DUAL PHASE VACUUM EXTRACTION FOR REMEDIATING SUBSURFACE HYDROCARBON IMPACTS IN CENTRAL ALBERTA – ITS DESIGN, OPERATION AND PERFORMANCE

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ABSTRACT

At a service station site in central Alberta, dual phase vacuum extraction (DPVE) technology is being used to remediate petroleum hydrocarbon (PHC) impacts to groundwater and soil. The DPVE system has been in operation since 2001 and remediation objectives are close to being achieved.

The main advantage of the DPVE technology is the simultaneous recovery of vapour phase PHCs in the unsaturated zone and liquid phase (free product and dissolved) PHCs from the saturated zone. Its main disadvantages over conventional technologies, such as soil vapour extraction, are the more complicated design process and the higher capital, operating and maintenance costs. To design a DPVE system properly, the soil properties governing contaminant transport in both the saturated and unsaturated zones must be adequately characterized and multiphase flow models such as MOVER should be used. At this site, the free product plume extended about 120 m offsite and covered an approximate area of 3500 m^2. The installed system was able to remove the free product from the subsurface in about 9 months and reduce the concentrations of the dissolved PHCs to below the governing criteria in approximately 2.5 years. This paper documents the design, installation, operation and performance of this DPVE system. Important factors concerning operating the system in a cold climate and optimizing system performance are also summarized.

RÉSUMÉ

La technologie d'extraction de phase double par vide (EPDV) est utilisé pour le traitement de la contamination d'hydrocarbures pétroliers (HP) dans les sols et l'eau souterraine à une station service au centre de l'Alberta. Le système EPDV a été en opération depuis 2001 et les objectifs de réhabilitation ont presque été atteints.

L'avantage principal de la technologie EPDV est la capture simultanée des HP en phase vapeur dans la zone non saturée et des HP en phase liquide (liquides immiscibles et phase dissoute) dans la zone saturée. Ses désavantages principaux, en comparaison avec des technologies conventionnelles telles que l'extraction de vapeurs, sont la conception complexe des processus, les capitaux plus élevés ainsi que les coûts d'opération et d'entretien. Afin de concevoir un système EPVD adéquat, les propriétés du sol affectant le transport des contaminants dans les zones saturées et non saturées doivent être caractérisées adéquatement et des modèles d'écoulement multiphase tel que MOVER devrait être utilisés. Sous le site d'étude, la phase liquide immiscible s'étendait à près de 100 m hors du site et couvrait une superficie d'approximativement 3500 m2. Le système installé a été capable d'enlever la phase liquide immiscible en 2.5 ans. Cet article documente la conception, l'installation, l'opération et la performance de ce système d'EPVD. Un sommaire des facteurs important concernant l'opération du système en climat froid ainsi que l'optimisation de la performance, est aussi présenté hydrocarbures pétroliers.

1. INTRODUCTION

In this paper the remediation activities and their results at a service station site located in central Alberta using dual phase vacuum extraction (DPVE) are summarized. DPVE uses high vacuum pump systems capable of extracting both gases and liquids from the subsurface. The pump systems under consideration can generate vacuum up to 26 inches of mercury when extracting air or water. It is a technology that can be used to remediate sites impacted by light non-aqueous phase liquids (LNAPL) such as petroleum hydrocarbons (PHC) in the subsurface.

PHC or other organic compounds, when released into the subsurface, can exist in four different phases: as a separate non-aqueous phase liquid, as dissolved contaminant in the aqueous phase, as vapour phase in the soil gas, and as adsorbed phase around the soil solids. In general, LNAPL can be removed by skimming or pumping, the dissolved phase by pumping and the vapour phase by soil venting. The adsorbed phase is usually the most difficult to remove. DPVE is capable of removing simultaneously the phase-separated liquid, the dissolved phase and the vapour phase.

The following sections describe a case history of the application of DPVE and outline its design, installation and performance monitoring results at a PHC-impacted site in Central Alberta.

Following the practice of the pump industry in North America, the units used in this paper are inches of mercury (“Hg) or inches of water (“H_2O) for vacuum, horsepower (hp) for pump power and actual cubic feet per minute (acfm) for airflow rate. SI units are used for all other parameters.

2. BACKGROUND INFORMATION

2.1 Site Location and History

The service station is located in the southwest corner of the intersection of Avenue B and Street J in a city in central Alberta. To maintain the confidentiality of the site location, generic Street and Avenue names have been used. A gasoline retail outlet has been in operation on this site since the mid-1920s. Site facilities were upgraded in 1995 and, at present, include a convenience store and car wash, 3 underground fibreglass storage tanks and 2 pump islands.

