REMEDIATION OF PETROLEUM HYDROCARBON IMPACTS UNDERNEATH AN APARTMENT BUILDING USING DUAL PHASE VACUUM EXTRACTION ENHANCED BY ELECTRICAL SOIL HEATING

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ABSTRACT
When subsurface soils impacted by petroleum hydrocarbons (PHC) or other organic chemicals are heated, vapour pressures and solubilities of the impacting volatile organic chemicals are increased. The increased volatility and solubility significantly enhance the rate of removal of the organic chemicals by conventional extraction technologies such as dual phase vacuum extraction (DPVE).

This paper summarizes the design, operating history and performance monitoring results of a thermally enhanced DPVE (TE-DPVE) system used to remediate PHC impacts underneath an occupied apartment building. The apartment building is founded on silty soils with a basement extending about 1.2 m below grade. The primary concern was impact by benzene in the soils underneath the north end of the building covering an area of approximately 56 m^2. In this area, an electrical resistive soil heating system employing the patented Electro-Thermal Dynamic Stripping Process (ET-DSP^{TM}) was implemented for enhanced vacuum extraction. The DPVE system was installed with recovery wells covering this and adjacent areas. The desired remediation target was achieved after 9 months of system operation during which 21 out of 23 apartment units in the building remained available for rental occupation. This case history will also highlight the special operational considerations and the overall cost of this remediation project.

RÉSUMÉ
Lorsque les sols contaminés par des hydrocarbures ou autres composés organiques sont chauffés, les pressions de vapeur et solubilités des contaminants organiques volatiles augmentent. Cette augmentation de la volatilité et de la solubilité accroît de façon significative le taux d'enlèvement des composés organiques par des technologies d'extraction conventionnelles tels que l'extraction multi-phase sous vide (EMPSV).

Cet article présente un sommaire de la conception, de l'historique des opérations et des résultats de la surveillance de performance de l'application d'un système EMPSV thermiquement augmenté (EMPSV-TA) pour le traitement des sols contaminés par des hydrocarbures sous un édifice à appartements habités. L'édifice à appartements est construit sur des sols silteux avec un sous-sol à une profondeur d'approximativement 1.0 m sous terre. La préoccupation majeure était la contamination par le benzène dans les sols sous la partie nord de l'édifice et couvrant une surface d'approximativement 96 m^2. Dans cette zone, un système de réchauffement des sols par résistance électrique utilisant le processus d'enlèvement dynamique électro-thermique breveté (electro-thermal dynamic stripping process ET-DSP^{TM}) a été installé pour accroître l'extraction sous vide. Le système EMPSV a été installé avec des puits d'extraction couvrants cette zone ainsi que celles adjacentes. L'objectif de remédiation a été atteint après 7 mois d'opération du système durant lesquels 21 des 23 appartements de l'édifice sont demeurés disponibles pour l'habitation. Cette étude de cas soulignera aussi les considérations opérationnelles spéciales ainsi que les coûts d'ensemble de ce projet de remédiation.
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1. INTRODUCTION

Organic contaminants, such as petroleum hydrocarbons (PHC), can exist in four different phases in the subsurface: as a separate non-aqueous phase liquid, as a dissolved contaminant in the aqueous phase, as a vapour phase in the soil gas, and as an adsorbed phase. In the adsorbed phase, the contaminant may be partitioned into the soil organic matter or adsorbed onto the soil mineral particles. In general, the non-aqueous and dissolved phases can be removed by pumping and the vapour phase removed by soil venting, the adsorbed phase is usually the most difficult to remove.

Ground heating has been identified as a potential means to enhance the recovery of organic chemical contaminants in the subsurface (Dev et al., 1989; US EPA, 1995; Newmark and Aines, 1995). In general, an increase in temperature will increase the volatility (vapour pressure) of a liquid contaminant, decrease its adsorbtivity, increase its molecular diffusivity in the aqueous and gaseous phases, increase its solubility in the aqueous phase, and decrease its viscosity in the liquid phase. Consequently, through heating, more contaminants are made available for removal by conventional remediation processes such as dual phase vacuum extraction (DPVE).

