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DUAL PHASE VACUUM EXTRACTION TECHNOLOGY FOR THE RECOVERY OF PETROLEUM HYDROCARBON CONTAMINATION FROM THE SUBSURFACE - A CASE STUDY

V.G. Kallur, O'Connor Associates Environmental Inc., Langley, British Columbia, Canada
J.G. Agar, O'Connor Associates Environmental Inc., Calgary, Alberta, Canada
T.T. Wong, O'Connor Associates Environmental Inc., Calgary, Alberta, Canada
J. Naus, O'Connor Associates Environmental Inc., Langley, British Columbia, Canada
A.P. Michielsen, Imperial Oil Limited, Burnaby, British Columbia, Canada

ABSTRACT: This paper presents a case history of the application of dual phase vacuum extraction (DPVE) technology for remediation of subsurface petroleum hydrocarbon (PHC) contamination in silty soils at a service station site in Vancouver, British Columbia. The design and performance monitoring results for this site are summarized along with the performance monitoring results from similar DPVE systems at 7 other sites in western Canada underlain by both fine-grained and coarser grained sandy soils. The documented performance of these systems provides useful design guidance and insight on the practical limitations of DPVE technology for PHC remediation.

RÉSUMÉ: Cet article présente une étude de cas de l'application de technologie d'extraction multi-phase sous vide (EMPSV) pour la remédiation des hydrocarbures pétroliers dans des sols silteux à une station service de Vancouver en Colombie Britannique. La conception ainsi que la performance des résultats de surveillance pour ce site sont présentées et comparées aux performances des résultats de surveillance de systèmes EMPSV semblables, et situés à 7 autres sites dans l'ouest canadien sur des sols fins ou des sols sablonneux plus grossiers. La performance documentée de ces systèmes fournit une information utile pour la conception ainsi qu'un aperçu sur les limitations pratique de la technologie d'EMPSV pour la remédiation des hydrocarbures pétroliers.

1. INTRODUCTION

Dual Phase Vacuum Extraction (DPVE) is a technology that can be used to remediate sites contaminated with light non-aqueous phase liquids (LNAPL) such as petroleum hydrocarbons (PHCs) in the subsurface. In this paper, DPVE is used to describe high vacuum pump systems capable of extracting both gases and liquids from the subsurface. The pump systems under consideration can generate vacuum up to about 26 inches of mercury when extracting air or water.

The following sections summarize a case history of the application of DPVE and outline performance monitoring results for DPVE systems at a range of PHC contaminated sites in western Canada.

Conforming to industry practice, the units used in this paper are “Hg (in. of mercury) and “H_2O (in. of water) for vacuum, scfm (standard cubic feet per minute) for airflow rate, and horsepower (h.p.) for power of pumps.

2. CASE HISTORY

2.1 Background

The service station site, BC Site A, is located in a commercial area of Vancouver, British Columbia, and is bordered by: buildings to the east and north across a city lane; an Avenue to the south; and a Street to the west. The nearest surface water body is located approximately 900 m from the site. A service station has been operated on the property since the 1930s prior to which the land use was residential. Other sources of PHCs were identified in the immediately vicinity. The facilities present onsite included diesel and gasoline underground storage tanks, pump islands and an oil-water separator.

Regulated parameters for remediation of contaminated sites in British Columbia include various constituents of petroleum hydrocarbons for both soil and groundwater. The numerical remedial standards depend upon the land use and travel time to the nearest receptor. Reference to petroleum hydrocarbons is limited to benzene, toluene, ethyl benzene and xylenes (BTEX), volatile petroleum hydrocarbons (VPH) in soil, and groundwater (VPHw), and volatile hydrocarbons that include both BTEX and VPHw (VHw).

