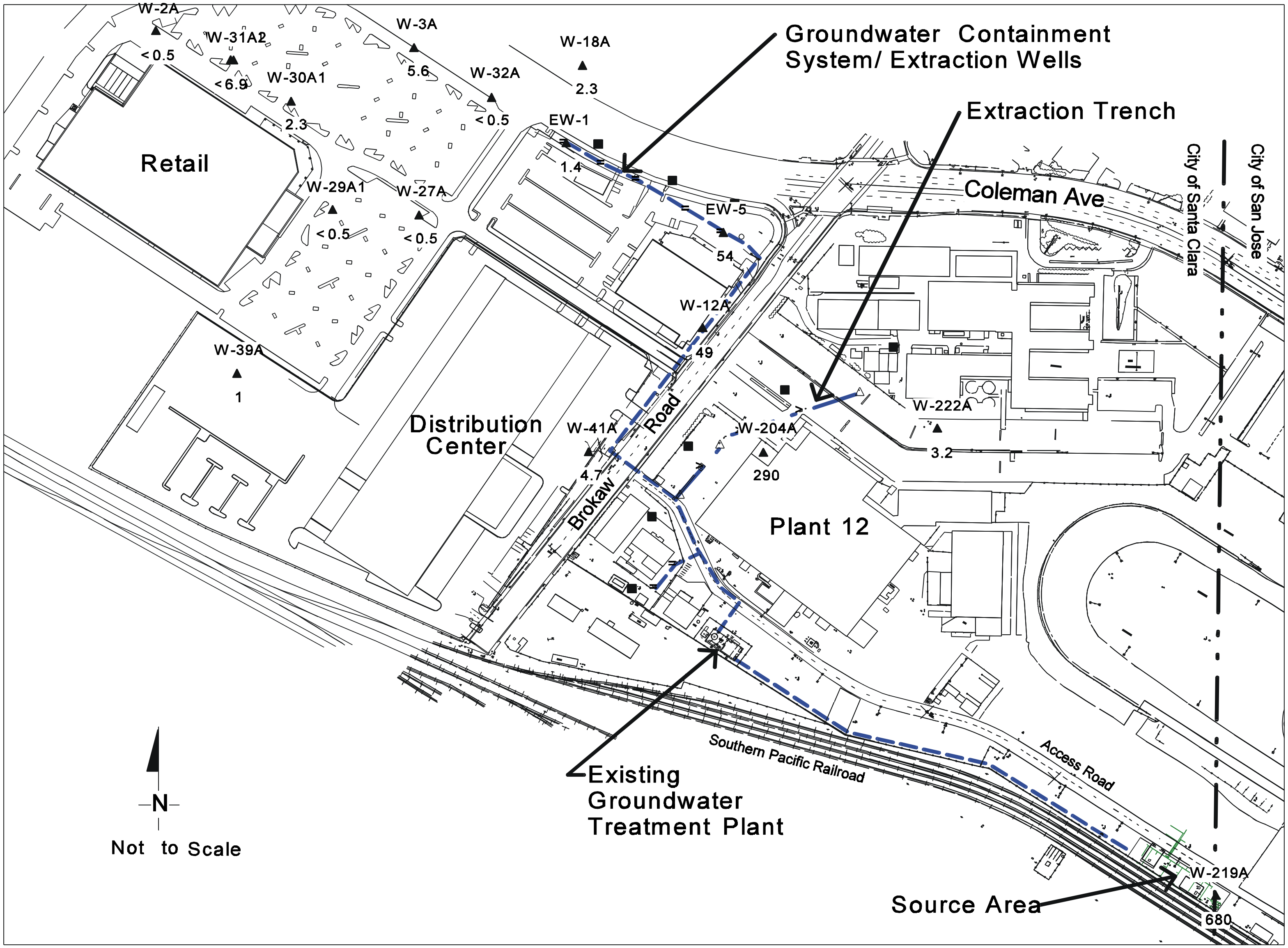
5.2.1 SUMMARY INFORMATION

A Dual Phase Extraction (DPE) system was designed, installed, and operated to remove VOCs from silty clay soils and shallow groundwater in a former waste storage area at a large industrial manufacturing facility. Air flow through the soils was enhanced by pneumatic fracturing (PF) between DPE extraction wells and by supplying continuous low flow/low pressure air to the fractured soils. The increased air flow caused by fracturing, within an otherwise tight clay formation, improved capture of VOCs by the vapor extraction system. In addition, concurrent groundwater extraction removed highly impacted shallow groundwater. Over 40 percent of the VOC mass removal occurred from the vadose zone during the first month of operation. Groundwater extraction provided greater mass removal rates than soil vapor extraction by the fifth month of operation. The combination of technologies has allowed soil vapor extraction to be effective in an area that is not well suited for in-situ remediation.

The 328 Site occupies approximately 27.1 acres in a primarily industrial and commercial area of San Jose and Santa Clara, California, near the San Jose Airport. The 328 Site was used for manufacturing military tracked vehicles, including assembly and painting operations, from 1963 through 1998. Manufacturing operations were discontinued in 1998 and the 328 Site is currently being remediated in anticipation of future commercial/industrial redevelopment. This project was conducted by FMC Corporation in accordance with the State of California San Francisco Bay Regional Water Quality Control Board *Final Site Cleanup Requirements Order Number 96-024,* with HSI GeoTrans and Terra Vac as engineer/primary contractor and subcontractor, respectively.

Figure 5.6 presents the 328 Site plan, including the source area and groundwater containment system. Table 5.7 provides a summary of the site setting information. The source area was a former waste handling area that is currently covered with asphalt paving. Downgradient migration of impacted groundwater extended to the northeast past the property boundary. A groundwater containment/treatment system was installed at the perimeter of the property in 1993 to prevent further off-site migration of impacted groundwater. The DPE

Figure 5.6. Map of 328 site (Zahiraleslamzadeh et al., 1998).



with PF system was installed at the 0.5-acre source area in 1996 to remediate shallow soils and groundwater.

Table 5.7. 328 site setting.

Parameter	Characteristics
Geologic Setting of Source Area	Silts and Clays, 0 to 20 feet below ground surface
Geologic Setting of Impacted Aquifers	Sandy Silts, Silty Sands, and Gravelly Sands, 20 to 90 feet below ground surface
Depth to Groundwater	8 feet below ground surface
Constituents of Concern	Trichloroethylene (TCE)
Initial Concentrations	46 mg/kg in Soil; 37,000 ug/L in GW

Sediments underlying the 328 Site include marine or basinal clays, coarse channel deposits, and inter-channel silts and clays. The first extensive lithologic unit encountered at the 328 Site is a dark gray to black silty clay. This unit is immediately below ground surface to depths of approximately 20 feet. Although groundwater is located approximately eight feet below ground surface, the first water-bearing zone (A-level aquifer) underlies the surficial clay, and is observed within a depth interval of approximately 20 to 50 feet below ground surface. The second water-bearing zone (B-level aquifer) is present at depths of 50 to 90 feet below ground surface.

VOCs, predominantly trichloroethylene (TCE), were the primary chemicals of concern. The highest TCE concentration measured in the soil during the remedial investigation was 46 mg/kg, and the highest concentration measured in shallow groundwater during the remediation was 37,000 ug/L. The objective of the DPE with PF system was to remediate shallow soil and groundwater to a depth of 20 feet below ground surface.

5.2.2 TECHNOLOGY DESCRIPTION AND SYSTEM DESIGN

Table 5.8 provides a summary of the technology used at the 328 site.

Table 5.8. Technology summary.

Technology	Mechanism
Soil Vapor Extraction	Volatilization of TCE from soil matrix by extracting vadose zone air; air flow increases volatilization processes.
Groundwater Extraction	Air entrainment lifts shallow groundwater droplets with extracted vapors.
Pneumatic Fracturing	Injecting high-pressured air for one to two minutes to create fractures within the clay soil matrix and allow increased air flow through impacted materials.
Air/Water Separator	Gravity separation.
Air Treatment	Vapor-phase carbon removes TCE from air by adsorption.
Groundwater Treatment	Air strippers and vapor-phase carbon at existing downgradient groundwater treatment plant.

