Enhanced In Situ Hydrocarbon Recovery: Dual Phase Vacuum Extraction and Pneumatic Fracturing Project


Abstract

Dual phase vacuum extraction (DPVE) is an in situ soil contaminant remediation technology that uses a single pump to remove suspended or water-soluble chemicals from subsurface soils and groundwater. The need for effective and economically feasible soil and groundwater remediation techniques has grown substantially in recent years due to increased environmental regulations and standards. Dual phase vacuum extraction is a highly efficient solution to this exigency as it addresses removal and treatment of each phase of hydrocarbon contamination.

Pneumatic fracturing is an enhancement technology that aids soil and groundwater contaminant recovery systems by increasing soil permeability. This technology uses compressed air to create and extend fractures in overconsolidated or desiccated low permeable soils. When pneumatic fracturing is used in conjunction with an in situ soil and groundwater remediation system, such as DPVE, the efficiency of the remediation process can be greatly enhanced and remediation timelines significantly decreased.

Stantec Consulting Ltd. (Stantec) was retained by TransGas Limited (TransGas) to design, commission and conduct performance monitoring for the DPVE system installed at the Cantuar Field Scrubber (Site) located near Success, Saskatchewan. The subsurface geology and groundwater at the Site was impacted with hydrocarbons in the naphtha range through past operations as a result of a leaking underground storage tank (UST). Groundwater monitoring and soil characterization at the Site identified an approximate total hydrocarbon volume of 55,000 L present in the subsurface to depths up to 15 m below grade level (mBGL). The subsurface soils consist of silts and clays and groundwater levels fluctuate from 11 mBGL to 13 mBGL.

An initial DPVE pilot scale DPVE program was operated in 2000, during which time a total of 7,800 L of hydrocarbons were recovered. The average hydrocarbon recovery rate was approximately 3 L/hour. The full scale DPVE remedial system, fabricated by Ground Effects Environmental Services Inc. (GEE), was commissioned at the Site in May 2001. Approximately 7,600 L of hydrocarbons were recovered from the subsurface in the vapour, biodegradation, liquid and dissolved phase at the Site during the 2001 operating season. The hydrocarbon recovery rate, however, decreased to approximately 1 L/hour. The decrease in hydrocarbon recovery rates were attributed to the local hydrocarbon impact surrounding the recovery wells being the first and easiest hydrocarbons to be recovered.

An enhancement technology was required to increase the hydrocarbon recovery rates since the previous decreasing trend was approaching diminishing returns. A two day
A pneumatic fracturing pilot study was conducted to test the potential to increase the hydrocarbon recovery rates. The pilot study proved extremely successful and demonstrated an increased hydrocarbon recovery rate from as low as 1 L/hr to as high as 55 L/hr.

The pneumatic fracturing pilot study demonstrated the potential to significantly enhance the recovery of subsurface hydrocarbons and therefore reduce the potential timeline for remedial operations at the Site. The results of the pneumatic fracturing pilot study suggest that an initial remediation timeline in the order of five additional years may be reduced to just months.

**Introduction**

Stantec Consulting Ltd. (Stantec) was retained by TransGas Limited (TransGas) to commission and conduct performance monitoring for the dual phase vacuum extraction (DPVE) system and to conduct a pneumatic fracturing pilot study at the Cantuar Field Scrubber (Site) located near Success, Saskatchewan. A site plan showing the recovery well locations, the DPVE system and the pneumatic fracturing system is shown in Figure 1.

**Background**

The Site is located in southwest Saskatchewan, north of Swift Current, approximately 250 km south of Saskatoon and 250 km west of Regina. The Site is located near the Town of Success and has the legal location of SW 30-16-16 W3M.

Monitoring wells were installed adjacent to the Cantuar Field Scrubber underground storage tank (UST) in 1996 and displayed up to one metre of naphtha during subsequent monitoring events. It was determined that the leaking UST had impacted a large area and the contaminants had the potential to move off TransGas’ property to the west, therefore, the UST was decommissioned and additional boreholes were completed to further delineate the extent of the hydrocarbon impacted area.

**Site Geology and Hydrogeology**

The surficial units at the Site consist of topsoil to a maximum depth of 0.5 m below grade level (mBGL). Underlying the topsoil is native silty clay and sand between 4 mBGL and 14 mBGL and clay till extending beyond 14 mBGL. In some areas, a sand layer was interbedded in or underlying the clay till from approximately 6.5 mBGL to 21 mBGL.

