Quantitative Comparison of the Remediation Efficiency between Conventional SVE and Additional Thermal Well Application

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Abstract

'Cold' soil vapor extraction (SVE) has been used extensively to remove contaminants from soils in the unsaturated zone. Although this technology has proven successful for sandy or gravel soil, as well as for contaminants with low boiling points, its success depends on different potentially limiting processes. Moreover, limited volatility of the contaminant will cause extended remediation times. For contaminated soils of low permeability, a thermal technique which works independent from the injection of a heat transfer fluid can work efficiently. Thermal wells combine the mechanism of conductive and convective heat transfers and promise successful soil remediation at high temperatures.

To quantify and compare the remediation efficiency of 'cold' SVE and thermal wells at technical scale, a large-scale container with a base of 6 m x 6 m and a height of 4.5 m was used. A fine grain layer (permeability, 1 x 10^{-5} m/s) was surrounded by a coarse grain layer (permeability 100 times higher). As a contaminant source, 30kg of Trimethylbenzene (TMB boiling point, 169°C) was infiltrated within the fine grain layer. After infiltration, a 'cold' SVE was operated for 2 months, while the vapor was extracted only by SVE wells within the coarse sand. Soil vapor fluxes and pollutant extraction rates were measured continuously. From the obtained data, the remediation efficiency of the standard technology for the given conditions could be estimated.

To enhance the remediation process, heating with four thermal wells operating on temperatures of up to 500˚C was applied. Energy input was focused within the layer of low permeability. The monitoring of the temperature distribution and water saturation allowed an interpretation of the heat transfer and drying processes during the experiment. About 300 temperature sensors and 35 specially developed heat and contaminant resistant Time-Domain Reflectometry (TDR) sensors were installed within the subsurface and connected with an automatically data logger system.

From the experimental data, it can be shown that the application of thermal wells is energy and time saving. Even by overestimating the remediation efficiency of the 'cold' SVE, further operation for 8 months would have been necessary for a complete cleanup. By starting the operation of the thermal wells, the contaminant recovery rate increased significantly during the first 7 days and reached a value more than 10 times higher in comparison with 'cold' SVE. After 20 days of heating, a contaminant mass recovery in gaseous phase of almost 100% of the initially injected contaminant was achieved. At this stage the temperature did not exceed 100°C within the former high-contaminated volume. Continued heating led to a temperature increase higher than the boiling point of TMB, indicating complete vaporization of infiltrated contaminant within the central area.

The economical and ecological benefits of thermal wells in comparison with the 'cold' SVE in this large-scale experiment were: the remediation time could be reduced by a factor of 10 (20 days instead of minimum 8 month), and, surprisingly, the total energy consumption of the thermal well operation (incl. SVE compressor) was less than 25% of the 'cold' SVE.

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Introduction

'Cold' soil vapor extraction (SVE) is operating on 'natural' subsurface temperatures of about 10°C and has been used extensively to remove contaminants from soil in the unsaturated zone. Although this technology has proven successful for the removal of volatile contaminants at many field sites worldwide, its application is restricted to sandy or gravely soils. To overcome these limitations, various thermally enhanced techniques, e.g., steam injection, have been successfully applied at field sites [THEURER ET AL. 2000, HERON ET AL. 2002]. The ecological benefit of steam injection, compared to 'cold' SVE, has also been quantified [HIESTER ET AL. 2003a]. Although steam injection is limited by low soil permeability, thermal wells promise to work efficiently in such soils (Figure 1).

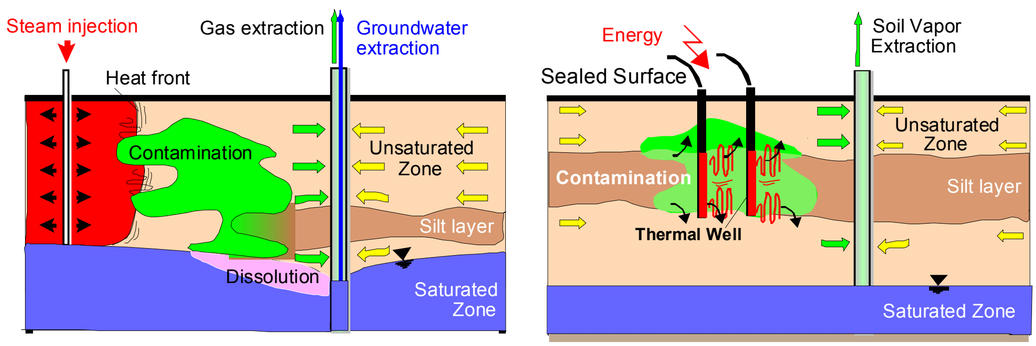

FIGURE 1: Principle of steam injection (left) and thermal wells (right).