The site is underlain by glacial sediments consisting of silt and clay (34% to 65%) with varying proportions of sand (17% to 59%) and gravel (7% to 20%). According to maps published by the Geological Survey of Canada, the native soils are Capilano sediments and Vashon drift that are comprised of lenses and interbeds of glaciolacustrine laminated stony silt and glaciofluvial sand and gravel over lodgement and minor flow till. The average depth to groundwater is approximately 6m below grade surface (bgs) and the principal flow direction is north-northwest with a hydraulic gradient of 0.035. Hydraulic conductivities measured by bail down tests in monitoring wells at the site range from 1.6×10^{-4} cm/s to 8.7×10^{-6} cm/s and are typical of silty till with coarser grained zones.

The interpreted areal extent of dissolved PHC and LNAPL are shown on Figure 1. The maximum apparent thickness of LNAPL measured onsite and offsite and the maximum PHC concentrations measured in the soils and groundwater prior to installation and operation of the

Table 1. Pre-DPVE Contaminant Distribution

Phase	Measured Values
Max. Apparent LNAPL Thickness (mm)	Onsite: 3777
	Offsite: 1219
Max. PHC Concentration in Soils 3.7m to 6.7m bgs (mg/kg)	VPH: 1155 to 8788
	BTEX: 50 to 1670
Max. Dissolved PHC Concentration (mg/L)	VPHw: 45 to 70

DPVE system are listed in Table 1. These data are based on the environmental site assessment and monitoring work conducted between 1994 and 1999 that included the drilling of 62 boreholes. Recovery of LNAPL by manual bailing was implemented as a due diligence measure prior to the DPVE and 1275 L of free phase LNAPL were recovered between November 1998 and June 1999.

The depth of PHC contamination in the soil varied from 2 m to 8 m bgs. LNAPL were detected onsite and offsite with apparent thicknesses shown in Table 1.

2.1 Why was DPVE chosen for Remediation?

Following preliminary screening of remedial technologies, DPVE was selected for detailed evaluation through pilot testing. DPVE was selected because deep excavation was deemed impractical at this site and because DPVE is better suited than other *in situ* technologies such as vapour and groundwater extraction (VEGE) to PHC remediation in soils with hydraulic conductivities ranging from 10^{-3} to 10^{-6} cm/s. Pilot testing with a 5-h.p. liquid ring pump (LRP) at one onsite recovery well over a four- day period demonstrated that LNAPL recovery would be feasible, as indicated in the summary of pilot test results outlined in Table 2, in which the vapour phase recovery is expressed in equivalent volume of liquid LNAPL.