Subsurface soil heating can be achieved by inducing an electric current between two or more electrodes installed in the ground. The intervening soil between the electrodes is heated because of its resistance to the electrical current, similar to a stove-top heating element. One such electrical resistive heating (ERH) process is the patented Electro-Thermal Dynamic Stripping Process (ET-DSP™) (McGee et al., 1994; McGee, 2003) using specially designed electrodes and a computer-controlled power delivery system (PDS). In 1998, a pilot test demonstrating the effectiveness of thermally enhanced dual phase vacuum extraction (TE-DPVE) using ET-DSP™ was successfully carried out at a decommissioned service station site that was impacted by PHC (Wong et al., 2000). Based on lessons learned from the pilot test, the design of the electrodes and the control of the PDS were improved.

Figure 1. North Hill Manor – View from the Southeast

In 2001, TE-DPVE was chosen to be the remediation technology to remediate the subsurface PHC impact underneath an apartment building, the North Hill Manor, which is located at 305 – 13th Avenue NE in Calgary, Alberta. As illustrated in Figure 1, the building is a 3-storey apartment building approximately 33 m long by 12 m wide. Including basements suites there are a total of 23 apartment units. A former service station property is situated to the east side of the building. The subsurface impact originated at the former service station, which was operated between 1958 and 1975. In 2000 and 2001, soil and groundwater samples from monitoring wells installed on the north and east sides of the building indicated there were likely PHC impacts in the subsurface underneath the building footprint. TE-DPVE was chosen over other conventional remediation methods, such as excavation, because it would cause the least disturbance to the residents of the building while being to achieve the remediation goal in a relatively short time period.

In the following sections, the design, operating history and performance monitoring results of the TE-DPVE system are summarized.

2. BACKGROUND INFORMATION

2.1 Site Geology and Hydrogeology

According to regional geologic information (Moran, 1986) and confirmed by subsurface investigations using boreholes, the site is underlain by till and associated stratified sediments consisting of silt, clayey silt and silty clay. The depth to bedrock is approximately 35 m below ground surface (bgs).

The potentiometric surface is generally located between 4.0 m and 5.0 m bgs with a seasonal variation of about 1.0 m. Based on monitoring results on 2002-05-17; the hydraulic gradient is approximately 0.015 in an east to west direction.

2.2 Site Sensitivity Assessment

A site sensitivity assessment conducted in 2001 according to guidelines outlined by Alberta Environmental Protection (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 fine-grained soils (hitherto referred to as the Alberta Level I criteria). The Level I criteria were also adopted as the remediation criteria for this site.

2.3 Previous Subsurface Investigations

Between 2000-06-26 and 2000-07-05, 8 boreholes (BH1 through BH8) were drilled to depths of about 7.6 m bgs in the areas surrounding the building. Locations of the boreholes are shown on Figure 2. Monitoring wells were installed in BH1, BH2, BH3, and BH4 from which groundwater samples were collected on 2000-07-05. These monitoring wells were subsequently decommissioned. Chemical analytical results indicated that benzene concentrations in some soil samples collected from BH1, BH2, and BH3 and in groundwater samples collected from BH1 and BH3 exceeded the referenced Alberta Level I criteria. In addition, it was determined that the zone of PHC impacts extended from 2.5 m to 6.6 m bgs vertically and possibly affected the area underneath basement Apartment 106. Phase – separated liquid hydrocarbons were not detected in any of the monitoring wells.

Additional offsite investigations were conducted to delineate the extent of PHC impacts in soil and groundwater. However, the discussion herein will be limited to the immediate area surrounding and underneath the building.