The silty clay soil had a hydraulic conductivity of $4 \times 10^{-7}$ m/s, the clay till soil had a hydraulic conductivity of $2 \times 10^{-7}$ m/s and the sandy soil had a hydraulic conductivity of $3 \times 10^{-5}$ m/s.

Groundwater levels varied across the Site from 11 mBGL to 13 mBGL and groundwater flow is directed to the west.
Figure 1  Site Plan.

Nature and Extent of Hydrocarbons

Liquid phase hydrocarbons (LPHs) resembling naphtha have been identified in monitoring wells located onsite and offsite. Naphtha is a class of colorless, volatile, flammable liquid hydrocarbon mixtures. Analysis of the LPH indicated the presence of detectable naphthalene and methylnaphthalene. The apparent LPH thicknesses measured in 13 monitoring wells varied from 0.005 m to 1.8 m. The total volume of hydrocarbon was originally estimated to be approximately 55,000 L and an estimated 2,800 L of recoverable LPH prior to any remedial activities.

Groundwater samples exhibited levels of benzene, toluene, ethylbenzene, and xylene (BTEX) below provincial water guidelines. Total petroleum hydrocarbons (TPH) levels in the C₆ to C₁₂ range were measured at trace concentrations to 12 mg/L.
Residual phase hydrocarbons in the C₅ to C₁₀ carbon range were encountered in soil samples collected during the drilling programs conducted between 1997 and 1999. Soil samples collected in the area of the former UST location at depths between 4 mBGL and 12 mBGL exhibited BTEX and TPH levels greater than the provincial guidelines. The soil vapour concentration readings (SVCRs) measured in the hydrocarbon impacted area exceeded 10,000 ppm. Soil samples in un-impacted areas had SVCR levels below 250 ppm which are considered background levels.

Elevated standpipe combustible vapour concentrations (SCVCs) greater than 10,000 ppm were measured in the casings of several monitoring wells in the immediate area of the known plume. Wells completed along the lateral edges of the plume exhibited elevated SCVCs in the range of 50 ppm to 2,500 ppm.

**Past Site Remediation**

TransGas had initially implemented a manual bailing program to collect LPH from groundwater monitoring wells at the Site. During the period from December 1998 to the end of 1999, approximately 2,300 L of naphtha had been recovered by bailing. A pilot scale DPVE remediation program was initiated at the Site in the spring of 2000, and by the end of October a total of 7,800 L of naphtha had been recovered form the subsurface. The initial pilot scale results made way for the implementation and commissioning of a full scale remedial DPVE system in 2001.

**Remediation Equipment**

The DPVE system and remedial equipment utilized at the Site was fabricated, supplied and installed by Ground Effects Environmental Services Inc. (GEE). The components of the DPVE system consisted of a Class 1, Division 1 main building and a 66,000 L (400 barrel) aboveground storage tank (AST).

The main building contained the DPVE system which consisted of a rotary tri-lobe positive displacement pump (vacuum pump), a 50 Hp electric motor powering the vacuum pump, two 1,500 L (390 gallon) oil/water separator (OWS) vessels and a mono progressive cavity effluent transfer pump. The OWS vessels separate air, water and contaminants through the utilization of stripping trays (integral air stripper) and coalescing packs. An LPH skimmer could also be added to the system, however, was not necessary for the current operation due to the high volatility of the contaminants present in the subsurface. The power for the DPVE system was supplied through a 200 volt, 100 amp above ground service, shown on Figure 1.

**Recovery Network**

Several existing 51 mm (2 inch) and 102 mm (4 inch) monitoring wells exhibiting LPH were converted to DPVE recovery wells. The DPVE recovery wells were fitted with a well seal cap, two valves, a vacuum gauge and a 25 mm (1 inch) PVC drop pipe. A typical well head construction detail diagram is presented in Figure 2.
The DPVE recovery wells were connected to the DPVE system by a temporary 102 mm diameter above ground header pipe network constructed of schedule 40 PVC pipe. The location of the DPVE system equipment and above ground header pipe is presented in the Site plan as shown in Figure 1.