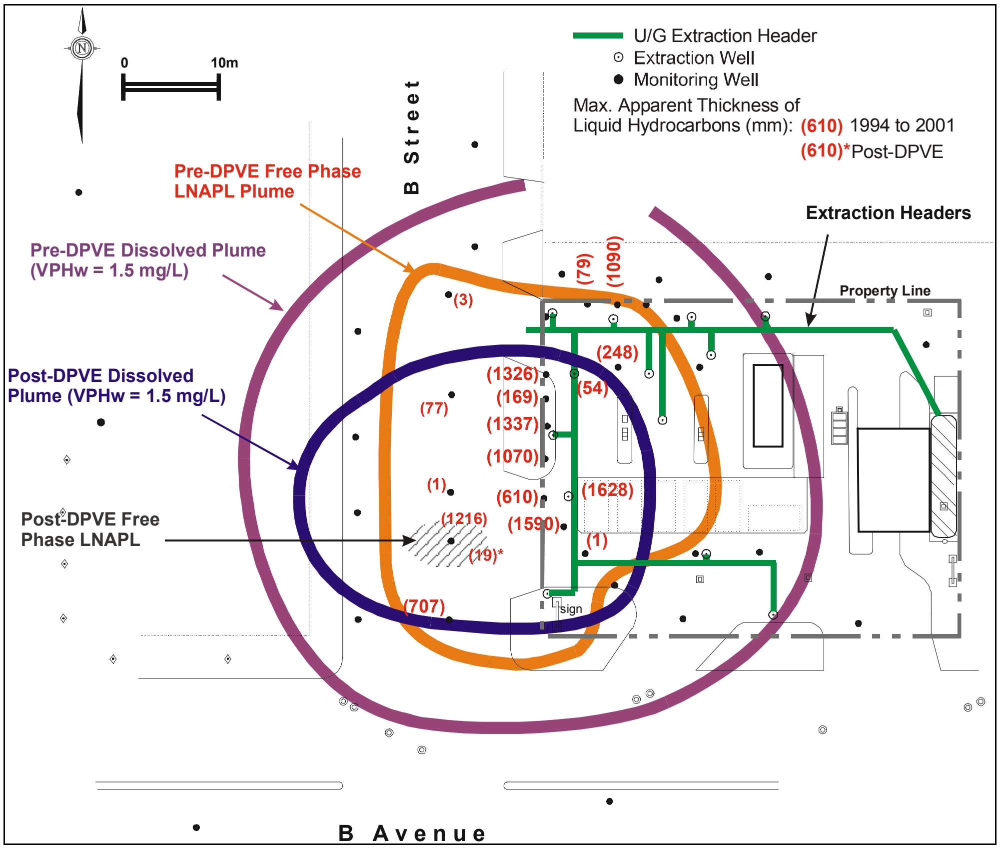

Figure 1. Site Plan Showing Free Phase LNAPL and Dissolved Plumes

Table 2. DPVE Pilot Test Results

Test Duration (hh:mm)	Drop Tube Depth (m bgs)	Vacuum (“ Hg)		Air Extraction Rate (scfm)	Liquid Phase Recovery		Vapour LNAPL Recovery (L)
		Drop Tube	Well		Water (L)	LNAPL (L)	
4:45	0.41	7.5	5.5	53	0	0	92
6:36	7.41	8.9	3.5	40	141	11	111
1:17	9.08	12.0	2.0	32	136	80	25
24:15	9.41	10.2	2.0	27	3893	234	239

3. REMEDIAL SYSTEM DESIGN AND INSTALLATION

Design of the remedial system for the site was undertaken based on the following considerations: remedial objectives for the site; feasibility analyses; pilot test results; regulatory requirements for treatment and discharge of recovered air and liquids, and future commercial land use onsite.

Natural bioremediation, with enhancements if necessary, was selected as a back-up and secondary remedial technology to address the remaining petroleum hydrocarbon impacts after DPVE is no longer deemed feasible to achieve the required remedial targets, specifically for groundwater. Excavation was identified as a back-up option for remediation of soil. Specific measures were adopted to verify that DPVE had been used to the maximum extent possible before shifting to natural bioremediation. These measures are discussed in a subsequent section.

3.1 Design Rationale and Details

The design rationale for the DPVE system was two-fold: (i) to recover the existing LNAPL beneath the site and mitigate the potential for further migration of the plume; and (ii) continue with soil and groundwater remediation until monitoring results indicate that LNAPL is no longer detected in the monitoring wells in the remediation area and operation of the DPVE is no longer cost effective. In addition, the design incorporated a possible expansion of the recovery well network onto the offsite plume area subject to approval by the municipality.

Several numerical models are available which can simulate air and liquid flow processes in the subsurface (USACE 1999). Typically these models are capable of modelling multiphase flow in the subsurface. However, for design purposes single phase flow (gas or liquid) models should be sufficient. The DPVE system for the subject site was designed using two models developed by O’Connor Associates; (i) SUMP, a groundwater flow model for simulating drawdown in a homogeneous aquifer in response to pumping, and (ii) AIRSUMP an air flow model for a homogeneous unsaturated zone based on the formulation presented in Baehr and Hult (1991). The *in situ* hydraulic conductivity was estimated using SUMP by evaluating the groundwater drawdown and pumping rate during the pilot test. The modelling results indicated an average *in situ* hydraulic conductivity of 5×10^{-4} cm/s. AIRSUMP was then used to calculate the spacing of recovery wells. The pressure distribution and airflow velocities were calculated for various extraction rates. The well spacing was then chosen based on data obtained from the pilot test and specific criteria considered for the minimum pressure and airflow velocity between wells. A well spacing requirement of 8 m was determined based on a mass flow rate of air of 10 g/s with the vacuum at the well being approximately 7 “Hg. For a ground temperature of 10 ºC the estimated air flow rate is approximately 21 scfm. Design parameters developed for the DPVE system for the subject site are summarized in Table 3.