3. REMEDIATION ACTIVITIES

3.1 Description of the Remediation Technology

As described in Section 1, the remediation technology adopted is the thermally enhanced dual phase vacuum extraction (TE-DPVE) process that is made up of three

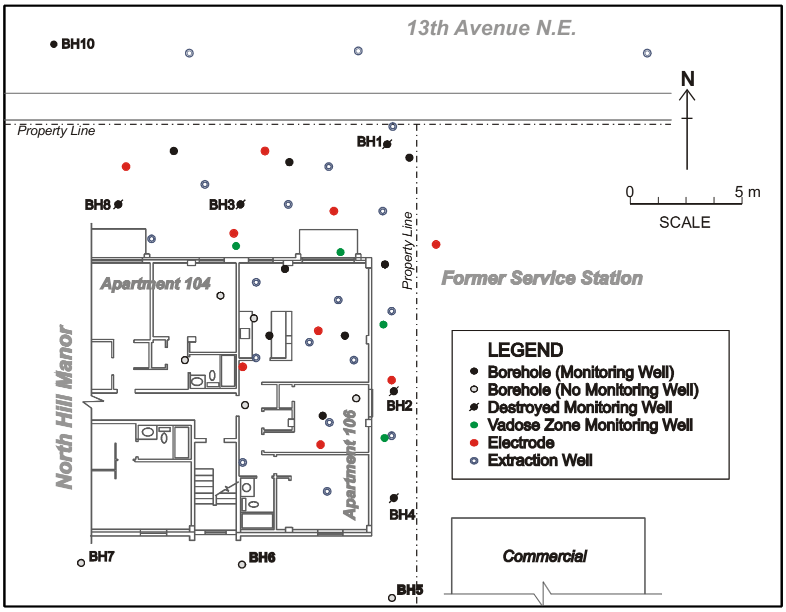

Figure 2. Site Plan and Borehole Locations

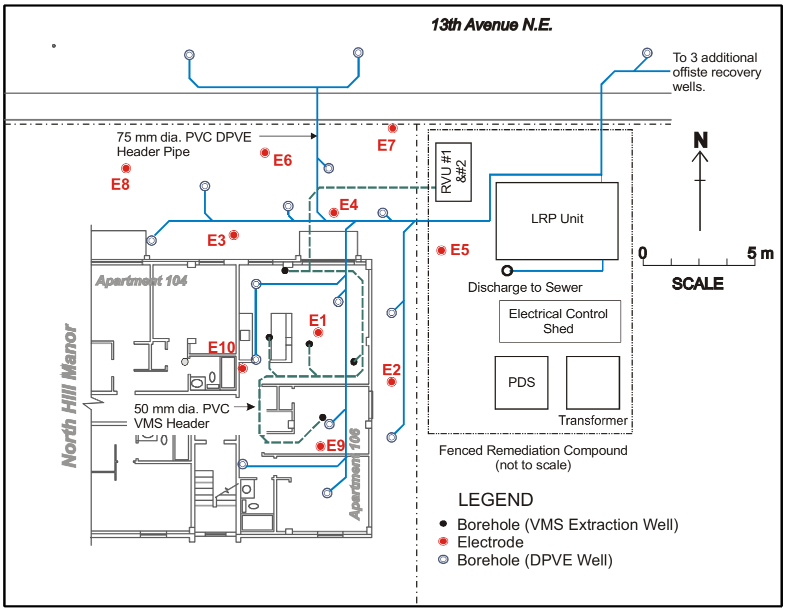

Figure 3. Schematic Plan View of the TE-DPVE Remediation System

major components: an electrical resistive heating (ERH) system using ET-DSP^{TM} technology, a DPVE system and a vapour management system (VMS). All mechanical and electrical equipment were housed in a secure area located on the adjacent former service station property.

Remediation activities to address the PHC impacts underneath the building were carried out between 2001-08-09 and 2002-04-30. Verification subsurface investigations were conducted between 2002-04-03 and 2002-06-28. A schematic plan view of the remediation system is shown on Figure 3.

The remediation project was managed by O'Connor Associates Environmental Inc. on behalf of Shell Canada Products Ltd. O'Connor was also responsible for performance monitoring and verification sampling. The ERH system was designed and maintained by McMillan-McGee Corp. The operation and maintenance contractor was Sequoia Environmental Remediation Inc. All four companies are based in Calgary, Alberta.