Adjacent land use consists of commercial properties surrounding the site. The closest residential properties are located approximately 40 m to the east and southeast.

Since 1989, O’Connor Associates (OAEI) has been retained to provide environmental consulting services at this site.

2.2 Site Geology and Hydrogeology

Geologic information from intrusive investigations using drilling indicates that the service station site and the immediate surrounding areas are underlain by surficial fill materials placed on a clayey silt layer between 5 m to 6 m thick. This fine-grained layer rests on a sand layer of variable thickness, which has been deposited on a lower silt/clay unit. In some areas the sand layer contains silt and/or clay lenses. Most of the documented soil impact was from samples obtained from the sand layer. Bedrock was not encountered during any of the intrusive investigations extending to a maximum of 10.5 m below ground surface (bgs)

Based on historical monitoring results, depths to the groundwater table in the subject area have varied from approximately 6.3 m to 8.0 m bgs. In general the water table has been located in the sand layer near the upper silt/sand contact. Regional groundwater flow is to the southeast toward a river valley.

2.3 Site Sensitivity Assessment

Free-phase liquid hydrocarbons (LPH) have been detected at the water table within the sand layer on the service station site and several downgradient boreholes.

A site sensitivity assessment conducted in 2001 according to guidelines outlined by Alberta Environment (1994) indicated that the most critical exposure pathway was vapour inhalation. As a result of the assessment, the applicable risk management criteria for soil and groundwater were the draft 1994 Alberta Level I criteria for the vapour inhalation pathway through coarse-grained soils (hitherto referred to as the Level I criteria). The Level I criteria were also adopted as the remediation criteria for this site and are summarized in Table 1 for benzene, toluene, ethylbenzene, xylenes (BTEX), total petroleum hydrocarbons (TPH) and lead.

2.4 Free Phase Liquid Hydrocarbons and Dissolved PHC

As shown on Figure 1, the LPH plume was elongated and trended in an east-southeast direction reaching about 100 m offsite. Laboratory gas chromatogram analyses of bailed product samples indicated that the primary contaminants of concern are gasoline range PHCs.

Benzene concentrations that exceeded the Level I criterion were identified in soil samples from the service station site and extending to the east-southeast as far as Street K, some 110 m offsite and covered approximately 3500 m^2. Similar to the liquid PHC, dissolved benzene concentrations in groundwater which exceed the Level I criterion have been observed in a plume trending from the service station to the south-southeast as far as the south side of Street K. The thickness of the impacted soil layer was estimated to be between 1.0 m and 1.5 m within the the zone of groundwater fluctuations.

Table 1. Level I Criteria for Vapour Inhalation Pathway through Coarse-Grained Soils

Constituent	Soil (mg/kg)	Water (mg/L)
Benzene	0.04	0.3
Toluene	10	15
Ethylbenzene	70	30
Xylenes	25	50
TPH	1000[1]	NS
Lead	50	NS

NS denotes not specified.
1 – criterion based on aesthetic and/or ecotoxicologic considerations.

3. REMEDIATION ACTIVITIES

3.1 Historical Activities

Prior to 1999, risk management activities in the project area included regular monitoring, operation of 4 vapour extraction systems (VESs), and recovery of liquid PHC using manual bailing and portable pumps.

In 1999, a pilot test was carried out to assess the potential for accelerating the recovery of liquid phase, dissolved phase and vapour phase PHC using a DPVE system to be located on the service station site.