Table 3. Design Parameters for the DPVE System

Parameter	Design Value
No. of Wells / Spacing	13 at 8 m
LRP Size / Capacity	50 h.p. / 700 acfm
Inlet Vacuum (“ Hg)	18 to 22
Wellhead Vacuum (“Hg)	8 to 10
Air Extraction Rate per Well	21 scfm
Thermal Oxidation Unit Capacity	750 cfm
Max. Water Flow Rate	100 L/min
Max. BTEX Conc. In Water	100 mg/L

3.2 Installation of the DPVE Remedial System

The DPVE was installed between February and June of 1999. The system was comprised of thirteen 75 mm diameter extraction wells connected via underground header piping to a 50-h.p. LRP. The header piping system is shown on Figure 1. As illustrated on Figure 2, a wellhead assembly was mounted on each recovery well to allow for the connection to both extraction and air injection headers. Each extraction header was connected directly to a manifold at the LRP, which was installed in a shipping container in an enclosed remedial compound. The thermal oxidation unit for offgas treatment was mounted on top of the shipping container to optimize space. Inside each extraction well, a 25 mm diameter drop tube was installed such that vacuum from the LRP could be applied at different elevations inside an extraction well.

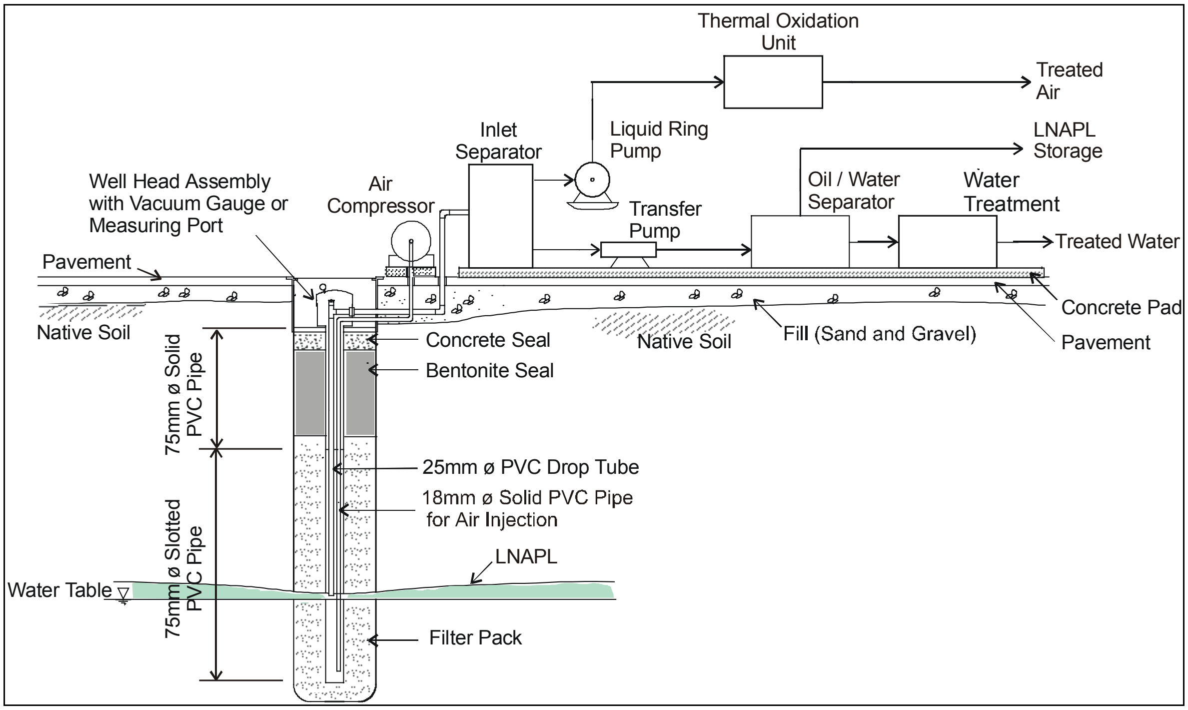

Figure 2. Extraction Well Details and Schematic of DPVE System

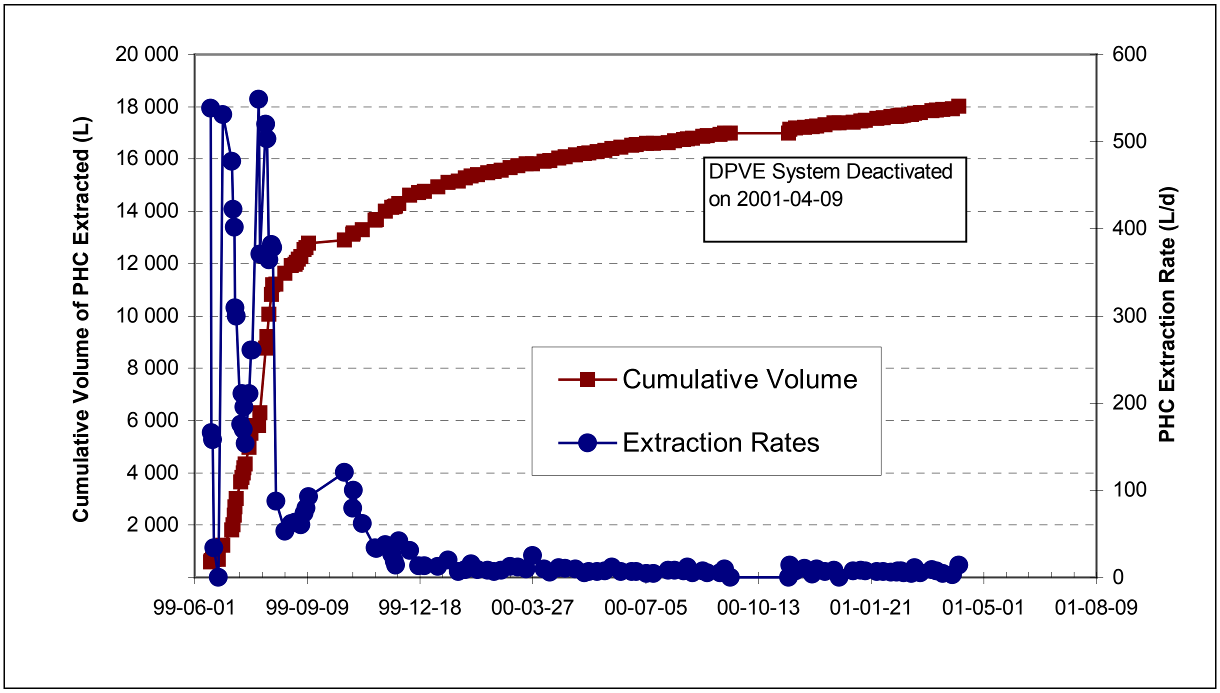

Figure 3. Petroleum Hydrocarbon Extraction History

4. OPERATION OF THE DPVE REMEDIAL SYSTEM

The DPVE system was activated on 1999-06-15. The elevation of the drop tubes in all wells was initially set at 1 m above the liquid levels to enable recovery of the liquid phase LNAPL. This position was maintained until the estimated extraction rates dropped to less than 50 L/day (on 1999-09-10 or after 87 days). The drop tubes were then lowered to approximately 1 m below the water table. On 2001-02-19 (after 615 days of operation) the drop tubes were furthered lowered to about 2.5 m below the water table to help enhance recovery of impacted groundwater. The DPVE system was deactivated on 2001-04-09 (after 664 days). Throughout its operation, the air injection system was only activated for short durations immediately after the drop tubes were lowered deeper into the water table.

4.1 DPVE Monitoring Results

The PHC extraction rates were estimated using the weekly monitoring results. When the DPVE system was deactivated, an estimated equivalent volume of approximately 18 000 L (14 000 kg) of petroleum hydrocarbons and approximately 1 117 m^3 of groundwater had been extracted by the DPVE. Based on the influent concentrations, the cumulative mass of petroleum hydrocarbons recovered by the DPVE system through the dissolved phase was approximately 27 kg (35L).