3.1.1 Electrical Resistive Heating System

The ERH system included a power delivery system (PDS) and 10 electrodes that are individually connected to a water circulation system. Locations of the electrodes (E1 through E10, see Figure 3) were determined and optimized by McMillan-McGee using computer modelling. The electrodes were intended to form a triangular grid.

Each electrode of the ERH system was constructed using a 200 mm diameter hollow steel rod 2.4 m in length and was installed inside a borehole drilled to a depth between 5.5 m to 6.1 m bgs when it is located outside the building or about 4.3 m below the basement floor when it is located inside the building. Conduits for water circulation and injection were included inside each electrode. The annulus between the electrode and the surrounding soil was backfilled with granular graphite in the bottom 2.7 m and then with hydrated bentonite to the ground surface. The distance between electrode pairs ranged from 3.75 m to 6.50 m.

The circulated water was designed to keep the temperature of an electrode below 90 °C during heating. From within each electrode, some water was also injected into the surrounding soil in order to maintain some moisture in the soil pores. Soil moisture is necessary for the conduction of electricity between electrodes.

Three-phase electric power was delivered to selected electrodes on a rotating basis by a computer-controlled PDS that was capable of delivering 150 kW to 180 kW of power. Initially, only 3 electrodes (i.e. 1 triangular area) were activated at any one time. However, in order to accelerate the remediation schedule, the PDS was

Table 1. Concentrations of Petroleum Hydrocarbons in Soil Samples Collected Prior to and Subsequent to Remediation (mg/kg)

CONSTITUENT	Before [b] E1	After [a] BH50	Before [b] BH41	After [a] BH51	Before [b] BH47	After [a] BH52	Before [b] E5	After [a] BH55	LEVEL I CRITERIA[c]
Benzene	**2.7**	<0.02	**1.8**	0.03	**1.0**	<0.02	**7.6**	<0.04	0.2
Toluene	<0.04	<0.04	3.8	<0.04	<0.04	<0.04	1.2	<0.10	40
Ethylbenzene	10	<0.04	7.4	<0.04	7.4	<0.04	8.3	<0.10	300
Xylenes	1	<0.09	11	<0.09	10	<0.09	12	<0.20	110
Total Volatile Hydrocarbons	750	<10	580	<10	510	<10	800	<10	NS
Total Extractable Hydrocarbons	46	<10	90	<10	35	<10	39	<10	NS
Total Petroleum Hydrocarbons [d]	46	<10	90	<10	540	<10	840	<10	NS

a - After remediation samples were collected on 2002-04-03
b - Before remediation samples were collected between 2001-08-09 and 2001-09-14
c - Draft Remediation Guidelines for Petroleum Storage Tank Sites (AEP, 1994)
Level I - risk management criteria for sites of high sensitivity
d - Total volatile plus total extractable hydrocarbons, as reported by laboratory
NS - Not specified
BOLD - Concentration exceeds referenced criterion

Note: Concentrations reported are the maximum concentration from all samples submitted for analyses at the same borehole

upgraded on 2001-12-08 so that 6 electrodes (i.e. 2 triangular areas) were activated at one time.

3.1.2 Dual Phase Vacuum Extraction System

Initially, the DPVE system employed a 30-horsepower (hp) liquid ring pump (LRP) that was replaced by a 50-hp LRP on 2002-11-02. The LRP was connected to 19 vertical extraction wells through an underground header system located approximately 0.6 m bgs. The headers were constructed using 75 mm diameter Schedule 40 PVC pipes that were insulated and heat-traced for winter operation. At the inlet of the LRP, a 6500 L sediment knockout tank was also installed. Spacing between recovery wells ranged between 1.50 m and 6.25 m.

Within the North Hill Manor property, thirteen 75 mm diameter Schedule 40 PVC extractions wells were installed with screened lengths typically extending between 2.4 m and 6.1 m bgs. In addition, 6 extraction wells screened typically from 1.5 m to 7.9 m bgs were located in the boulevard between the site and roadway to the north.