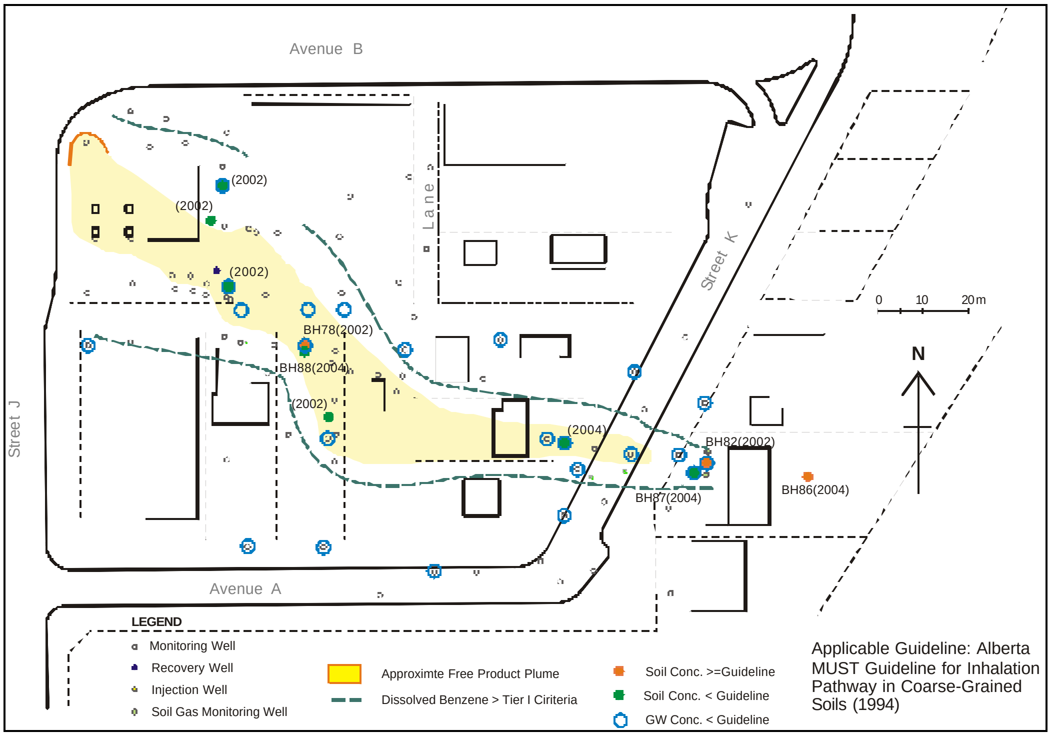

Figure 1. Site Pan Showing Initial Free Product Plume, Impacted Groundwater Plume and Verification Borehole Locations.

3.2 DPVE Pilot Test

For the pilot test, a recovery well (RW1) was installed on 1999-07-19 using an air-rotary drill rig in the southeast corner of the service station site near boreholes where LPH had been detected historically. This well was installed inside a 150 mm diameter borehole drilled to 9.15 m below ground surface (bgs). A 75 mm diameter PVC well casing and a 25 mm piezometer were installed to the bottom of the hole. The lower 3.7 m of the well casing and the piezometer were constructed using .010 slots while the upper 5.4 m were unslotted. The borehole annulus was backfilled with 20/40 silica sand to slightly above the screened length. Hydrated bentonite was used to backfill the annulus to the surface. Once the installation was completed, the well was developed for 3 hours using compressed air.

Between 1999-07-22 and 1999-07-23, a pilot DPVE test was carried out using a 20 hp liquid ring pump (LRP) equipped with an inlet separator with sight tubes and high and low level controls. Dial gauges and a flow totalizer were also installed in the pump unit for vacuum and water flow measurements, respectively. Flow rate, vapour concentration and temperature of the discharge air were measured manually. Liquid levels in 30 selected piezometers in the project area were measured at regular intervals (between 30 and 60 minutes) throughout the test. Vacuum readings were also taken in 11 piezometers at 60-minute intervals. Liquid samples were recovered hourly from the discharge water stream for headspace vapour measurements and 5 sets of samples were collected for chemical analyses of BTEX and TPH. At the completion of the pilot test, liquid levels in RW1 and 4 surrounding piezometers were monitored as the potentiometric surface recovered.

The pilot test was carried out in 3 stages: Stage 1 was intended to assess air extraction while Stage 2 and 3 were to assess dual phase (liquid and air) extraction. The operating parameters of the three stages are shown in Table 2.

The pilot test results indicated that:

1. Groundwater flow direction was influenced within a 15 m radius from RW1
2. Significant vacuum was not measured in the surrounding observation wells.
3. The average PHC recovery rates were approximately 0.5 L/d and 15 L/d for liquid phase and vapour phase, respectively.
4. The average water extraction rate was 3.4 L/min when the wellhead vacuum was 17.0 “Hg.