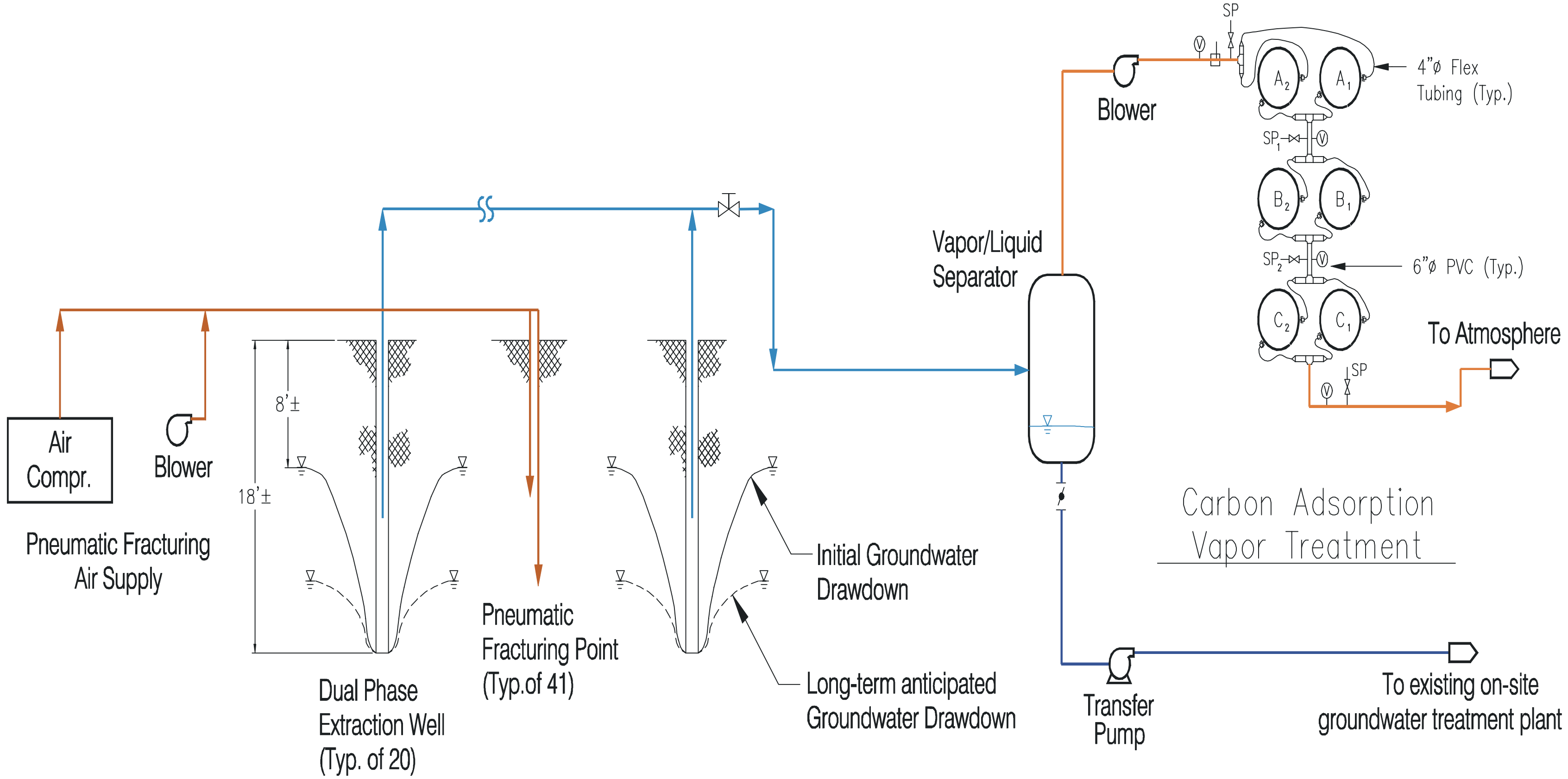
Twenty dual phase, single pump extraction wells were installed at the source area based on the results of previous SVE and PF pilot tests. Two pneumatic fracture points, at specific depths, were installed between each pair of extraction wells - a total of 41 fracture locations. Following initial fracturing, a low flow/low pressure compressor provided continuous air injection into each fracture point. A process flow diagram is shown in Figure 5.7. According to the site owner and their consultant (Zahiraleslamzadeh, 1998) this system offered the following advantages:

1. The pneumatic fracture locations specifically target the low flow regions at the midpoints between extraction wells.
2. The low flow/low pressure air supply maintains open fractures and supplies air to the low flow regions.
3. Air entrained extraction is cost-effective given the shallow groundwater and clay soils.

5.2.3 TECHNOLOGY PERFORMANCE

The DPE with PF system began operating in November 1996; Table 5.9 provides an overall operations timeline. In theory, the groundwater extraction rate would decrease as the water table was lowered in the vicinity of each well, and additional wells could be brought on-line; however, groundwater production was approximately five gallons per minute (gpm)

Figure 5.7. Process flow diagram (Zahiraleslamzadeh et al., 1998).



per well instead of the 0.5 to 2.0 gpm anticipated by the design. This was attributed to the presence of high-permeability lenses in the formation that provided preferential flow paths. Groundwater drawdown a few feet away from operating extraction wells was limited to three to five feet, while drawdown greater than one foot was observed over 100 feet away from the nearest operating DPE wells.

Table 5.9. Operations timeline.

Dates	Activities
May 1996 – August 1996	Work Plan and Design
September 1996 – November 1996	Construction and Startup
December 1996 – April 1997	Pneumatic Fracturing and Cluster Operations
May 1997 – May 1998	Continued Operations focused in areas of highest impacts
June 1998 – August 1998	Shutdown and Rebound
September 1998 – October 1998	Restart and Continued Operation
November 1998	Confirmation Soil Sampling
January 1999	Final Reports and Preparation for System Shutdown

The DPE system extracted approximately 35 gpm of groundwater on a continuous basis. This limited the number of extraction wells that can operate simultaneously. As such, clusters of extraction wells were operated on a rotating basis to accommodate the unexpected high groundwater production. Cluster operations were focused on areas of higher VOC concentrations.

Pneumatic fracturing of the source area soils was conducted using a portable air compressor and an air supply manifold. The manifold pressure was set at approximately 75 pounds per square inch gauge (psig) and the valve slowly opened to apply an increasing pressure to the pneumatic fracture point. The fracture point pressures ranged from 6 to 60 psig and averaged approximately 19 psig. These fracture pressures were lower than expected for the silty clay soils. The fracturing data also indicates that the formation likely contains high-permeability lenses that provided preferential flow paths.

Extraction vapor flow rates increased significantly following pneumatic fracturing. The average vapor flow rate from the DPE wells increased from approximately 39 scfm to over 65 scfm. In addition, numerous wells experienced order of magnitude increases in vapor flow rate. VOC mass removal, however, remained relatively constant as VOC concentrations were lower in extracted vapors following pneumatic fracturing.

5.2.3.1 VOC MASS REMOVAL

VOC mass removal followed a typical SVE system decline, as shown in Figure 5.8. The VOC mass removal rate was approximately 90 pounds per day during the first four days of operation and declined to less than 30 pounds per day by the eighth day of operation. The DPE system removed approximately 1,220 pounds of VOCs from the source area soils and shallow groundwater. Figure 5.8 illustrates VOC mass removal over time.

VOC concentrations in groundwater declined similar to VOC mass removal. The average source area VOC concentration in groundwater has declined from over 12,000 micrograms per liter (ug/L) to less than 800 ug/L, during operation of the DPE system. Groundwater monitoring results are shown in Table 5.10 and illustrated on Figure 5.9.

During initial operation, the VOC concentration in groundwater transferred from the DPE system to the groundwater treatment plant was 380 ug/L. As such, the air entrained extraction process strips nearly 97 percent of the VOCs from the groundwater, based on the initial average VOC concentration in groundwater of 12,000 ug/L. Therefore, the mass of VOCs transferred to the groundwater treatment plant is considered insignificant compared to the mass of VOCs removed through the vapor-phase carbon treatment system.

Figure 5.8. VOC mass removal.