The DPVE system was designed to extract groundwater water, subsurface vapours, and injected water. The extracted water was treated as required and discharged into a sanitary sewer. The water was continually sampled and tested as required by the City of Calgary Sewer Service Bylaw.

3.1.3 Vapour Management System

A VMS was installed to remove any fugitive PHC vapours, which might collect underneath the basement floor slab during the remediation process. The VMS consisted of 5 recovery wells constructed using 50 mm diameter PVC pipes installed through the concrete floor slab to approximately 0.3 m below the slab surface. Each pipe was screened only below the concrete and the annular space between the pipe and concrete was sealed using polyurethane sealant. Each recovery well was connected by an above slab header piping system to one of the two 1 hp regenerative vacuum units (RVU#1 and RVU#2).

3.2 System Installation and Delineation Investigation

Between 2001-08-09 and 2001-09-14, 29 boreholes were drilled using a truck-mounted auger drilling rig, a track-

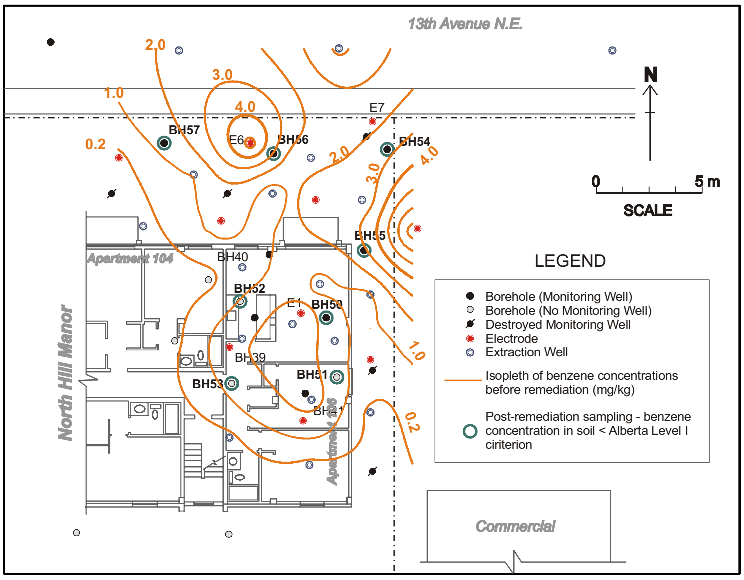

Figure 4. Contours of Benzene Concentration in Soil and Locations of Boreholes for Verification Sampling Program

Table 2. Concentrations of Petroleum Hydrocarbons in Groundwater Samples Collected Prior to Remediation (mg/L)

CONSTITUENT	Sample Date: 2001-09-13 BH40	BH41	CRITERIA [a]
Benzene	0.012	0.150	0.4
Toluene	0.0012	0.032	25
Ethylbenzene	0.017	0.180	50
Xylenes	0.022	0.150	80
Total Volatile Hydrocarbons	0.3	2.3	NS
Total Extractable Hydrocarbons	<0.1	0.3	NS
Total Petroleum Hydrocarbons [b]	0.3	2.7	NS

a - Draft Remediation Guidelines for Petroleum Storage Tank Sites (AEP, 1994)
Level I - risk management criteria for sites of high sensitivity

b - total volatile plus total extractable hydrocarbons, as reported by laboratory

NA - not specified

Note: Concentration reported is the maximum from samples collected from the monitoring well

mounted auger drilling rig or a tripod mounted (Heli) auger drilling rig. The available working space and headroom dictated the type of drilling rig used for each borehole. Fifteen of the boreholes were completed as 75 mm diameter DPVE extractions wells, 5 were completed as shallow 50 mm diameter VMS wells and 9 were completed with the installation of a 200 mm diameter electrode. Locations of the boreholes are illustrated on Figure 2. All of the boreholes were drilled either inside the building (Apartment 106) or in areas surrounding the northeast corner of the building.