Table 2. Operating Parameters for DPVE Pilot Test

Duration (hr)	Wellhead Vacuum (“ Hg)	Drop Tube Elevation (m bgs)
2.0	6.5 to 11.5	6.37 (at water table)
22.0	15.0 to 17.0	7.87
4.25	16.5 to 17.5	7.87

The limited vacuum influence observed may have been due to a number of factors including the relatively low permeability of the overlying clayey silt unit and the fact that air flow in the saturated sand unit would be minimal until the sands were desaturated. However, the influence on groundwater flow and PHC recovery rates during the DPVE test did indicate that an onsite DPVE system would be able to accelerate the remediation of the service station site and surrounding properties. It was decided that numerical modelling would be useful to study the possible influence on system performance imposed by local geological and site development conditions and to determine if hydrodynamic control of the LPH and dissolved phase PHC could be accomplished.

3.3 Numerical Modelling

The main objectives of the DPVE remediation system were to remove LPH from the service station site and the immediate surrounding areas, to reduce further migration of PHC-impacted groundwater offsite and to promote *in situ* bioremediation.

Numerical modelling for the design of the DPVE system was carried out using two commercial codes, SPILLVOL (Environmental Systems & Technologies, 1990) and MOVER (Draper Aden, 1996). SPILLVOL was used to estimate the volume of LPH occurring within the project area while MOVER was used to estimate the vacuum distribution around recovery wells and determine the appropriate spacing of the recovery wells of the DPVE system.

SPILLVOL is a program for estimating hydrocarbon spill volume and recoverable product using fluid level measurements from a network of monitoring wells. MOVER is an areal three-phase (water, LPH and air) finite-element model. It can be used to model flow of water, oil and gas in the subsurface, and optimize the recovery of LPH and water by minimizing the volume of LPH trapped in saturated and unsaturated zones. Both codes use the van Genuchten constitutive model, along with fluid scaling parameters to simulate the variable degree of saturation for both water and LPH associated with the capillary pressure in the unsaturated zone. The major limitation for both codes is that the soil layer is assumed to be homogeneous vertically, although soil properties and thickness can vary from element to element in MOVER.

Properties of the sand used in the modelling include grain size distribution and saturated hydraulic conductivities. An example grain size distribution is shown in Table 3.

Table 3. Example Grain Size Distribution for Silty Sand

Sieve Size (mm)	0.63	0.40	0.25	0.16	0.075
% Passing	100	97	89	79	57

The distribution is typical for silty sand. Saturated hydraulic conductivities (K_{sat}) from bail tests carried out at 4 selected monitoring wells ranged from 3.8×10^{-4} to 5.2×10^{-4} cm/s.

Based on the soil type and the hydraulic conductivities, values of model parameters were input as: ϕ, total porosity = 0.35; van Genuchten parameters: $a = 5.9$ m^{-1}, $n = 1.5$; S_m; the irreducible water saturation = 0.20; S_{og}, the maximum residual LPH saturation in the unsaturated zone = .05 and S_{or}, the maximum residual LPH saturation in the saturated zone = 0.25; LPH density = 0.75 g/cm3; air-LPH scaling parameter = 3.5 and LPH-water phase scaling parameter = 1.4. These parameters are average values according to Carsel and Parish (1988) and Rawls et al. (1982) and are listed in the program manuals according to soil texture.

SPILLVOL showed that the approximate volume of LPH that could be removed by liquid extraction (skimming or pumping) was 16.7 m^3 and the subsequent residual LRP volume fraction in both saturated and unsaturated zones was 0.3. A portion of this residual volume of LPH would be susceptible to vapour extraction.

Using MOVER, the drawdown influence surrounding RW1 was approximately matched by using a K_{sat} of 5×10^{-4} cm/s at a wellhead vacuum of 16 “Hg. For this K_{sat} value, the optimum recovery well spacing was determined to be at 8 m centres. A parametric study was then carried out by varying the water extraction level and applied vacuum at a series of recovery wells. It was determined that the design remediation system design would consist of 22 vertical recovery wells connected via a common header to a pump system capable of extracting 600 acfm of air when the inlet vacuum was at 20 “Hg. The expected water extraction rate was around 140 L/min keeping in mind that a higher extraction rate would be encountered at start-up. It was anticipated that the vacuum at each wellhead would be at least 3 “Hg.

3.4 Remediation System Installation

The remediation system included a DPVE system and an air-injection system. The remediation system did not extend into the property immediately adjacent to the site since access was not granted by the property owner.