Pneumatic Fracturing Pilot Study

The pneumatic fracturing pilot study involved the installation of two 12.2 m (40 feet) length, 25 mm schedule 80 threaded black iron pipe injection wells perforated between 7 mBGL and 12 mBGL. The fracturing wells were connected to a diesel powered compressor with a rated output of 760 kpa (110 psi) and 5.25 m$^3$/sec (185 cfm) via an electric valve assembly. The valve assembly was programmed to pulse the air injection flow between the two injection wells on 15 second intervals. The pulsed injection process provides an increased effect of the pneumatic fracturing process as the amount of preferential flow channels are significantly reduced comparatively to applying a constant pressure air stream to the fractured zone.

Operation and Maintenance Program

The operation and maintenance requirements for the DPVE system were developed by GEE and Stantec in consultation with TransGas. The general operation and maintenance for the DPVE system was primarily completed by TransGas personnel as part of regularly scheduled site visits. During each site visit a regular list of tasks were completed pursuant to the GEE Operation and Maintenance Manual. Stantec provided technical support throughout the operation and conducted monthly Site inspections during which time recovery wells were pulsed to optimize the subsurface hydrocarbon recovery.
Performance Monitoring Program

A performance monitoring program was conducted by Stantec, which included the measurement of fluid levels and pneumatic conditions, the estimation of hydrocarbon removal rates, measurement of formation airflow and analysis of the groundwater treatment system efficiency.

Groundwater level and apparent LPH thicknesses were measured at each of the monitoring wells in the surrounding area around the Site. Additional monitoring wells located outside the radius of influence of the DPVE system were also monitored to evaluate the natural changes in groundwater elevation due to seasonal fluctuations. The changes at the regional monitoring wells were compared to the monitoring wells within the influence of the DPVE system to assess the actual drawdown and establish the hydraulic radius of influence for the DPVE system.

The vacuum at monitoring wells and the operating DPVE recovery wells were measured with a slip cap vacuum gauge in order to assess the pneumatic response induced by the DPVE system. Combustible vapour concentration readings, gaseous oxygen (O₂) and gaseous carbon dioxide (CO₂) were also measured at surrounding monitoring wells to assess the pneumatic communication with the recovery wells.

The exhaust vapours from the DPVE system were vented through a 152 mm (6 inch) diameter exhaust pipe. A Pitot tube was inserted into the exhaust pipe to measure airflow rate. The exhaust vapour was monitored for: air pressure differential, air temperature, combustible vapour concentration, O₂ and CO₂. The standard airflow rate was calculated from the exhaust air pressure differential across the Pitot tube for the corresponding exhaust air temperature. The hydrocarbon removal rate in the vapour phase was determined by multiplying the exhaust air TPH concentration expressed as hexane by the standard exhaust airflow rate.

The reduced O₂ concentration from atmospheric background can be related to the consumption of hydrocarbons in the biodegradation phase. The degradation rate was calculated through the stoichiometric relationship of hexane biodegradation. The hydrocarbon removal rate in the biodegradation phase was calculated by multiplying the degradation rate by the airflow rate.

Emulsified LPH partitions from the water within the OWS vessel and manually drains to a storage tank. The volume of LPH was calculated using the measured depths and the dimensions of the LPH storage tank.

Water samples collected from downstream of the effluent transfer pump were analyzed for TPH concentration. The cumulative effluent water volume was calculated based on periodic water level measurements from the storage tank. The storage tank groundwater volume multiplied by the dissolved hydrocarbon concentrations established the dissolved phase hydrocarbon removal rate.
The total hydrocarbon recovery was calculated from the summation of the vapour, biodegradation, liquid and dissolved hydrocarbon phases described above.

Formation airflow curves were performed on the DPVE system while operating the DPVE system under three different scenarios, which included operating the system recovering from one recovery well, two recovery wells, and three recovery wells. Air flow and air temperature were measured with a Pitot tube at the 152 mm exhaust, 152 mm air intake, 102 mm air bleed and at 51 mm primer at the operating recovery wells. During each of the three operating scenarios air flow and air temperature changes were recorded throughout the system as the vacuum was adjusted. The vacuum was adjusted by opening or closing the 102 mm air bleed. Ambient temperature was also recorded during each change in vacuum.

To evaluate the effectiveness of the remediation system in removing LPH and dissolved phase hydrocarbons, water samples were collected at three sampling tap locations. The water sampling locations included the influent extracted from the operating recovery wells prior to entering the groundwater treatment system, the groundwater effluent discharged from the groundwater treatment system prior to reaching the AST and the treated groundwater contained within the AST after possible further biodegradation as a result of prolonged retention time. The sample locations were selected to establish the dissolved phase hydrocarbons upstream of the DPVE unit, downstream of the DPVE unit, and following retention time in the AST.