The aim of this project was to develop and optimize a thermal in-situ remediation scheme, THERIS, using thermal wells [HIESTER ET AL. 2003b], and to quantify its benefit compared to the conventional 'cold' SVE. A thermal well consists of one or more heating elements (HE), which are electrically powered and can be operated at temperatures of several hundred degrees Celsius. To avoid difficulties such as heat loss and boundary limitations of laboratory-scale experiments, the remediation efficiency of thermal wells should be quantified at a large scale. To evaluate the level of enhancement, the efficiency of the conventional 'cold' SVE was determined under the same conditions.

Experimental Setup

A large-scale *VEGAS* stainless steel container with a base of 6 m x 6 m and a height of 4.5 m was used to install the experimental set-up with a square of thermal wells in the center. With the given dimensions, energy losses across the container boundaries were almost negligible. To simulate the mass flow and heat transport processes in different soils, a three-layered system with a central fine grain layer of 1 m thickness was implemented in the centre of the container, surrounded by coarse sand material (Figure 2). The permeability of the fine grain layer was 100 times less than the surrounding coarse sand. The operation of the thermal wells and SVE was optimized in a former heat transport experiment [HIESTER ET AL. 2003b].
For the remediation experiment, 30 kg of Trimethylbenzene (TMB) (with a boiling point of 169°C) was infiltrated into the fine grain layer. This served as the controlled contamination source. In the container, more than 300 temperature sensors and 35 specially developed heat and contaminant resistant Time-Domain Reflectometry (TDR) sensors enabled the observation of characteristic parameters in the subsurface.

To characterize the remediation process, the experiment was divided into two periods. First, a two month period of 'cold' SVE operated with 'natural laboratory temperatures' of about 20°C. From this, the remediation efficiency of the 'cold' SVE on a large scale could be quantified. Afterwards, the thermal wells were switched on. This period of THERIS enhanced SVE lasted three weeks and resulted in complete contaminant removal.

‘Cold’ SVE started three days after the TMB-infiltration, which allowed an initial ‘spreading’ of the contaminant. Soil vapor was extracted only by wells located in the coarse sand above and below the fine grain layer (Figure 2). TMB-concentrations in the extracted soil vapor were continuously measured with gas chromatography. After two months, no significant change in extracted TMB concentrations was detected. The situation for the ‘cold’ SVE could be interpreted as quasi-stationary.

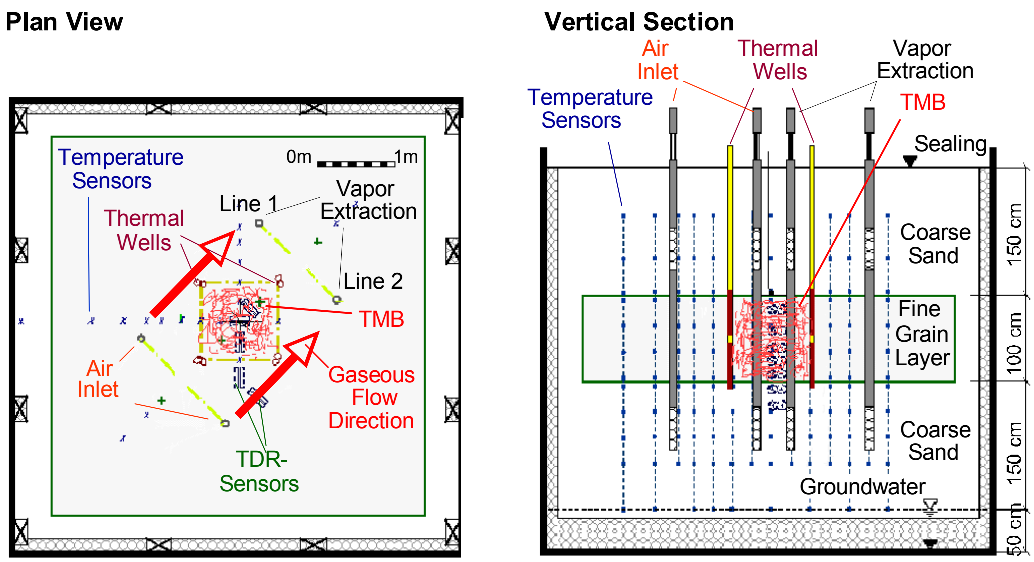

FIGURE 2: Plan view and vertical section of the *VEGAS* large-scale container.