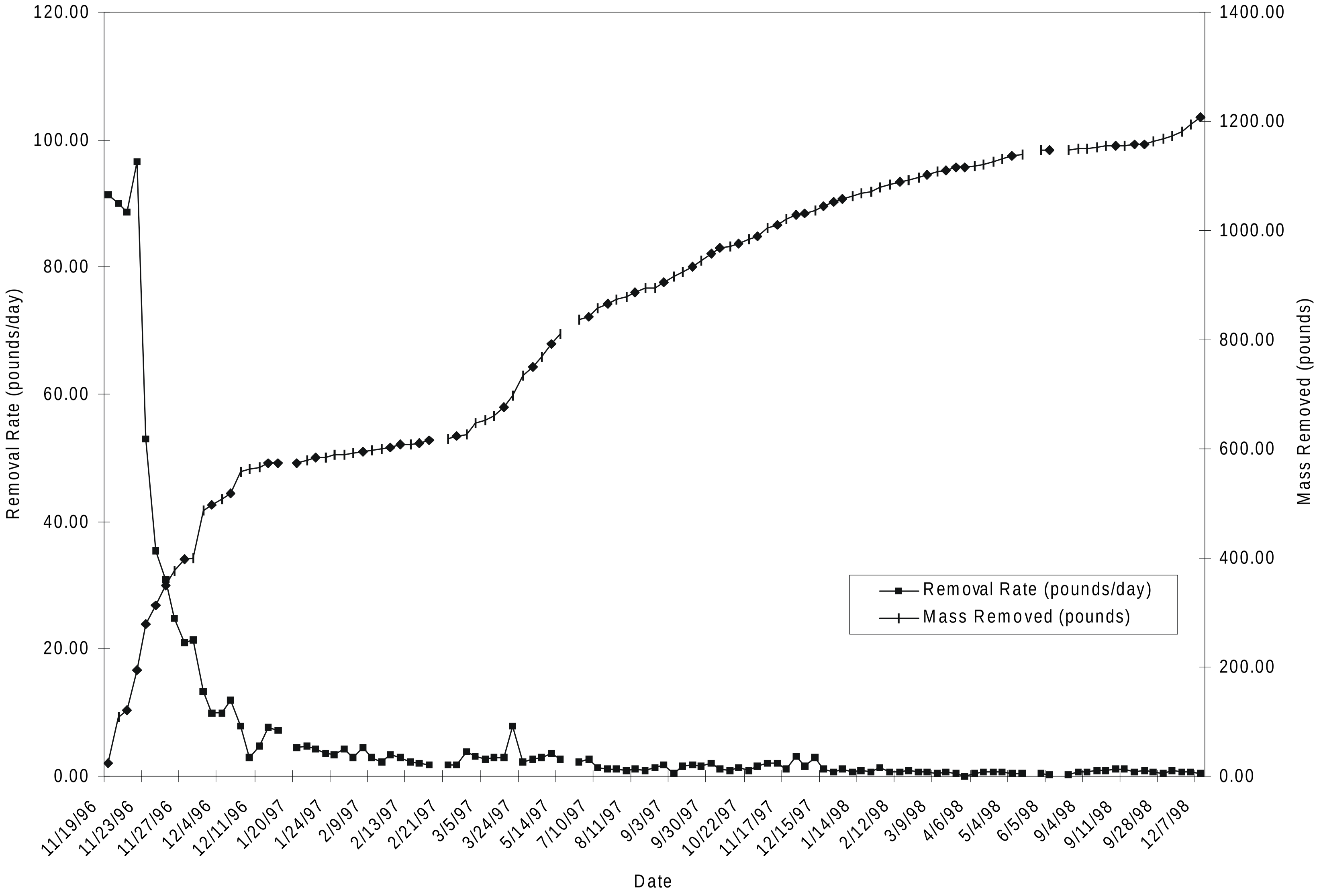


Figure 5.9. Average VOC concentrations of groundwater over time.

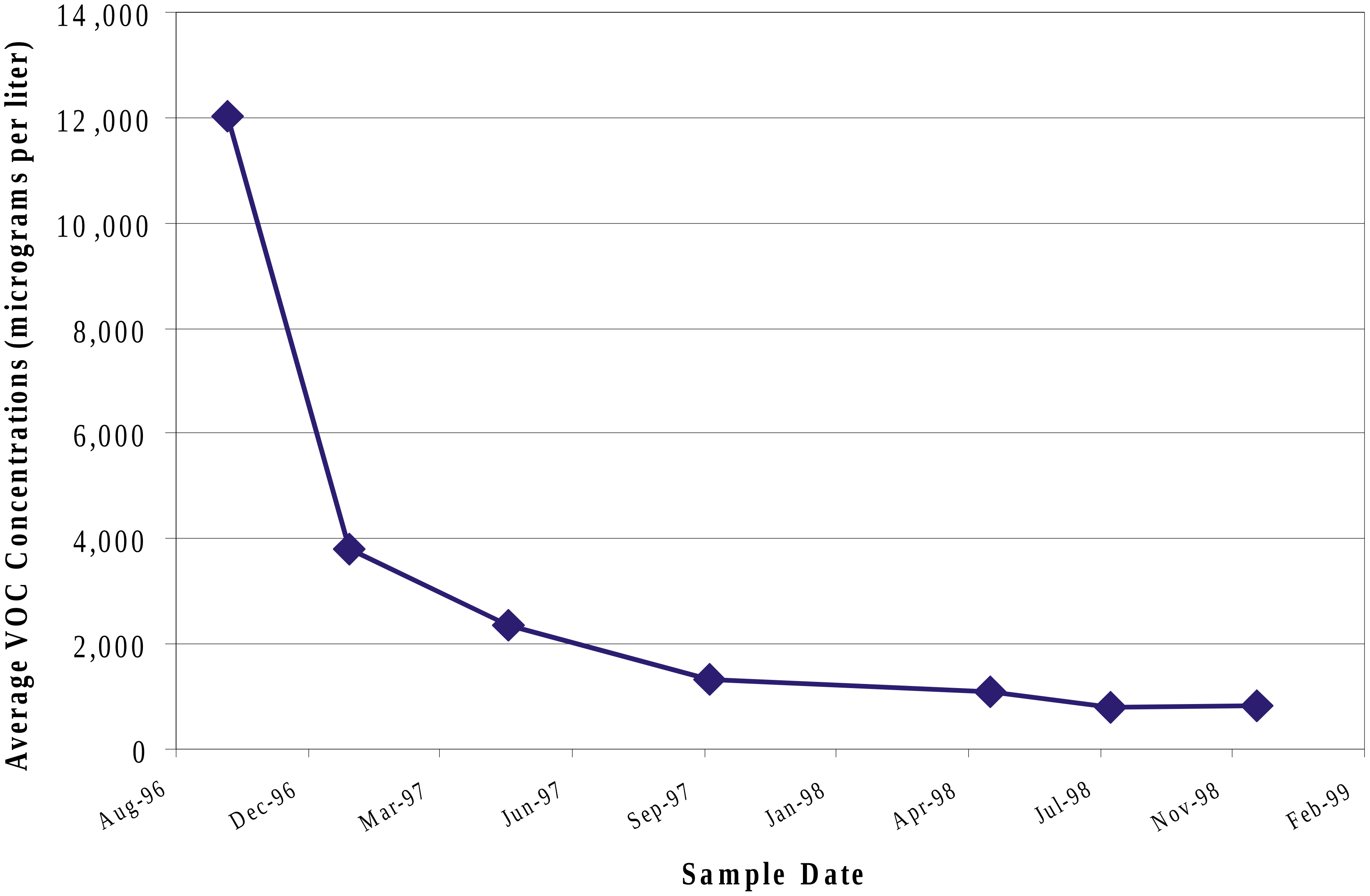


Table 5.10. VOC concentrations in groundwater.

DPE Well	Oct-96(1)	Jan-97(2) Feb-97	May-97(3)	Oct-97(4)	May-98(5)	Aug-98(6)
DP-1			1,704	990	954	1,134
DP-2	14,000	9,900	4,700	1,000	1,477	1,039
DP-3		4,300	2,900	920	953	611
DP-4		3,700	2,200	1,500	1,100	1,510
DP-5	8,900	2,100	1,694	1,200	947	956
DP-6		2,000	1,169	770	839	367
DP-7			8,600	6,500	4,200	573
DP-8	23,000	9,300	3,200	3,200	3,400	2,214
DP-9			1,900	2,000	550	1,744
DP-10			512	330	224	237
DP-11			219	95	95	109
DP-12	1,300	2,100	640	270	199	200
DP-13			650	300	220	343
DP-14	800	130	58	41	20	131
DP-15	10,000	3,200	1,671	1,400	913	1,598
DP-16			2,200	1,700	1,294	1,154
DP-17	37,000	3,300	750	260	597	308
DP-18	8,900	4,400	5,500	1,900	1,400	369
DP-19	4,400	1,100	816	470	560	456
DP-20			6,200	1,700	1,600	906
Average	12,033	3,794	2,364	1,327	1,077	798

All concentrations in micrograms per liter (ug/L)
VOC=Volatile Organic Compounds
DP-# = Refers to DPE well designations on site plan
(1) Prior to implementation of dual phase extraction system
(2) Approximately one month after system startup
(3) Approximately six months after system startup
(4) Approximately one year after system startup
(5) Prior to shutdown and rebound period
(6) Following shutdown and rebound period, prior to restart

Table 5.11. Mass removal of VOCs from groundwater and soil vapor extraction.