**Results and Analysis**

The DPVE system operated throughout the summer months at a frequency of 99% of the time, the shutdowns throughout the season were solely related to scheduled maintenance programs. The system was operated at an average inlet vacuum of 35 kPa (10 inches of Hg) and an exhaust back pressure of 1.5 kPa (0.2 psi) throughout the operational season.

Monitoring of groundwater levels and apparent LPH thickness in the vicinity of the DPVE system and regional monitoring wells outside the influence of the DPVE system were conducted on a regular basis. The ongoing monitoring was conducted to assess the hydraulic radius of influence of the DPVE recovery system. The DPVE system was operated on several recovery wells throughout the 2001 operating season, as such, analysis on individual recovery wells was not possible due to the overlapping effects of the simultaneously operating recovery wells. Therefore, system performance was analyzed in terms of the overall system. The analysis suggested that the DPVE system displayed a hydraulic radius of influence of approximately 30 m from the closest operating recovery well.

Formation vacuum was measured in monitoring wells during normal DPVE operation. A vacuum distribution develops in the area of the recovery well during the process of recovering fluids and formation air with a DPVE system. The data suggested that the operating recovery wells were influencing an area within a radius of approximately 10 m of the operating DPVE recovery wells.
The estimated total hydrocarbon recovery for the 2001 operating season was 7,600 L, or an equivalent of 2.3 L/hr. As stated in previous sections, essentially all of the total hydrocarbon recovery volume was recovered in the vapour phase. The total hydrocarbon recovery was recovered in the following fractions: 7,580 L in the vapour phase (99.7%), 20 L in the biodegradation phase (0.3%), 0 L in the liquid phase (0%) and 0 L in the dissolved phase (0%). The total hydrocarbon recovery versus elapsed time is shown in Figure 3.

![Figure 3](image)

**Figure 3  Total Hydrocarbon Removal versus Elapsed Time.**

An operational analysis was conducted on the DPVE system in efforts to develop system flow curves for the actual system operating in DPVE priming mode. The DPVE system curve demonstrates that as the applied vacuum increased, the flow from the formation also gradually increased. Formation airflow rates in the order of 250 standard cubic feet per minute (scfm) were measured. The continual gradual increase in the formation flow rate was a result of the low fluid recovery rates experienced by the operating system. The system was responding similar to a vapour extraction system as minimal amounts of groundwater were recovered. The resulting optimal operating vacuum would be as high as possible to maximize the recovery from the formation, since minimal groundwater was being recovered.

The effectiveness of the groundwater treatment system can be determined by the comparison of the BTEX and TPH analytical results for water samples collected at each phase of the GTS system. The TPH concentrations at the various sampling locations within the GTS system for each of the sampling events are also graphically presented in Figure 4. The TPH concentrations were effectively reduced from as high as 100 mg/L to below 10 mg/L. The graph also shows that the majority of the reduction occurred in the inlet separator.
Based on the laboratory results for 2001, TPH concentrations have been effectively reduced by the GTS system with the highest concentration of effluent sampled from the retention tank reaching 6.3 mg/L and as low as below the detection limits.

Throughout the operation of the DPVE system during the 2001 operating season a total of 110,700 L of groundwater was recovered as shown in Figure 5. The recovered groundwater was collected and processed through the GTS system and initially stored onsite in the AST. The effluent from the AST was hauled to a landfarm treatment area for hydrocarbon impacted soils operated at a nearby TransGas facility where it was used as irrigation water.

**Figure 4** Total Petroleum Hydrocarbon Concentration versus Treatment Process.

**Figure 5** Groundwater Recovery Rate versus Elapsed Time.
Performance monitoring results collected during the pneumatic fracturing pilot study indicated a relatively rapid response in the DPVE system as the exhaust vapour concentration increased from the initial 350 ppm too as high as 5,500 ppm (50% LEL) after two hours. A second indicator that the injected air was either creating fractures or in communication with DPVE recovery wells within the subsurface was the rapid drop in the required injection pressure at both of the injection points. The initial injection pressure required was 90 psi and after 0.5 hours the required injection pressure ranged from 48 psi to 53 psi, however, exceeding the approximate overburden pressure of 29 psi. As well the fluid recovery rates from each of the recovery wells also visually increased during the operation of the air injection system.