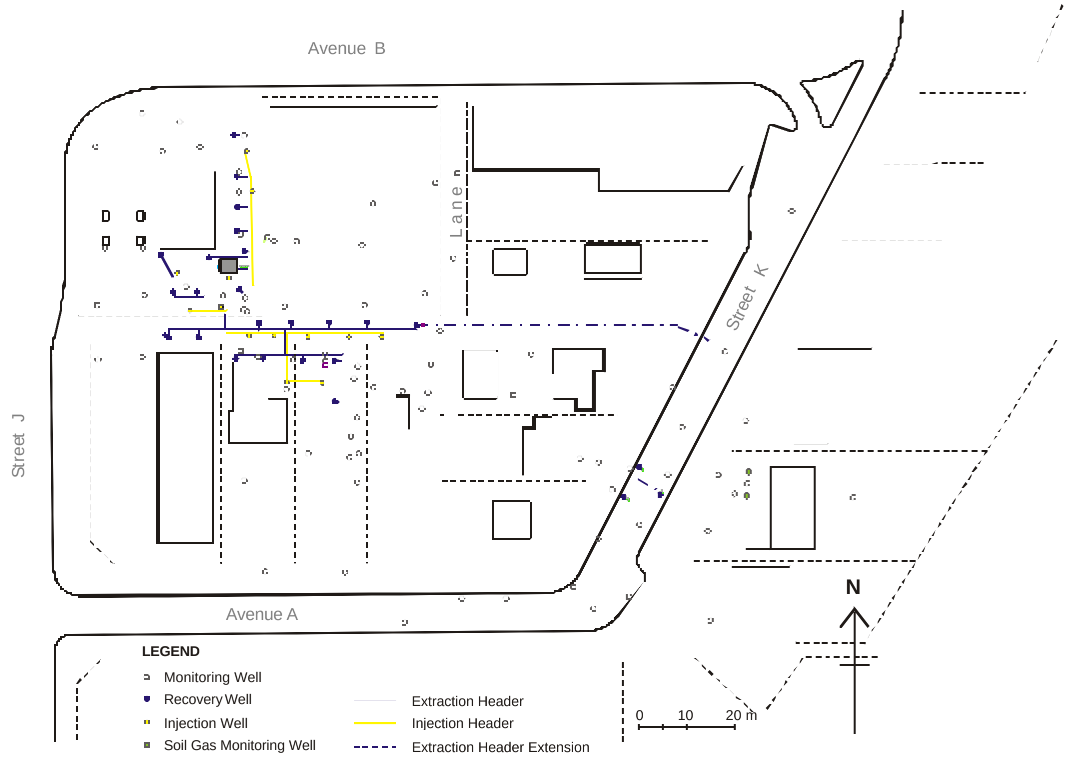

Figure 2. Site Pan Showing the Initial Header and Recovery Well System and System Extension to Street K in 2002.

The DPVE system installation included a network of extraction headers, 22 vertical recovery wells and a pump unit made up of 2-25 hp liquid ring pumps (LRPs). Figure 2 shows the layout of the extraction headers and locations of the recovery wells. Initially the extraction header extended only about 40 m offsite in an easterly direction in the laneway to the south of the service station. The extraction headers were constructed using 100 mm diameter Schedule 40 PVC pipes and were insulated and heat-traced. The header network was buried in a trench about 0.2 m deep. After the headers were in place, the trench was backfilled with compacted pea gravel and native material and topped up with a layer of asphalt to the original grade elevation. Risers were installed at the extremities of the headers to facilitate system maintenance

Recovery wells were drilled to a maximum depth of 10.5 m bgs using an air-rotary drill rig in most cases. Water was circulated, as required, while drilling through the sand strata to prevent sidewall sloughing. Because of access restrictions, 8 wells were drilled using a solid stem auger drill rig. PVC well casings 75 mm in diameter were installed to the bottom of each well. The lower sections of the well casings, starting from just above the top of the sand layer, were constructed from 10-slot perforated pipes while solid pipes were used for the upper segments. The annulus around the screened interval of each borehole was backfilled with 20/40 silica sand; the remainder of the annulus was backfilled with hydrated bentonite to the surface. The slot size and sand backfill grain size gradation were selected after a detailed analysis of the native sand formation. Once the installation was completed, each well was developed using compressed air for about 3 hours.

The wellhead of each recovery well was connected to a tee installed in the header using a section of flexible Tigerflex hose. The well casing was fitted with a valved pitless adaptor assembly from which a drop tube was extended down the well to the impacted zone. The top cap of the wellhead was equipped with a 25 mm brass valved nipple to facilitate pressure measurements. The entire wellhead assembly was contained inside a 450 mm diameter steel service box set in concrete. To prevent freezing, the wellhead assembly was heat-traced and a 100 mm thick layer of Styrofoam insulation was glued to the underside of the bolt-down steel cover.