Date	Run Time (days)	Total Mass Removed (lbs)[1]	Mass Removed During Operating Interval				Mass Removed from Soil [3]	
			Total Mass		Mass Removed from GW [2]			
			(lbs)	(lbs/day)	(lbs)	(lbs/day)	(lbs)	(lbs/day)
1-Nov-96	0	0	**0**	0	**0**	0	**0**	0
11-Feb-97	30	603	**603**	20.0	**100**	3.3	**503**	16.7
16-May-97	97	810	**207**	3.1	**87**	1.3	**120**	1.8
22-Oct-97	213	984	**174**	1.5	**90**	0.8	**84**	0.7
11-May-98	386	1,139	**155**	0.9	**87**	0.5	**68**	0.4
21-Sep-98	432	1,164	**25**	0.5	**18**	0.4	**7**	0.2
12-Jan-99	544	1,221	**57**	0.5	**38**	0.3	**19**	0.2

1. Based on routine monitoring data of VOC concentrations and flow rates of extracted vapor influent to the carbon treatment units.
2. Based on average VOC concentrations in groundwater from operating DPE wells and an average groundwater extraction rate of 35 gallons per minute.
3. Equal to the Total Mass minus the Mass Removed from Groundwater.

Table 5.12. VOC concentrations in extracted vapor.

DPE Well	May-98 (1)	Sep-98 (2)
DP-7	20	50
DP-8	12	47
DP-18	18	11
DP-20	29	69

VOC = Volatile Organic Compounds

DPE = Dual Phase Extraction

Concentrations in micrograms per liter (ug/L)

Only 4 wells operating during restart

(1) Before shutdown and rebound period

(2) After restart

The mass of VOCs removed from the groundwater and the mass of VOCs removed from soil vapor varied during system operation (see Table 5.11). Over 40 percent of the VOC mass was removed from the vadose zone during the first month of operation. By the fifth month of operation, however, groundwater extraction was removing more VOC mass than soil vapor extraction. The total mass removed from groundwater is approximately 382 pounds, based on average groundwater VOC concentrations and an average extraction rate of 35 gpm. The total VOC mass removed by soil vapor extraction is approximately 782 pounds. Figure 5.10 shows the declining removal rate over time, for both groundwater and soil vapor.

Substantial VOC mass removal by groundwater extraction is likely due to significant groundwater production from a highly impacted area, lack of groundwater drawdown that would create a larger vadose zone, and completion of existing vadose zone remediation. These data illustrate the greater removal efficiency by extracting vapors from the vadose zone rather than groundwater from the saturated zone.

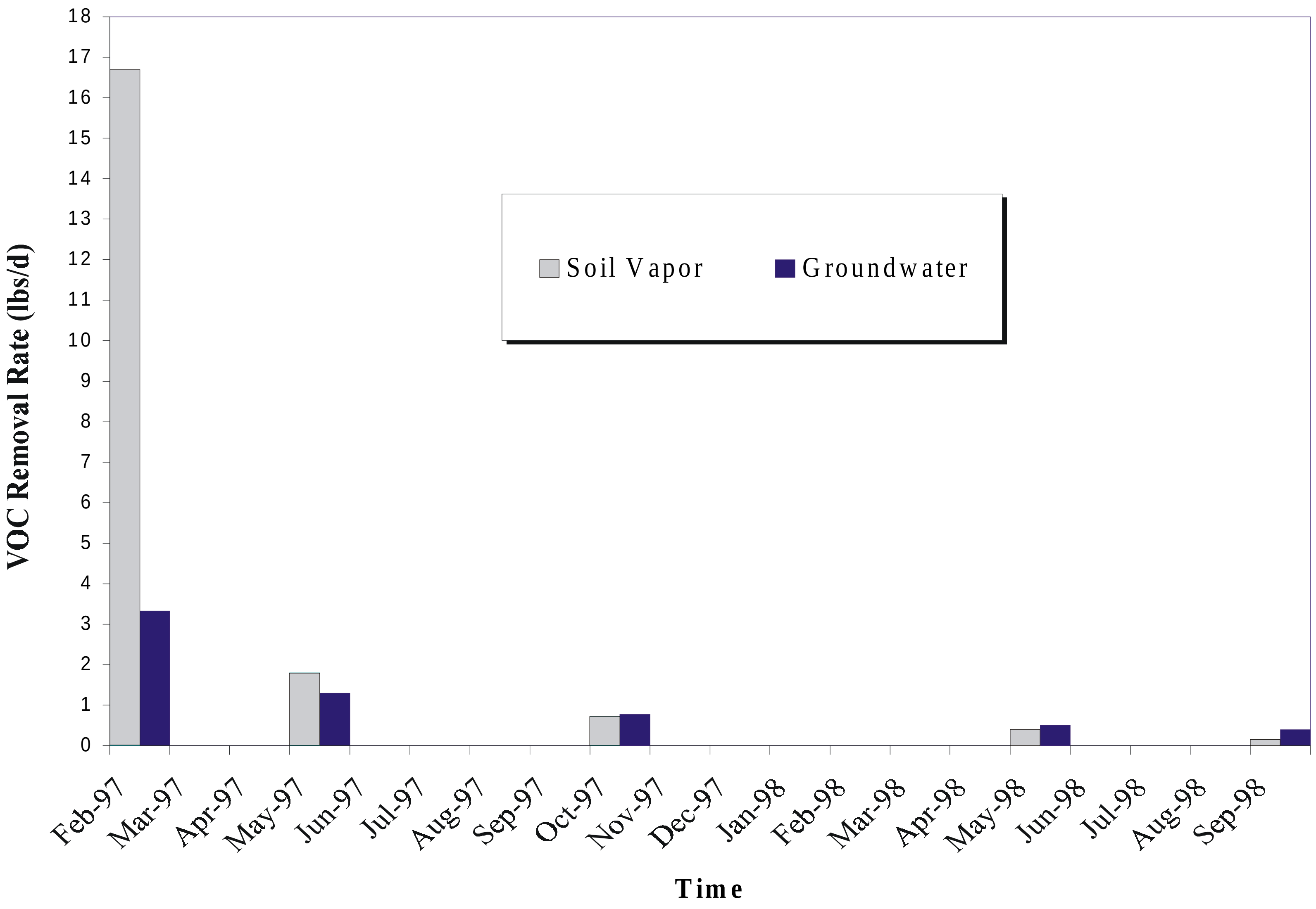
5.2.3.2 SHUTDOWN AND REBOUND

The DPE system was shutdown from June 5, 1998 through August 31, 1998 to assess any residual impacts that may provide a continuing source of VOCs after the remediation system is removed. Increases in VOC concentrations (rebound effects) were also evaluated to determine if remediation performance could be improved.

Concentrations of VOCs detected in groundwater from the DPE system extraction wells declined during the shutdown and rebound period (Figure 5.12). Conversely, the VOC concentrations detected in extracted vapor increased slightly during the shutdown and rebound period. It is likely that VOCs volatilized from the groundwater to the vadose zone during the shutdown period.

The VOC mass removed during the month prior to shutdown was approximately 12 pounds. After three months of shutdown, the VOC mass removed during the first month of operation was approximately 19 pounds. Although VOC mass removal increased, it appears that continued operation would have removed more VOC mass over the four month period (three months shutdown plus first month of operation) than system shutdown and restart.

Figure 5.10. VOC removal rates during operation.



The relatively modest increase in VOC mass removal provides further indication that the DPE system has achieved the remediation goals.

Groundwater monitoring well W-219A is located within the source area and screened in the A-level aquifer. VOC concentrations in this well appeared to have stabilized above 4,000 ug/L prior to startup of the DPE system. By use of DPE, VOC concentrations have declined from 4,000 ug/L in November 1996 to 650 ug/L in August 1998.

5.2.4 TECHNOLOGY COSTS

The cost to design and install the DPE system with pneumatic fracturing was approximately \$300,000. Approximate costs for two years of operation and maintenance services, reporting, and analytical fees were \$450,000, averaging \$225,000 per year. Approximately \$100,000 was required for the disposal of spent carbon. The unit cost for the 0.5-acre source area from 0 to 20 feet bgs was on the order of \$53 per cubic yard of soil (for treatment of 16,000 yd^3).