In the ‘THERIS-phase’, the remediation process was enhanced by operating four thermal wells at temperatures up to 500˚C. Each thermal well consisted of two heating elements of 0.5 m length located one above the other in the central fine grain layer of low permeability (Figure 2). Temperature distribution and water saturation were monitored during the experiment, and the heat transfer and drying processes could therefore be interpreted. The TMB extraction rate increased significantly and was completed after only 20 days of heating.

Experimental Results

During the two months of ‘cold’ SVE, the extracted TMB-concentrations remained between 0.1– 0.2 g/m^3 soil vapor, at an average rate of 35 m^3 extracted soil vapor per hour (Figure 3d). The ‘natural laboratory temperature’ was about 20°C (Figure 3b). In total, 6.4 kg of TMB-contaminant was removed (Figure 3e).

By applying a linear extrapolation of the extraction rate (Figure 3e), it was predicted that a minimum of eight months would have been required for the removal of the remaining TMB. This extrapolation, however, neglects the usual tailing of the remediation process, and thus overestimates the efficiency of the ‘cold’ SVE.

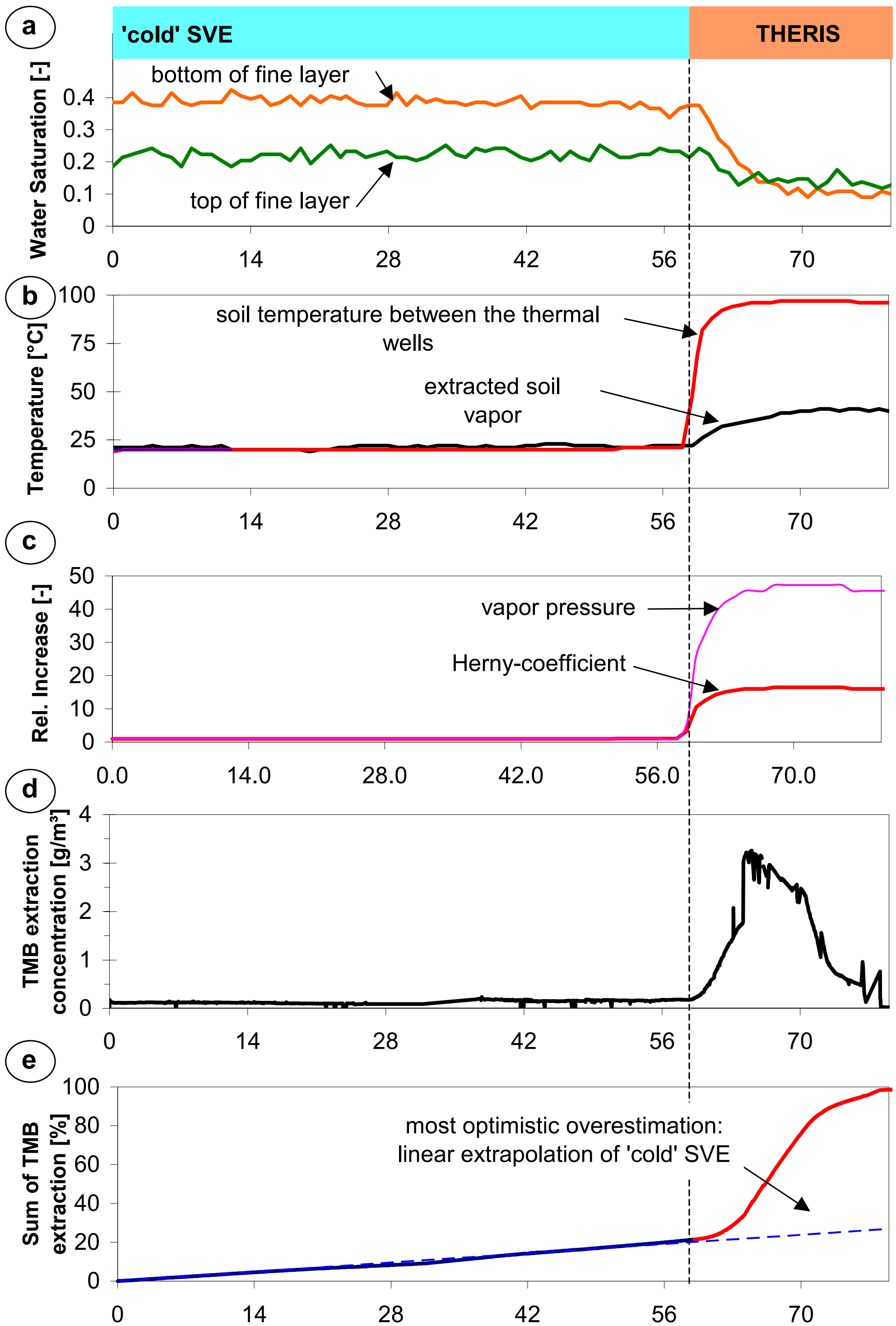

FIGURE 3: Development over time of: a) water saturation, b) temperatures, c) relative increase of vapor transfer processes, d) TMB extraction concentration, e) sum curve of extracted TMB