The pump system was made up of 2-25 hp LRPs, an inlet fluid separator, an oil-water separator and a 4-tray air-stripper. The unit was housed in a winterized enclosure equipped with a heater capable of maintaining the interior temperature at >10ºC when the outdoor temperature was -40ºC and the LRPs were not operating. The system was also equipped with programmable logic controls (PLC) capable of dialling out using a phone modem on alarm conditions and automatic datalogging for critical operational parameters. Exhaust air was discharged directly into the atmosphere through a 75 mm diameter pipe while treated water was discharged into the City sewers under a discharge permit. Exhaust air from remediation systems is not regulated in Alberta.

In order to improve air flow in the subsurface, 9 injection wells together with 3 existing piezometers were connected to an injection header 75 mm in diameter. If necessary, a 10-hp regenerative vacuum unit (RVU) could be connected to the injection header. Wherever possible, the air injection and extraction headers shared a common trench in order to reduce construction costs. At start-up, the injection system was operated in a passive mode by opening the top valve and the RVU was not installed.

Drilling for recovery and injection wells was started in November 1999 and was completed in March 2000. The header systems were constructed between 2000-04-25 and 2000-05-18 The LRP system was delivered to site and connected on 2000-08-17. After a running-in period of 2 days and the quality of discharge water confirmed to be within the permit guidelines, the remediation system went into full operation on 2000-08-22.

3.5 System Operation

At present the DPVE system is still being operated. A field technician, who checks and records all system operation and discharge parameters, visits the site weekly. In addition, the system is checked daily by dialling in from Calgary.

Initially the drop tubes were set at 0.15 m below the water level in each recovery well. During the first month of operation, lengths of drop tubes were adjusted every two weeks such that eventually the drops tubes were located at between 0.5 m and 1.5 m below the initial water table. Subsequently, the drop tubes were adjusted every 6 months such that the water level in each well stayed within 1.5 m of the initial water depth.

Major operational difficulties encountered included overheating of the pumps, seal oil blow-by resulting in oil spewing from the discharge vent stack and excessive iron fouling in the pump components and recovery wells. Overheating was caused by the clogging up of the heat exchanger radiators by poplar lint and/or the malfunctioning of the thermostatic valves controlling the circulation of the cooling oil. The overheating problem was addressed by increasing the size of the exhaust fan, installing additional venting louvers on the doors of the pump enclosure, cleaning the radiator screen regularly and replacing the thermostatic valves. Oil blow-by was eliminated by installing an oil knockout and by maintaining a higher vacuum (>16 "Hg) at the pumps. Iron deposits inside the system components, including the inlet separator, oil-water separator, air-stripper trays and sight-tubes, necessitated cleaning manually or by circulating Rydlyme, a biodegradable descaler, on a quarterly basis. In 2003, the extraction headers were rotor-routed and the recovery well redeveloped by acid treatment and surging.

In order to address the LPH impacts at the downgradient portion of the plume on Street K, three extraction wells were installed in October 2002. In November 2002, the 100 mm diameter recovery header pipe was extended about 110 m to include the three new recovery wells as shown on Figure 2. The header extension was not insulated but was encased in an insulated box built using 50 mm thick Styrofoam board insulation and was buried in the laneway. Drop tubes of the three new wells were raised in the late Fall to about 6 m above the water table in order to minimize the humidity in the extracted air. This arrangement was necessary since the cost to provide electrical power to the heat-tracing that would be required for year-round was prohibitive. In the past three years, frost built up was not detected in the header extension during winter and DPVE was resumed in May.

3.6 System Performance

Wellhead vacuum measured ranged from 0.2 "Hg to 10 "Hg depending on the position of the drop tube and the water extraction rate at the recovery well. A lower vacuum reading was usually associated with a high water flow.

From 2000-08-22 to 2005-02-28, the DPVE system was operational for 87.6% of the time. During this period, the total equivalent liquid volume of hydrocarbons extracted was approximately 51600 L at an average estimated extraction rate (EER) of 57.5 L/d. The majority (>98%) of this volume was in vapour phase with the remainder in dissolved phase and through air-stripping of the discharged water. Free phase LPH was not detected within the pump system. The total volume of treated water discharged to the sewers over this period was 5222 m^3 at an average rate of 3.2 m^3/d.