5.2.5 SUMMARY OF OBSERVATIONS AND LESSONS LEARNED

A significant portion of the VOC mass was removed by soil vapor extraction during the first month of operation, while approximately equal VOC mass removals, by soil vapor and groundwater extraction, were achieved during continued operation. This demonstrates the efficiency of soil vapor extraction compared to groundwater extraction, and also demonstrates the benefits of dual phase extraction.

The system reached a steady state with respect to further remediation by the existing DPE system. VOC concentrations in groundwater and extracted vapor remained relatively constant over an extended shutdown period, and these concentrations are substantially less than they were when the DPE system began operation. In addition, VOC concentrations in the A-level aquifer have declined since the source area remediation began.

5.2.6 CONTACT INFORMATION

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5.2.7 REFERENCES

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Zahiraleslamzadeh, Z.M., J.C. Bensch, and W.G. Cutler, 1998, *Enhanced Soil Vapor Extraction for Source Area Remediation Using Dual Phase Extraction with Pneumatic Fracturing*, Presented at the 14th Annual Conference on Contaminated Soils, University of Massachusetts, Amherst, MA, October 22, 1998.

5.3 TINKHAM'S GARAGE SUPERFUND SITE, LONDONDERRY, NH

A full-scale Dual Vacuum Extraction (DVE) system was designed and constructed at the Tinkham's Garage Superfund site to simultaneously draw down the water table and remediate approximately 9,000 cubic yards (cy) of VOC-contaminated soil by vapor extraction. Soil cleanup goals were achieved within ten months of operation. Groundwater cleanup goals were not met in this time, and groundwater is currently being addressed through a pump-and-treat remedy. Remediation efforts were lead by the potentially responsible parties (PRPs) with Terra Vac, Inc. performing the design and operation of the DVE system and U.S. EPA Region 1 providing regulatory oversight.

5.3.1 SUMMARY INFORMATION

The Tinkham's Garage site includes 375 acres of residential and undeveloped land in Londonderry, NH, situated in the southern portion of the state. Land use at the site includes a 400 person residential condominium complex, single-family homes, and undeveloped wooded areas, open fields, and wetlands. The Tinkham Realty Company and Tinkham's Garage, a large steel building, are located in the northeastern section of the site.

EPA site investigations in 1981 revealed onsite soil and groundwater contaminated with VOCs, including PCE, TCE, and BTEX compounds. These contaminants were determined to be the result of unauthorized surface discharges of liquids and sludge in 1978 and 1979. Three source areas were delineated. Two source areas included a soil pile behind the condominium complex and soil overlying the condominium complex leachfield. The third source area, of approximately one acre in size, is located behind Tinkham's Garage ("Garage Area" or "1 ppm Area") and is the focus of the remedial action summarized in this case study.

The nature and extent of soil and groundwater contamination at the site has been characterized by several site investigations. These investigations included a remedial investigation in January, 1985, a feasibility study in July, 1986, a pre-design study in July, 1988, and a vapor extraction pilot test in July, 1988. These investigations found total VOCs as high as 652 ppm in soil and 42 ppm in groundwater located in shallow, overburden and bedrock aquifers. A site characterization summary is provided in Table 5.13 and a chronology of events in Table 5.14.

The Superfund Record of Decision (ROD) issued in September, 1986 identified the selected remedy as excavation of approximately 10,800 cy of contaminated soil with onsite treatment by either thermal aeration, composting, or soil washing. The local wetlands impacted by excavation and groundwater were also to be remediated. As a result of the pre-design and pilot studies, the ROD was amended in March, 1989 to require the treatment of approximately 9,000 cy of onsite soil by DVE. DVE was selected to target VOCs in soil beneath the saturated zone. This would be achieved by simultaneously lowering the shallow water table and exposing formerly saturated soil to air flow. The rationale for using DVE for soil remediation was based on its ability to dewater the shallow aquifer and expose the contaminated soil to SVE. Both the original and amended RODs set cleanup goals at 1 ppm total VOCs for soil and 5 ppb each for PCE and TCE in groundwater. The ROD also called for long-term management of migration (MOM) through groundwater pumping of deep bedrock wells and a shallow recovery system until cleanup standards for PCE and TCE are obtained. Pumped groundwater was to be discharged to the Derry, New Hampshire publicly-owned treatment works (POTW).

5.3.2 TECHNOLOGY DESCRIPTION AND SYSTEM DESIGN

Consolidation of all VOC impacted soil was determined to be the most cost-effective means for remediation. Approximately 3,000 cy of contaminated soil from three areas near the condominium complex was excavated and hauled to the Garage Area. The excavated soil was then spread within the garage 1 ppm Area and compacted in place. The volume of soil requiring remediation, including the native and excavated soil, totaled 9,000 cy.

The DVE system consisted of 33 DVE wells divided into 25 shallow DVE wells, screened in the overburden, and 8 deep DVE wells, screened in the upper bedrock and overburden. Five existing pilot test wells were left in place and used for vapor extraction. The wells were distributed over three manifold lines to provide the greatest coverage over the area of contamination. The DVE well configuration used was the two-pump system described in Section 2.4.2, however, a central pump station consisting of two, 7.5-hp jet

Table 5.13. Site characterization summary for Tinkham's Garage.

Parameter	Characteristics
Geologic Setting of Source Area	• Overburden consisting of inorganic and organic silty clay and sand grading to fine and medium-grained sand with depth • Weathered metamorphic bedrock at approximately 14 feet bgs
Depth to Groundwater	5 to 6 feet bgs
Aquifer Parameters	Approximate Values: • K = 1 ft/d (overburden silts and clays) • K = 10 ft/d (overburden sands) • T = 900 gpd/ft (bedrock)
Constituents of Concern	Tetrachloroethene (PCE) and Trichloroethene (TCE)
Pre-Remediation Concentrations	Total VOCs in Soil: 652 ppm, maximum Total VOCs in Groundwater: 42 ppm, maximum
Volume of Contaminated Media	Soil: 9,000 cubic yards

Unit Notes: bgs = below ground surface; ft/d = feet per day; gpd/ft = gallons per day per foot; ppm = parts per million

Source: U.S. EPA (1989); Terra Vac (1996), HSI GeoTrans (1999)

Table 5.14. Timeline of remedial activities at Tinkham's Garage.

Activity	Period of Performance/Date of Completion
Remedial Investigation	January 1985
Feasibility Study	July 1986
Record of Decision (ROD) Signed	September 30, 1986
Vapor Extraction Pilot Study	December 1987 - January 1988
Pre-Design Study	July 1988
ROD Amended to Include Dual Vacuum Extraction (DVE)	March 1989
Discharge Strategies Evaluated	August 1990 - July 1992
Construction of Sewer Line Between Derry and Londonderry Begins	August 1993
DVE Work Plan Submitted	February 1994
Excavation and Restoration of Condominium Areas	March - April 1994
DVE Construction and Drilling at Tinkham's Garage Begins	May 1994
Issuance and Approval of Industrial Discharge Permit to Town of Derry POTW	August - October 1994
DVE System Operation Begins	November 22, 1994
Closure Sampling Plan Submitted	July 1995
DVE System Operation Terminated	September 29, 1995
Final Soil Sampling Conducted	October 1995
Final Site Inspection	October 25, 1995
Demobilization of DVE System	November 1995
Construction of Groundwater System for Management of Migration (MOM)	November - December 1995
MOM System Operation	January 1996 - Present

Source: After Terra Vac (1996).

pumps was used for groundwater extraction instead of submersible pumps at each well. The jet pump system was capable of a flow of 1.5 gpm per well and was regulated by a valve at each wellhead. A schematic of a typical DVE well and wellhead manifold is provided in Figure 5.11. Wellhead vacuum and vapor extraction was achieved by two, parallel operating portable vacuum extraction units. Each unit included a 40-hp positive displacement blower capable of extracting 500 scfm at a vacuum of 12 inches of mercury (in Hg). Vapor treatment was achieved by four 1,000 pound canisters of activated carbon. Two of these four canisters operated in series with the remaining two serving as secondary units. Two additional canisters were kept onsite to provide immediate replacements, if necessary. Initially, groundwater treatment by air stripping was necessary to meet the Derry POTW pre-treatment standards. Air stripper off-gas treatment was provided using vapor phase carbon. Figure 5.12 provides a process flow diagram of the DVE system.

5.3.3 TECHNOLOGY PERFORMANCE

Operation of the DVE system lasted 311 days from November 22, 1994 to September 29, 1995. During system operation, operational data were routinely collected to serve as a means of monitoring system performance. A summary of the performance data from the DVE system is provided in Table 5.15.