On 2001-10-17, after the TE-DPVE system had been activated, one of the extraction wells inside Apartment 106 was removed and replaced with an electrode. An additional borehole was also drilled and completed as an extraction well.

On 2001-11-19, two additional boreholes were drilled in Apartment 104 (adjacent to Apartment 106) in order to complete the delineation of the PHC impact underneath the building.

During drilling, soil samples were selected from each borehole and were submitted for laboratory chemical analyses of concentrations of benzene, toluene, ethylbenzene, xylenes (BTEX), total volatile hydrocarbons (TVH), and total extractable hydrocarbons (TEH). The selection criteria included maximum headspace combustible vapour concentration, visual characteristics and/or stratigraphic location. Results of the chemical analyses indicated that benzene concentrations in the soils underneath the northeast corner of the building exceeded the Alberta Level I criteria. Table 1 presents the chemical analyses results for some of the samples together with the Alberta Level I criteria. The chemical analyses results for benzene concentrations in subsurface soils are contoured and plotted on Figure 4. The 0.2 mg/kg contour in the figure marks the approximate perimeter of the zone within the North Hill Manor property that required remediation.

As shown in Table 2, chemical analyses of groundwater samples collected from two extraction wells on 2001-09-14 did not show any exceedance of the Alberta Level I criteria.

Between 2001-09-14 and 2001-09-25, the DPVE headers and VMS headers were constructed. During this period, mechanical and electrical equipment for the TE-DPVE system were also installed onsite.

3.3 Operation of Remediation System

Prior to system start up, a site safety plan and operations manual were developed. On 2001-09-26, the TE-DPVE system was activated.

Electrodes for the ERH system were operated in rotating groups of 3 until 2001-12-08 when the PDS was upgraded. Subsequently, 2 groups of 3 electrodes were activated until 2002-04-03 when the TE-DPVE system was deactivated and decommissioned based on the outcome of a verification sampling program. The DPVE system continued to operate until 2002-05-17. The VMS was operated continuously between 2001-09-26 and 2002-06-25. Both the DPVE and VMS were monitored on approximately a weekly basis. In addition, the ambient air inside the North Hill Manor (Apartment 106) was monitored for benzene concentrations using an Ultra-Rae photoionization detector, also on a weekly basis.

3.4 Remediation System Performance

3.4.1 Subsurface Soil Temperature

Subsurface soil temperatures were measured using a multi-level device made up of thermocouples installed at approximately the centroid of the triangle formed by electrodes E1, E9, and E10 inside Apartment 106. Figure 5 shows the vertical temperature profile measured on 2002-03-18.

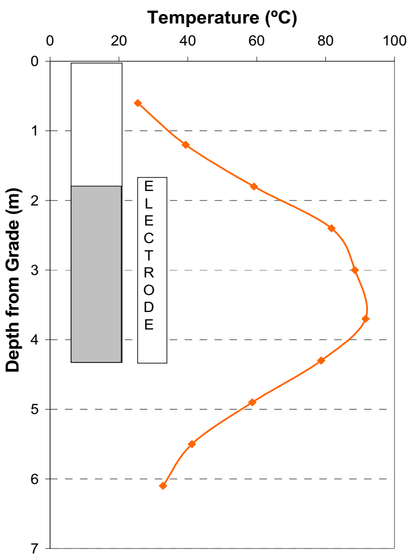

Figure 5. Vertical Temperature Profile

3.4.2 Dual Phase Vacuum Extraction System

The DPVE system for the remediation project was operated between 2001-09-26 and 2002-05-17. Based on timer readings the system was operational 94% of the time. During this period, a total of 1520 m^3 of groundwater and injected water was extracted and discharged to the City of Calgary sanitary sewer. The average water extraction rate was 6.5 m^3/d (4.5 L/min). A total of approximately 1620 L of PHC was also extracted in the vapour phase and the estimated extraction rate (EER) ranged between 34.3 L/d and 1.4 L/d. Figure 6 shows the variation in EER with time during the LRP operating period. The cumulative estimated volume of PHC extracted by the DPVE system and VMS as well as the total volume of PHC extracted are shown on Figure 7.