The system performance with respect to hydrocarbon extraction and groundwater extraction are summarized in Figures 3 and 4, respectively. Figure 3 shows a typical hydrocarbons extraction curve for vapour phase extraction. The initial high EER (>100 L/d) tailed off after 6 months and the current rate is about 4 L/d.

3.7 Remediation Performance Assessment

The performance of the remediation system was assessed using a combination of fluid level monitoring, groundwater sampling and chemical analyses and vacuum measurements at selected monitoring wells. The monitoring program varied slightly from year to year. In 2004, the fluid monitoring program consisted of monthly measurements in 30 monitoring wells and a semi-annual monitoring of all accessible monitoring wells, extraction wells and injection wells. Groundwater samples were collected from 13 to 16 selected wells.

Based on fluid levels and chemical analysis results of the groundwater samples, the following milestones can be established for the initial project area (before header extension): LPH was removed in 7 to 9 months, dissolved phase PHC concentrations were reduced to below the Tier I criteria in about 18 months. Approximately 1500 pore volumes of air were extracted before the LPH was removed; the equivalent air flow rate was 3.6 L/min per m^3 of pore volume of impacted soil (Kallur et al., 2003)

After 18 months of DPVE operations, LPH and groundwater exceedances were still detected at the distal end of the plumes on Street K (see Figure 1). *In situ* dissolved oxygen measurements taken in monitoring wells in this area ranged from 0.5 to 1.0 mg/L. These readings were similar to background values indicating that bioremediation would be occurring anaerobically and the DPVE system was not able to deliver additional dissolved oxygen to this area some 65 m from the closest recovery well. Aerobic bioremediation is the preferred biological process for breaking down benzene. Consequently, in November 2002 the extraction header was extended about 110 m to three additional recovery wells as described in Section 3.5.

Subsequent to the header extension, LPH have not been detected in any boreholes after 2003-01-07 and groundwater concentrations exceeding the Tier I criteria have not detected within the project area after 2003-08-28. However, it should be noted that groundwater sample has not been obtained from borehole BH86, located at the tip of the plume, since it has remained dry after its installation in July 2004. There were some indications that the dissolved oxygen (DO) concentrations might have also increased at the tip of the plume. From six monitoring wells in this area, higher DO was measured in three wells, two remained unchanged and one with no reading (dry).

Two drilling programs, using auger drill rigs, were carried out to assess the progress of remediation. In November 2002, 6 boreholes were advanced at the locations shown on Figure 1. Soil PHC concentrations exceeding Tier 1 were detected at BH78 and BH82. BH78 was located in the middle of the plume while BH82 was at the eastern tip of the plume. The second drilling program took place in July 2004 during which 4 boreholes were advanced. Soil PHC concentrations exceeding Tier 1 were not detected in BH88, which was drilled about 1 m from BH78, and BH87, which was drilled within 3.2 m of BH82. However, exceedances were detected in soil samples obtained from BH86, which was located at the east side of the house on Street K indicating that the hydrocarbon plume would require further delineation.

4. CONCLUSIONS

The performance assessment sampling and chemical analyses conducted to date indicate the DPVE system at the project site has remediated the majority of the project area to comply with Alberta Tier I criteria for inhalation pathways at coarse-grained sites. Although the eastern tip of the PHC-impact plume has yet to be fully delineated, it is the authors' opinion that a more localized remediation technology such as excavation and backfilling or *in situ* chemical oxidation may be more appropriate to address the relatively small area at the tip of the plume. Of course, final confirmation drilling and sampling will need to be conducted before the remainder of the project area can be declared to be satisfactorily remediated.