Vapor extraction flow rates averaged 500 sfcm at 5 inches of Hg vacuum (approximately 68 inches of water). Vapor extraction emissions were routinely monitored at the blower inlet to support mass removal calculations. A plot of the variation of vapor phase VOCs in the DVE system influent is provided in Figure 5.13. VOCs extracted in the vapor phase were at the highest concentrations (16 ppm) at the onset of DVE system operation and continued downward, over time, averaging 1.6 ppm for the project duration. One of the three DVE manifolds was shut down permanently after one month of operation due to negligible concentrations of VOCs in the vapor influent. This allowed for recovery efforts to focus on the most contaminated regions of the source area. All remedy performance verification samples collected at soil borings located throughout the site at the conclusion of the project indicated that the soil had been remediated to or below the remedial action objectives for soil (1 ppm total VOCs).

Figure 5.11. Schematic of DVE Well and Manifold (Terra Vac, 1996).

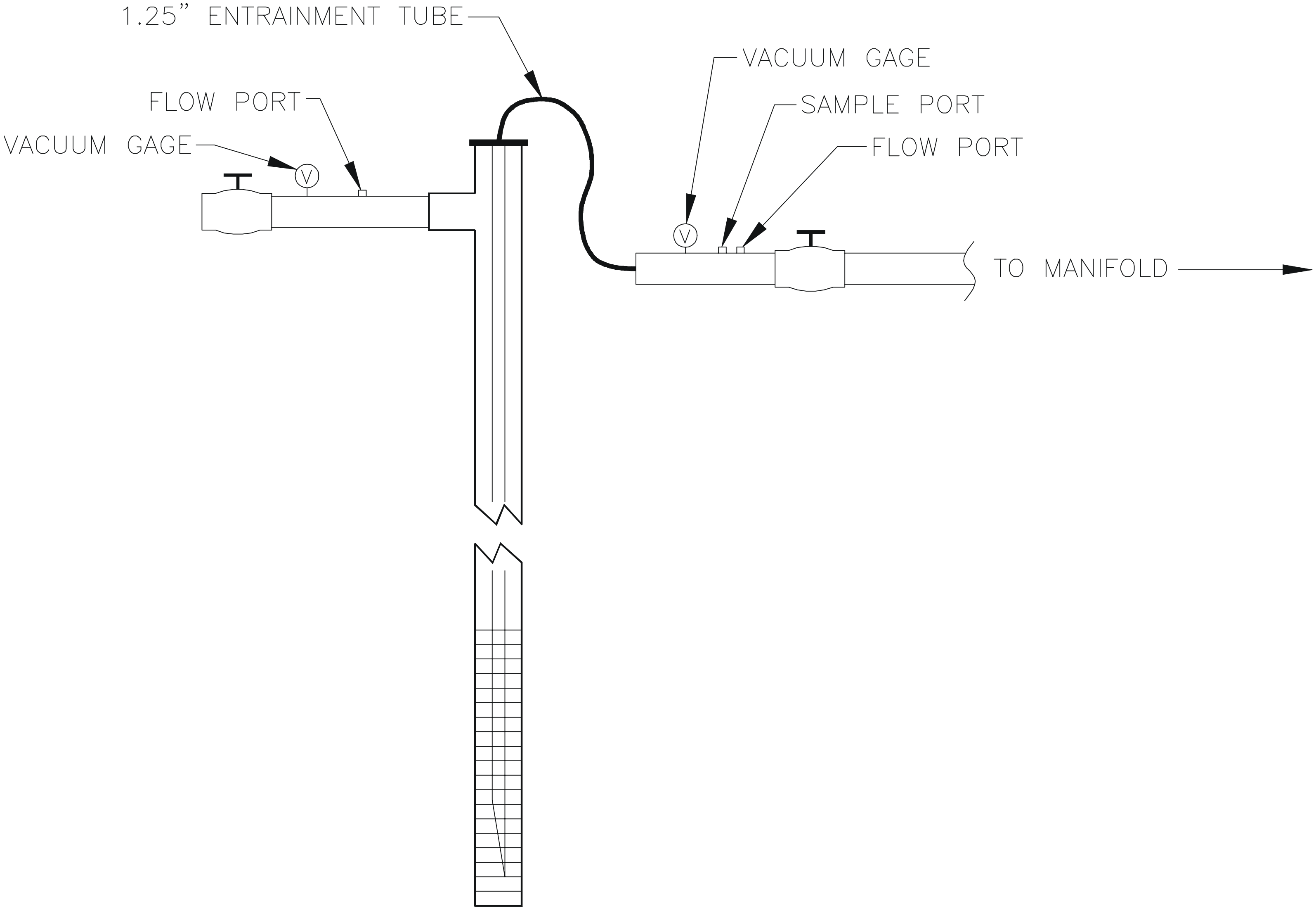


Figure 5.12. Process Flow Diagram of DVE System (modified from Terra Vac, 1996).