The pneumatic fracturing pilot study was operated for a total of 21 hours of elapsed time over a 32 hour period. During that time the air injection pressure stabilized within a pressure range of 44 psi to 48 psi. Similarly the exhaust vapour concentrations from the DPVE system seemed to reach and maintain a vapour concentration between 4,000 ppm to 5,500 ppm (36% LEL to 55% LEL).

The recovery effectiveness of the DPVE significantly increased during the operation of the pneumatic fracturing system as shown by the increase in the exhaust combustible vapour concentration. The increased exhaust combustible vapour concentration relates to an increased vapour phase hydrocarbon recovery rate from as low as 2 L/hr to as high as 55 L/hr, as shown in Figure 3.

During the operation of the pneumatic fracturing pilot study the SCVC level survey conducted in the surrounding monitoring wells indicated elevated levels in the majority of the wells. The results indicated that the air injection was influencing a radius beyond the operating recovery wells 30 m away from the closest air injection point.

The pneumatic fracturing process also had a significant impact on the total fluid recovery rate, which increased from below 5 L/hr to over 30 L/hr during the operation of the pneumatic fracturing pilot study as shown on Figure 5.

A full scale pneumatic fracturing enhancement system was designed for the Site and commissioned in the spring of 2002. The pneumatic fracturing system consists of a 25 horse power compressor rated for 103 actual cubic feet per minute (acfm) at 100 psi, a Nema controller system and a 7 PLC valve assembly mounted within a steel, sound attenuated, skid building. As an addition enhancement to the pneumatic fracturing system an automated nutrient injection system, which allows for the operation of 7 nutrient injection points was also included in the system. The nutrient injection system will provide additional enhancement for the remedial system by increasing the in situ biodegradation of residual subsurface hydrocarbons and will be initiated once the majority of the recoverable hydrocarbons have been recovered from the Site.

Four additional pneumatic fracturing wells were installed in 2002 to effectively provide pneumatic influence throughout the Site. Additionally, in efforts to maximize the recovery operation without causing additional migration of subsurface contaminants,
additional monitoring wells present at the Site were converted to recovery wells and two additional recovery wells were also installed to ensure that each of the injection points were surrounded by recovery wells. The total number of available recovery wells was increased to fifteen. The recovery wells operating at any given time will be rotated to optimize recovery while coordinating the recovery with the operating arms of the pneumatic fracturing system and maintaining optimal system operation.

To maximize the recovery potential and utilize the pneumatic fracturing system to its full potential the extra available ports of the pneumatic fracturing system were connected to the drop tubes on the operating recovery wells and programmed to provide a pneumatic lift cycle. The additional pneumatic lift allowed for the effective simultaneous operation of numerous recovery wells.

The overall effectiveness of the DPVE system enhanced through the simultaneous operation of the pneumatic fracturing system has effectively increased the hydrocarbon recovery rates in the 2002 operational season at a sustainable rate consistent with the pilot study results.

**Summary**

The hydrocarbon recovery rates at the Site through the operation of the stand alone DPVE system were demonstrating a decreasing trend which was approaching diminishing returns. The successful implementation of a two day pneumatic fracturing pilot study as an enhancement technology demonstrated the potential to significantly increase the recovery of subsurface hydrocarbons and therefore reduce the potential timeline for remedial operations at the Site.

The effectiveness of the remedial efforts completed at the Site to date and the predicted recovery rates and remedial timelines for the various operational scenarios are visually depicted in Figure 6. As shown in Figure 6 the successful results of the pneumatic fracturing pilot study indicated that the commissioning of a full scale pneumatic fracturing system as an enhancement to the currently operating DPVE system could reduce the remedial timeline for the Site. The remedial timeline could effectively be reduced to less than one additional operational season as compared to the predicted four to nine operational seasons that may be required through the operation of a stand-alone DPVE system. Through the reduction of remedial timelines the site remediation operational costs can be significantly reduced.

The recovery results from the 2002 operational season were not available at the time of the submission but preliminary analysis indicates that pneumatic fracturing will provide significant and sustainable increases in the hydrocarbon recovery rates over the 2002 operational season.
Figure 6  Past & Predicted Operational

References

Clifton Associates Ltd.  2000 August.  Stage I Dual Phase Vapour Extraction Program Cantuar Field Scrubber Site, Cantuar, Saskatchewan.  Regina, Saskatchewan.