A summary of the results of DPVE system performance monitoring is presented in Table 4. PHC recovery during the operation of the DPVE system is presented graphically in Figure 3. As indicated, over 12 000 L of LNAPL were recovered during the first two months of operation with extraction rates decreasing from an initial value of 538 L/day to less than 50 L/day. Eventually the extraction rates dropped to less than 20 L/day after 9 months and less than 10 L/day after 11 months of operation of the DPVE. LNAPL were not detected in the onsite monitoring wells after 1999-11-26 (approximately 5.5 months following commencement of operation of the DPVE). Vacuum influence of a minimum of 1 "H_2O extended offsite to about 10 m beneath the Street. Groundwater draw down influence of a minimum 0.1 m extended to over 20 m from the site beneath the Street when the drop tubes were positioned at 2.5 m below the water table. The changes in the areal extents of the dissolved hydrocarbon impacts and LNAPL plumes are shown in Figure 1.

Table 4. DPVE System Performance Data

Description	Result
Volume of LNAPL Recovered (L): Vapour / Liquid / Dissolved Phase	18 000 / 1 / 35
Volume of Water Extracted (m^3)	1117
Vacuum in Drop-Tubes ("Hg)	11 to 14
Vacuum at Wellheads ("Hg)	5 to 14
Initial Rate of LNAPL Recovery (L/d)	538
Finial Rate of LNAPL Recovery (L/d)	<10
Residual VPH in Soil prior to deactivation (mg/kg)	205 to 8 878
VHw in Groundwater (mg/L)	66

5. PERFORMANCE RESULTS FOR OTHER DPVE SYSTEMS

In addition to BC Site A, 7 other PHC affected sites in British Columbia (BC) and Alberta (AB) have been or are being remediated using DPVE systems. The performance of the systems is summarized in Table 5.

As shown in Table 5, the sites are underlain by various soil types ranging from silty sand and gravel to sandy silt with groundwater located between 5 m and 15 m bgs. Based on the measured hydraulic conductivities and the observed air extraction rates, Sites A, E, G and H are underlain by coarser grained soils than Sites B, C, D and F. It should be noted when reviewing this data that the thicknesses of the coarser grained strata vary at these sites. For example, the coarse grained layers at Sites G and H are approximately 3 to 4 m in thickness while the coarse layer at Site E is over 10 m thick. The spacings of the recovery wells range from 6 m (in sandy silt) to 10 m (in silty sand and gravel).

LNAPL (free product) with apparent thicknesses ranging from 0.45 m to 3.78 m was observed in the monitoring wells at all 8 sites prior to DPVE operations. The free product was removed completely from the zone of influence in 6 to 30 months for all of the sites. For the purpose of this discussion, the zone of (vacuum) influence is the zone defined by the boundary of 1" H_2O vacuum excluding barometric effects.

6. DESIGN CONSIDERATIONS FOR DPVE SYSTEMS

The performance monitoring results for the DPVE systems discussed in this paper highlight some of the important engineering design considerations and limitations of this technology.

Experience at these and other sites shows that DPVE can be applied to effectively remove LNAPL and reduce residual PHC concentrations in a range of fine-grained and coarse-grained soils. However, DPVE frequently cannot be applied cost effectively to meet provincially or federally regulated soil and groundwater remediation guidelines. Once DPVE recovery rates reach a low asymptotic level, other remedial technologies such as monitored natural attenuation, bioremediation and excavation should be considered.

As illustrated in Table 6 and Figure 4, DPVE systems should generally be designed to ensure that an average airflow rate of at least 1 L/min per cubic metre of soil pore volume is achieved within the PHC affected soils. Depending on the mass and type of PHCs to be removed, DPVE systems typically need to be operated for a sufficient time period to exchange approximately 1000 or more pore volumes of air through the PHC affected soils in order to ensure effective removal of LNAPL.