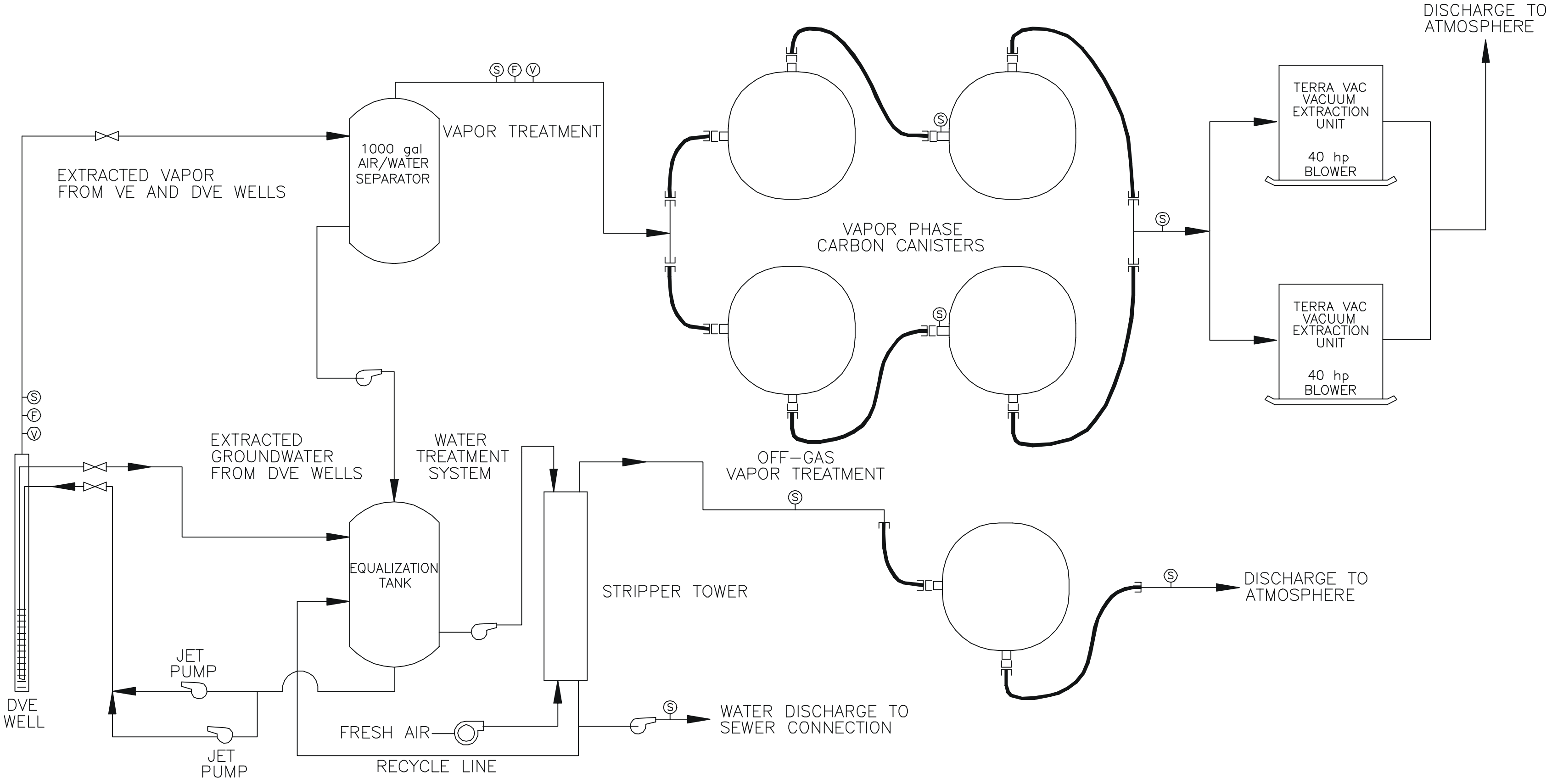


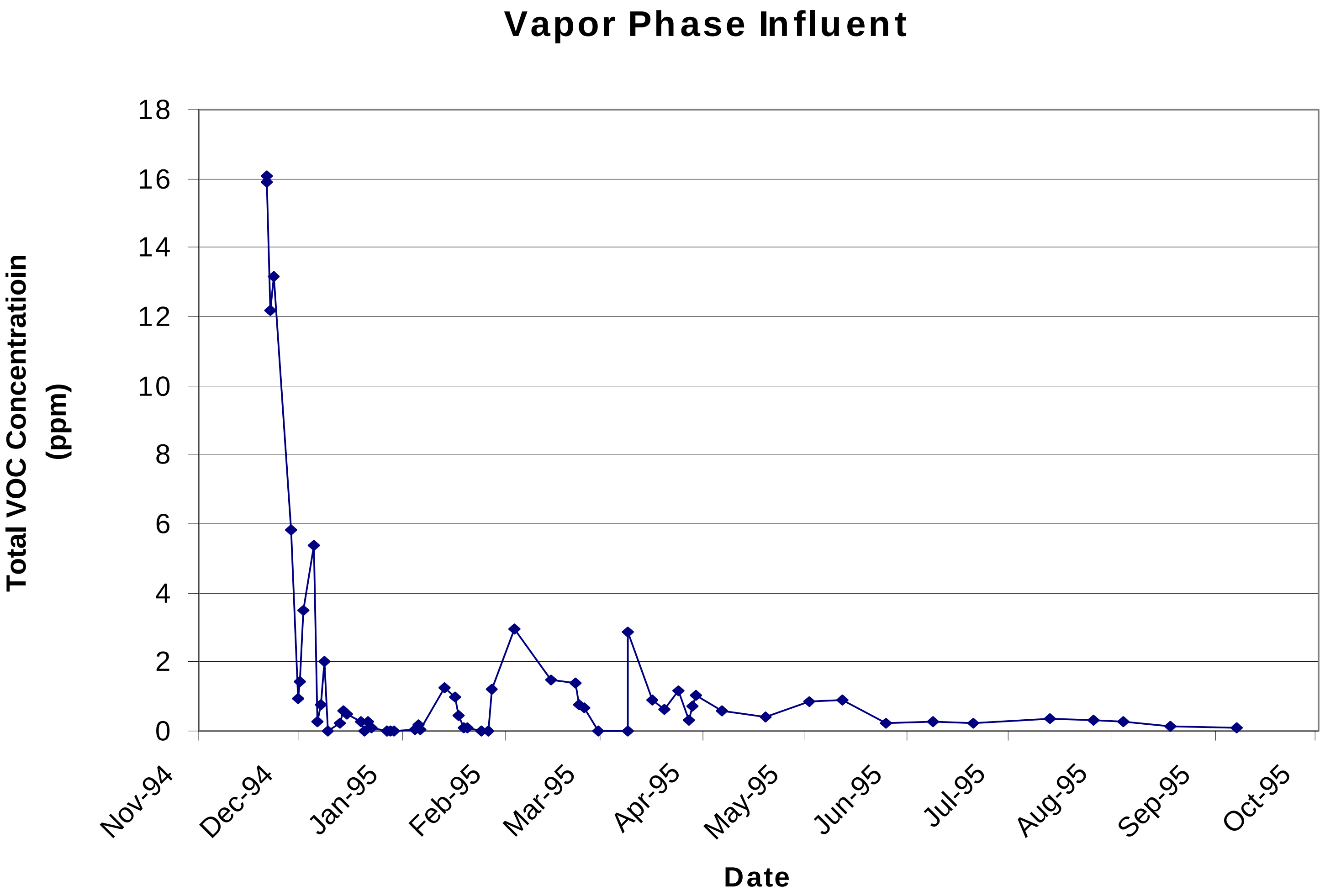
Table 5.15. Summary of DVE system performance data.

Parameter	Value
DVE System Operation	311 days
SVE Vacuum at Blower	5 in Hg (≈68 in WC), average operational value
SVE Flow Rate	500 scfm, average operational value
Cumulative Volume of Extracted Groundwater	1,116,500 gallons
Typical DVE Well Spacing (Radius of Influence)	30 ft, approximately
Vapor Influent - Total VOCs Concentrations	16 ppm, maximum 1.7 ppm, average (see Figure 5.13)
Groundwater Influent - Total VOCs Concentrations	446 ppb, maximum 81 ppb, average (see Figure 5.14)
Soil VOC Mass Removal (Rate)	48.25 lb (0.17 lb/d), Total VOCs
Groundwater VOC Mass Removal (Rate)	5 lb (0.02 lb/d), Total VOCs

Unit Notes: in Hg = inches of mercury; in WC = inches of water column; scfm = standard cubic feet per minute; ft = feet; ppm = parts per million; ppb = parts per billion; lb = pounds; lb/d = pounds per day

Source: Terra Vac (1996)

Figure 5.13. Time variation of vapor phase VOCs in DVE system influent.[2]



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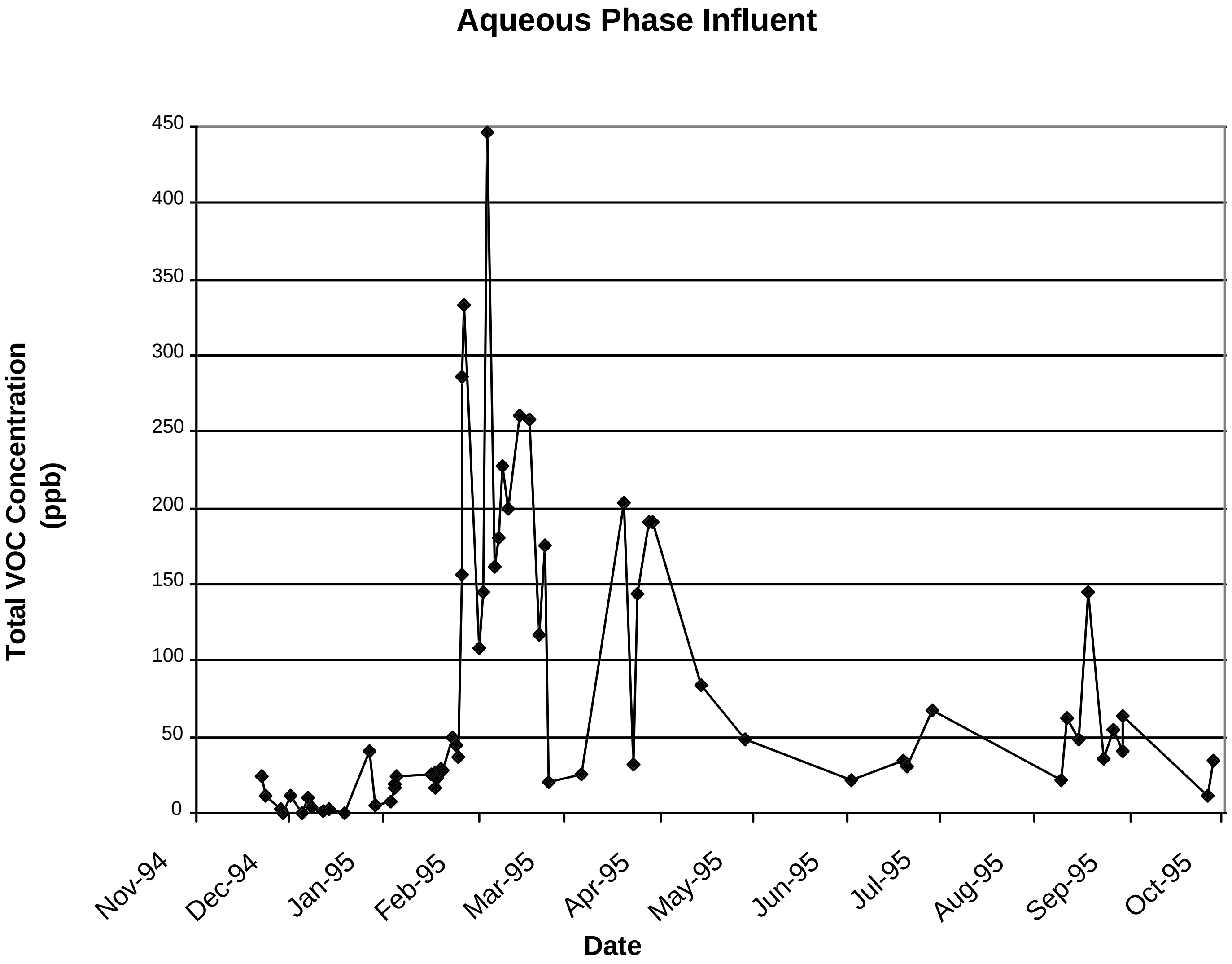
[2] Plot reproduced from data reported in Terra Vac (1996).