3.4.3 Vapour Management System

The VMS operated continuously between 2001-09-26 and 2002-06-25. The VMS performance parameters were monitored approximately on a weekly basis. The time history of the cumulative estimated volume of PHC extracted is shown on Figure 7. The highest combustible vapour concentration measured was 50 parts per million by volume (ppm). The air extraction rate ranged from 102 scfm to 126 scfm. The EER varied between <0.1 L/d and 1.1 L/d with higher rates recorded at the beginning of the remediation.

Benzene concentrations in the ambient air inside Apartment 106 were measured on a weekly basis. The readings did not exceed 0.2 ppm and were generally below the detection limit of the measuring instrument.

3.5 Verification Sampling Program

A total of 8 verification boreholes were drilled for the remediation program. On 2001-11-19, BH50 was drilled inside Apartment 106 to assess the progress of the remediation process. The remaining 7 boreholes (BH51 through BH57) were drilled on 2002-04-30; 3 of these boreholes were located inside Apartment 106 while the remaining boreholes were located in the lawn area surrounding the northeast quadrant of the building.

Soil samples were selected from each borehole based on headspace vapour concentrations, visual soil characteristics, and stratigraphic position and submitted for laboratory chemical analyses of BTEX, TVH, and TEH concentrations. Temperatures of the soil samples collected from similar elevations as the electrodes ranged between 36 ºC and 55 ºC. Concentrations of PHC constituents in the analyzed samples did not exceed the Alberta Level I criteria. In addition, except for the benzene concentration in one soil sample at BH51, all of the analyzed PHC constituent concentrations were below the laboratory detection limit. To illustrate the significant reduction in PHC concentrations as a result of the TE-DPVE process, PHC concentrations in samples collected from a particular borehole prior to remediation are compared to samples collected from a nearby location during the verification program in Table 1.

Groundwater samples were collected from selected boreholes on the property at about 40 days, 63 days and 73 days after the deactivation of the ERH system on 2002-04-03. These samples were submitted for laboratory chemical analyses of BTEX, TVH, and TEH concentrations. None of the analyzed PHC constituent concentrations in the groundwater samples exceeded the Alberta Level I criteria.

4. PROJECT COST

The overall project cost is summarized in Table 3.

Table 3. Cost Summary for the TE-DPVE Remediation Process at North Hill Manor

ITEM	COST
ERH System: Rental & Maintenance	$ 123,000
Drilling	$ 35,204
System Installation: Headers and Pumps	$ 109,011
System Operation & Maintenance	$ 153,953
Monitoring & Sampling	$ 15,047
Reporting & Permitting	$ 22,853
Project Management	$ 23,547
Laboratory Analyses	$ 20,450
Electrical Power	$ 35,000
Total:	$ 538,065

The total cost of the project was $538 065, which included $35 000 for power consumed. If one could take the area bounded by the electrodes as the footprint of the remediated area (approximately 11 m by 12 m) and estimate the thickness of soil remediated as 4.3 m, the volume of soil remediated was approximately 600 m^3. Thus, the unit cost for the TE-DPVE remediation of North Hill Manor is about $900 / m^3.

5. CONCLUSIONS

The verification sampling and chemical analyses conducted after the site remediation indicated that none of the analyzed PHC constituent concentrations in the subsurface soil or groundwater samples collected within the North Hill Manor property exceeded the applicable 1994 Alberta Level I criteria. TE-DPVE technology was able to remediate the site within 7 months and had caused minimal disruptions to the occupants of the building. During remediation, only 2 apartment units (out of 23 units) were vacated. One apartment unit was occupied by the remediation system while another apartment unit was vacated for a short period of time during delineation drilling.