A correlation between the design airflow rate (DAFR) and saturated soil hydraulic conductivity is given in Figure 4. As the data in Figure 4 illustrates, cost effective DPVE design, i.e. with extraction well spacings greater than 4 m, is typically limited to soils with hydraulic conductivity greater than 5×10^{-6} cm/s. Similarly, for thick deposits of coarse soil with hydraulic conductivity greater than 10^{-3} cm/s, i.e. such as Site E in Figure 4, other technologies, such as combined vapour and groundwater extraction (VEGE), that generate higher airflow at lower vacuum are typically more cost effective than DPVE.

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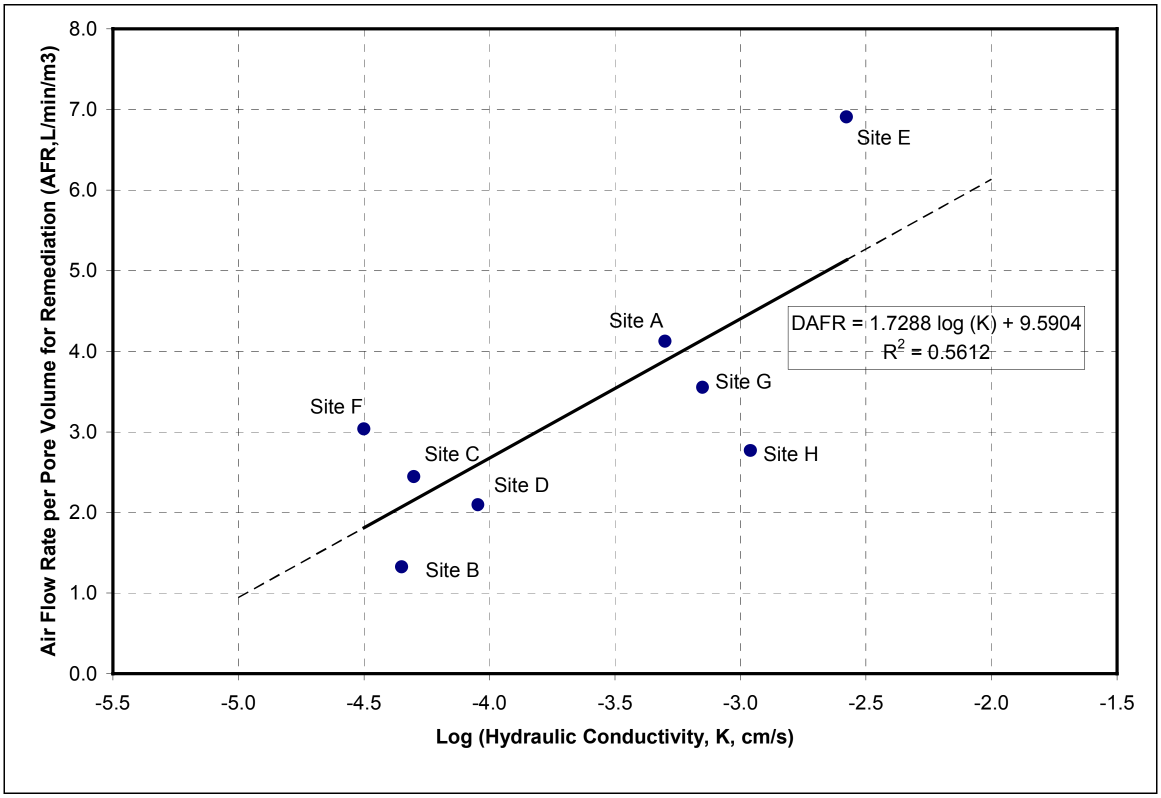

Figure 4. Airflow Rate and Hydraulic Conductivity Relationship for Extraction Well Spacings of 6 m to 10 m