Groundwater concentrations in the influent increased significantly after approximately two months of operation. The influent concentrations then generally decreased such that by the tenth (last) month of operation they were similar to initial levels. Figure 5.14 illustrates this observation. The maximum total VOCs detected in the influent was 446 ppb and averaged 81 ppb for the project. The overwhelming majority of VOCs recovered were PCE and TCE. The BTEX compounds comprised only a small portion (< 5 ppb) of the VOCs recovered in the aqueous phase. Concentrations of VOCs in groundwater in the source area showed notable decreases over the period of DVE operation. Of the two wells in the source area, one showed a decrease in total VOCs concentration of over 99% and the other 64%. However, remedial action objectives for groundwater were not obtained at the conclusion of DVE system operation. Groundwater quality data collected since the termination of DVE show total VOCs concentrations ranging from 29 to 237 ppb in the source area and averaging 82 ppb in five source area wells. Long-term operation of a management of migration system (pump-and-treat) has been implemented for this area. The total volume of groundwater recovered during DVE system operation was 1,116,500 gallons.

Mass removal rates were calculated based on analytical sampling and volumetric flow rates of vapor emissions and groundwater. In total, approximately 53 pounds of VOCs were removed by the DVE system. The vapor extraction portion of the system accounted for the most significant removal at approximately 48 pounds. This figure was derived based on measurements obtained at the inlet of the SVE blowers. It is likely that the actual removal is greater than 48 pounds since air-bleed valves, used to balance system vacuum, diluted the concentration of influent vapor prior to measurement at the blower inlet. A plot of VOC removal in the vapor phase over the project duration is provided in Figure 5.15 and is based on the blower inlet data. Vapor phase VOC removal rates were steady over the system operation and averaged approximately 0.17 pounds per day. Approximately 5 pounds of VOCs were recovered in the aqueous phase through groundwater extraction averaging 0.016 pounds per day over the project duration.

Figure 5.14. Time variation of aqueous phase VOCs in DVE system influent.[3]



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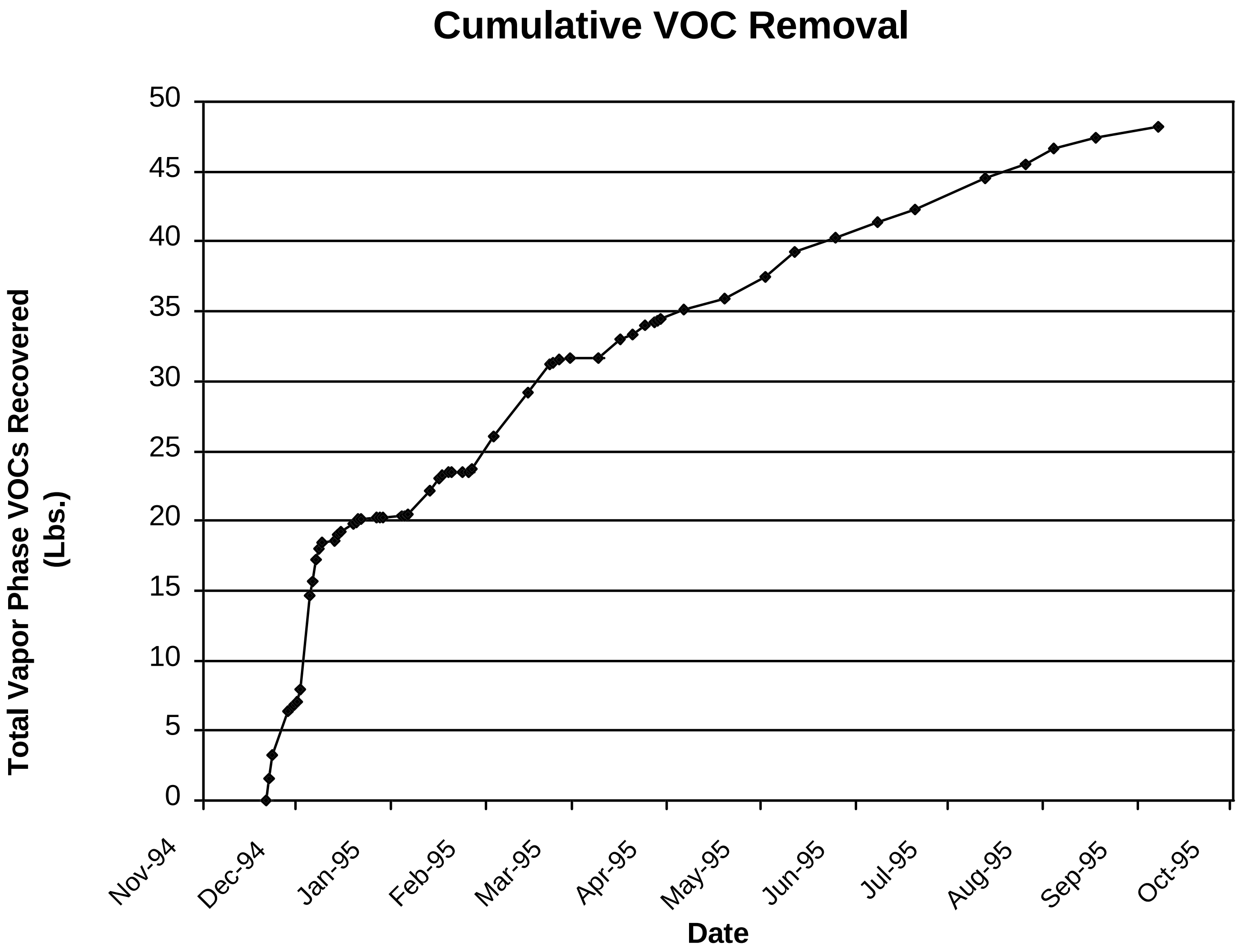
[3] Plot reproduced from data reported in Terra Vac (1996).

Figure 5.15. Cumulative vapor phase VOC removal by DVE.[4]



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[4] Plot reproduced from data reported in Terra Vac (1996).

5.3.4 TECHNOLOGY COST

The actual cost, not including permitting and oversight costs, was $170/cy ($1.5 million based on 9,000 cy treated). This figure includes an inflationary cost adjustment, granted due to significant time delays, and design changes for system winterization measures. The majority of the cost increase was realized during the period prior to completion of the sewer line, as a result of performing additional field tests to evaluate interim water discharge alternatives.

Costs for on- and off-site soil remediation alternatives were estimated prior to the remedial design phase. These estimates, based on 1986 dollars, included on-site thermal aeration at $288/cy, biological treatment at $133/cy, and off-site incineration at $2,400/cy. The original estimate for DVE in the source area was $116/cy. Project delays of two years, primarily due to the lack of availability of a groundwater discharge point (see Table 5.14) and regulatory permitting for off-site discharge, added to the overall cost of the DVE system.

5.3.5 SUMMARY OF OBSERVATIONS AND LESSONS LEARNED

The following conclusions and recommendations were identified based on the reported performance of the DVE system during its operational period.

- According to the RPM, at this site, soil remediation was dependent upon the ability to extract and discharge groundwater. DVE, like any groundwater extraction and treatment technology, is highly sensitive to the existence of a feasible discharge point. The project proceeded under the expectation that groundwater discharge could occur. However, an acceptable discharge point would not be made available until the sewer connection to the Derry POTW was completed. Significant project delays (two years) and subsequent increased costs were realized as a result of a lack of availability of an acceptable discharge point.

Additional observations were provided by the PRP's consultant (Terra Vac, 1996).

- The site conditions were favorable for DVE to be implemented for soil and groundwater remediation.

- DVE proved effective at remediating a significant volume (9,000 cy) of contaminated soil to below remedial goals (1 ppm) in a relatively short period of time (10 months) with overall project costs competitive with other applicable remedial technologies.

- DVE affected some mass removal of VOCs dissolved in groundwater within the source area. It is important to note that DVE was not intended to obtain remediation goals for groundwater. The extraction and treatment of groundwater was necessary to target and remediate soil contamination located in the saturated zone. A long-term migration control remedy (pump-and-treat) is currently operating to obtain groundwater remediation objectives.

5.3.6 CONTACT INFORMATION

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