5. ACKNOWLEDGEMENT

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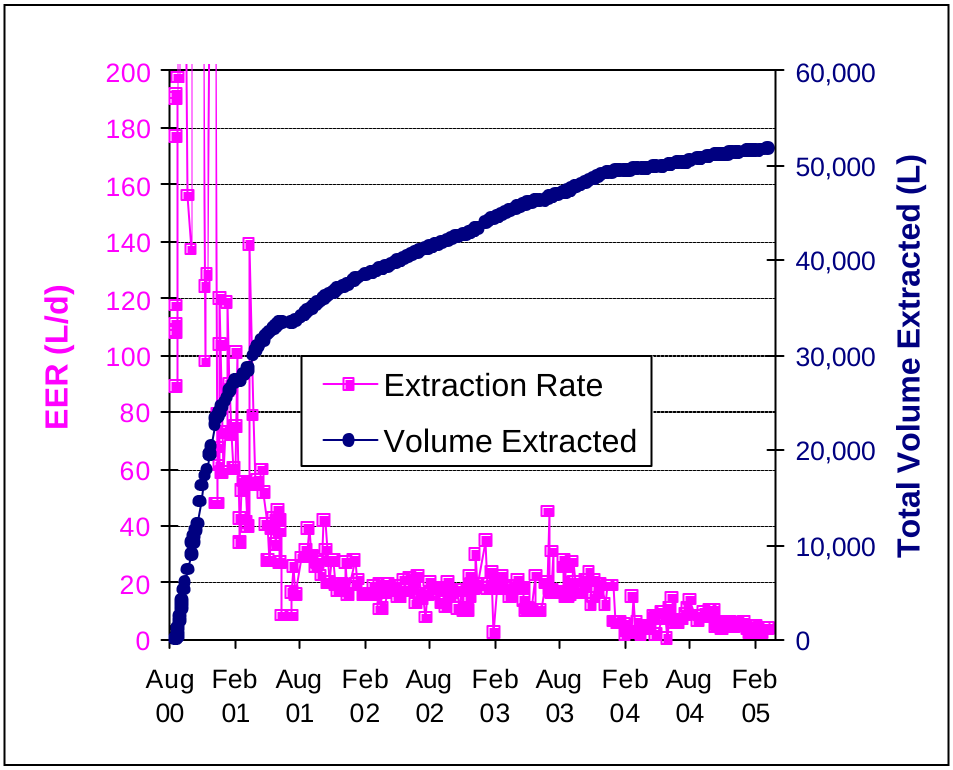

Figure 3. Petroleum Hydrocarbons Extraction Performance

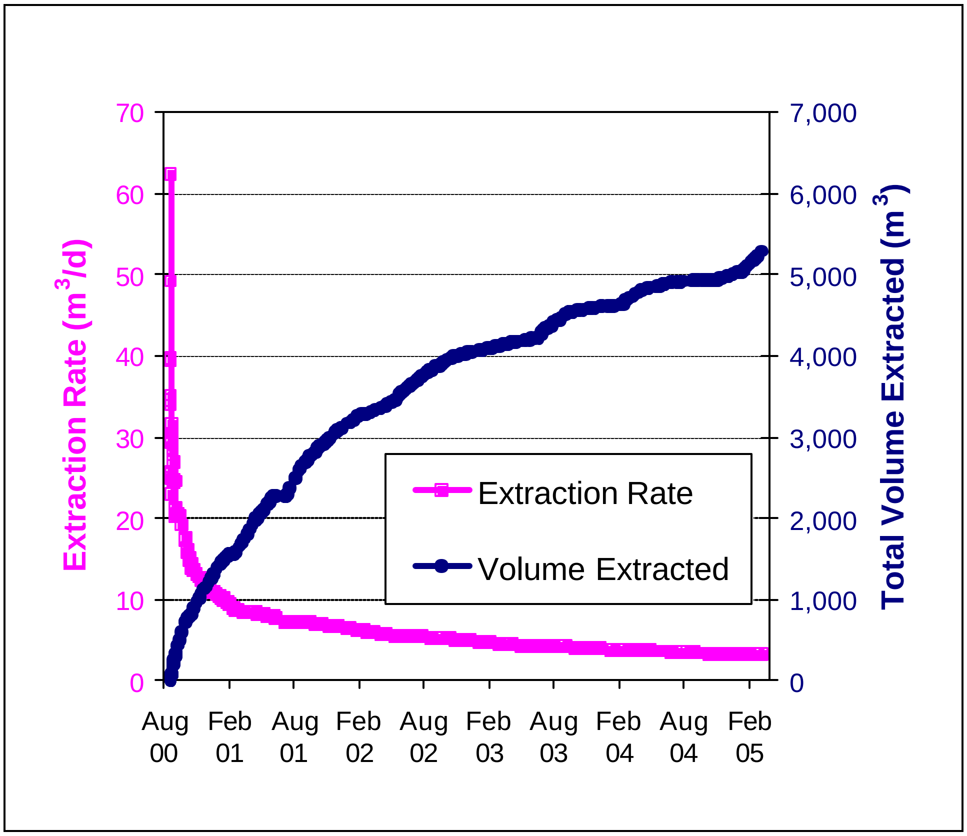

Figure 4. Groundwater Extraction Performance