Table 5

. Summary of Performance of Selected DPVE Systems in Western Canada

Site ID	**Soil Type**	**Hydraulic Conductivity**	**No. of Wells/ Well Spacing**	**LRP Size**	**Avg. Depth to Ground-water Table**	**Approx. Screened Interval**	**Duration of System Operation (months)**	**Max. Apparent LNAPL Thickness**	**Air Extraction Rates**	**Pore-Volume (PV) of ZOI**	**Complete Removal of LNAPL from ZOI**		**Liquid Hydrocarbons Recovery (Vapour Phase)**		
		(cm/s)			(m bgs)	(m bgs)	(months)	(m)	(scfm)	(m3)	Operating Time (months)	Pore-Volumes Exchanged	Initial Rate (L/d)	Asymptotic Rate (L/d)	Total (L)
BC Site A	Silty sand, trace gravel (till)	9 x 10^{-6} - 2 x 10^{-4}	13@ 8m	50 hp	6	2.0 - 9.1	22	3.78	399	2 741	5.5	996	538	<10	18 005
BC Site B	Sandy gravel (till)	1x10^{-5} - 2x10^{-4}	5@ 10 m	25 hp	7 and 15	4.6 - 16.8; 12.2 - 16.8	52+	0.45	78	1 652	11.0	642	16	9.9 - 0.3	2 720
BC Site C	Silty sand and gravel (till)	5 x10^{-5}	18@ 10 m	25 hp	7	2.0 - 14.0	33+	0.71	197	2 280	7.0	752	150	47	5 512
BC Site D	Silty sand and gravel (till)	9 x10^{-5}	3@ 10- 20 m [C]	2 × 5 hp	5	2.0 - 14.0	12	2.85	30	405	no product since start-up	800[C]	400	118[C]	43190[c]
BC Site E	Silty sand and gravel (till)	7 x10^{-4} - 1x10^{-2}	5@ 8 m	25 hp	5	3.0 - 10.0	14+	1.40	288	1 178	10.0	3 034	150	62	22 000
AB Site F	Sandy silt	1x10^{-5} - 1x10^{-4}	13@ 6 -10 m	2 × 25 hp	11	9.5 - 18.9	45+	3.45	85	792	30.0	4 003	150	50	85 000
AB Site G	Silty sand	5x10^{-4} - 1x10^{-3}	22@ 8 m	2 × 25 hp	7	5.0 - 9.9	34+	1.66	187	1 491	9.5	1 482	756	16	45 703
AB Site H[a]	Sand, some silt	6x10^{-4} - 2x10^{-3}	31[a] @ 8 m	2 × 25 hp	7	5.0 - 10.7	23+	0.47	176	1 800	12.0	1 459	452	6	17 187

Notes:
[a] - wells are on 5 separate headers; only 4 headers were operated at any one time
[b] - based on bail down tests in monitoring wells
[c] - asymptotic recovery rate indicates that extraction well spacings are under-desgined;
pore-volumes exchanged is an approximation.
+ - operation is on-going
- ZOI denotes zone of influence.

Table 6. Extraction Rates and Pore-Volumes for Selected DPVE Sites

Site ID	**Soil Type**	**Mean Hydraulic Conductivity**	**Air Extraction Rates**	**Area of ZOI**	**Average Thickness of ZOI**	**Effective Porosity**	**Pore-Volume (PV) of ZOI**	**Airflow/ PV**
		(cm/s)	(scfm)	m^2	(m)	(-)	(m^3)	L/min/m^3
BC Site A	Silty sand, trace gravel (till)	5.E-04[a]	399	2030	4.50	0.3	2 741	4.1
BC Site B	Sandy gravel (till)	4.E-05	78	1836	3.00	0.3	1 652	1.3
BC Site C	Silty sand and gravel (till)	5.E-05	197	1900	4.00	0.3	2 280	2.4
BC Site D	Silty sand and gravel (till)	9.E-05	30	450	3.00	0.3	405	2.1
BC Site E	Silty sand and gravel (till)	3.E-03	288	842	3.50	0.4	1 178	6.9
AB Site F	Sandy silt	3.E-05	85	1320	3.00	0.2	792	3.0
AB Site G	Silty sand	7.E-04	187	1420	3.50	0.3	1 491	3.6
AB Site H	Sand, some silt	1.E-03	176	2400	2.50	0.3	1 800	2.8

Note: [a] - based on pilot test results
- ZOI denotes zone of influence