6. ACKNOWLEDGEMENT

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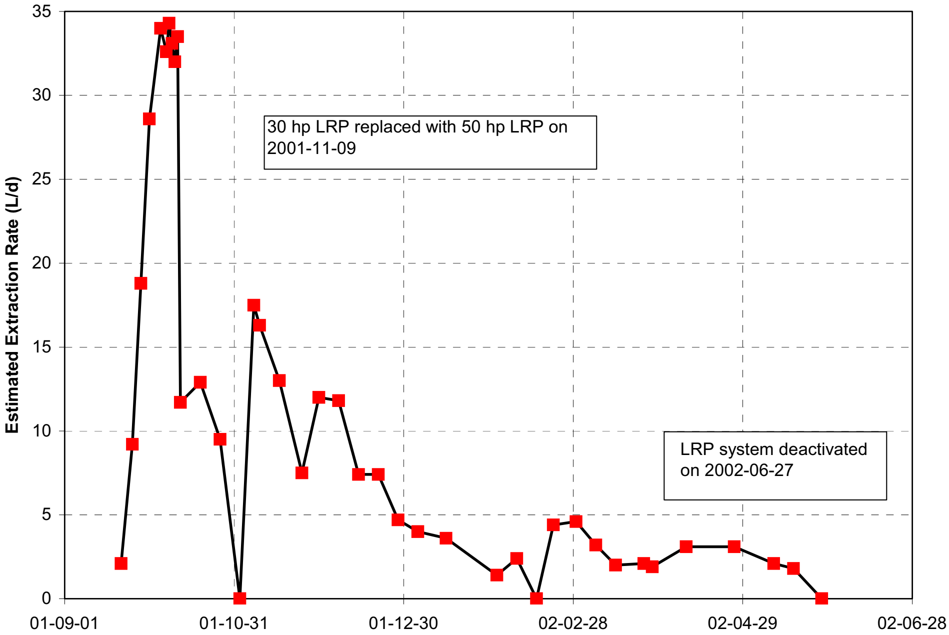

Figure 6. Variation of Estimated Extraction Rate with Time – LRP System

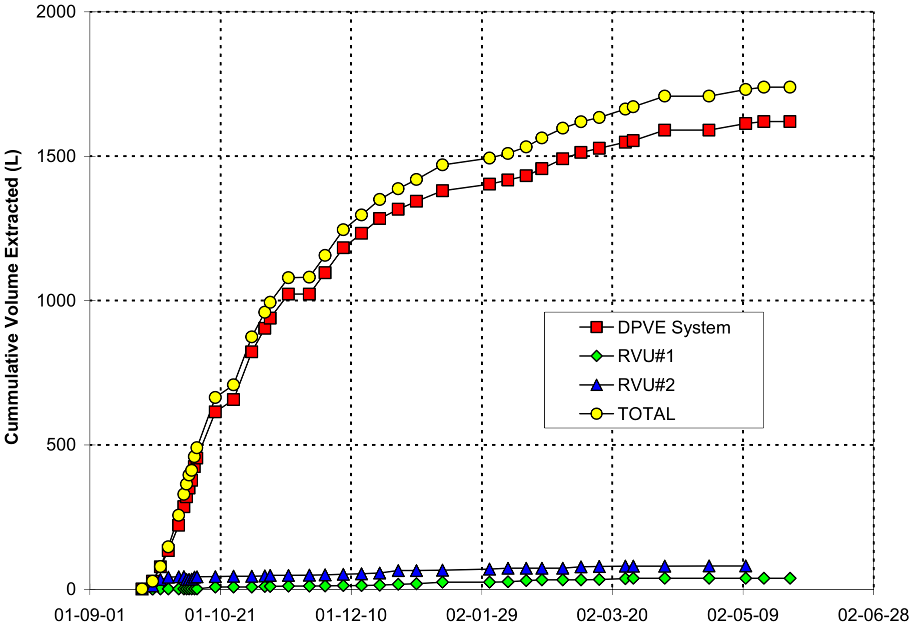

Figure 7. Estimated Volume of Petroleum Hydrocarbons Extracted during TE-DPVE Operation