After starting the thermal well operation, the temperatures in the central cube between the thermal wells rose more than 90°C in one week, but did not exceed 100°C (Figure 3b). This accelerated the transfer of TMB from liquid to gaseous phase. Calculated for the central cube, the Henry-coefficient rose by a factor of more than 10, the vapor pressure of more than 40 compared to the initial temperature of 20°C (Figure 3c).

In addition, the initial water saturation decreased significantly, especially at the bottom boundary of the low permeable layer (Figure 3a). This effected a significant growth for the permeability of the gaseous phase, as known from relative permeability-saturation-relationship.

During the first seven days of thermal well operation for the THERIS method, TMB concentrations in the extracted soil vapor increased by a factor of ten (Figure 3c). The high water saturation in the central soil layer accelerated the remediation process: NAPL and water were vaporized simultaneously by the process of steam distillation.

After the ‘cold’ SVE, the remaining 23.6 kg of TMB were extracted over 20 days of THERIS-operation (as opposed to the eight months estimated using the conventional SVE).

All four SVE-wells (two in the top layer and two in the bottom layer of the coarse sand) extracted the same soil vapor flux, with about one quarter of the total flux per well. After applying heat with the thermal wells, the fluxes remained nearly the same. A similar behavior could be seen for the TMB removal. It could be determined that the thermal well operation accelerated the mass removal, but did not change the principle extraction paths.

Spartial Temperature Development

To understand the spatial temperature development, a diagonal section across the container (Figure 2 plan view: from down left to top right) in the middle of the low permeability layer is shown in Figure 4. It can be seen that the subsurface temperatures rose over a large area.

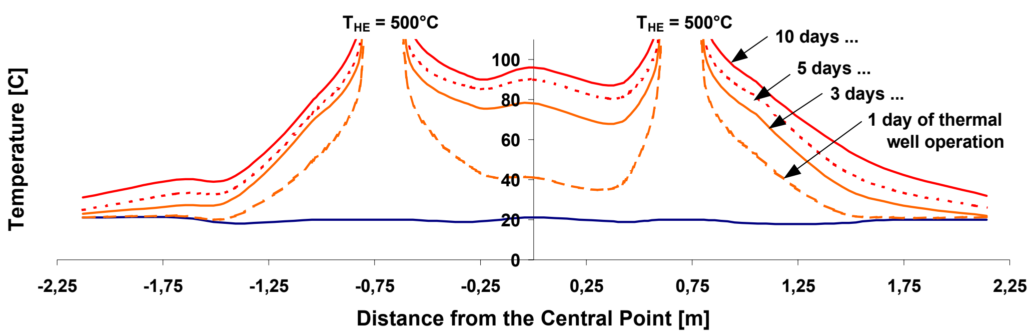

FIGURE 4: Temporal subsurface temperature development in the diagonal section of the container in the middle of the layer of low permeability.

The four heating elements effected higher temperatures in the central area (between –0.75m and +0.75m). Temperatures at the boundaries were lower, yet still exhibited significant temperature increases up to a distance of 0.5m from the thermal wells (position –1.25. and 1.25). One of the reasons is a circulating water-steam flow, so called Heatpipe [UDELL & FITCH 1985]. The area of significant temperature increase has a diameter larger than 2.5m.

Comparison of Energy Consumption and Remediation Time

The SVE system was driven by a 3kW compressor, though a more economical compressor of only 1.5kW would have been sufficient. The following calculations are all made by estimating a ‘virtual’ 1.5kW compressor in order to remove the disadvantage due to the less efficient compressor. This leads to an overestimation of the efficiency of the SVE system.

The total power required for all of the thermal wells during the remediation period was approximately 3kW. The required power for the SVE compressor was calculated for this period as well by 1.5kW.
The experiment resulted in 6.4kg TMB being removed by the 'cold' SVE system within two months. This leads to an energy demand of about 1200 MJ per extracted kg TMB (Figure 5a). In contrast, THERIS removed 23,4kg of TMB in 20 days. The energy demand, including the energy required for the heating elements, was nearly one quarter of that for the 'cold' SVE.

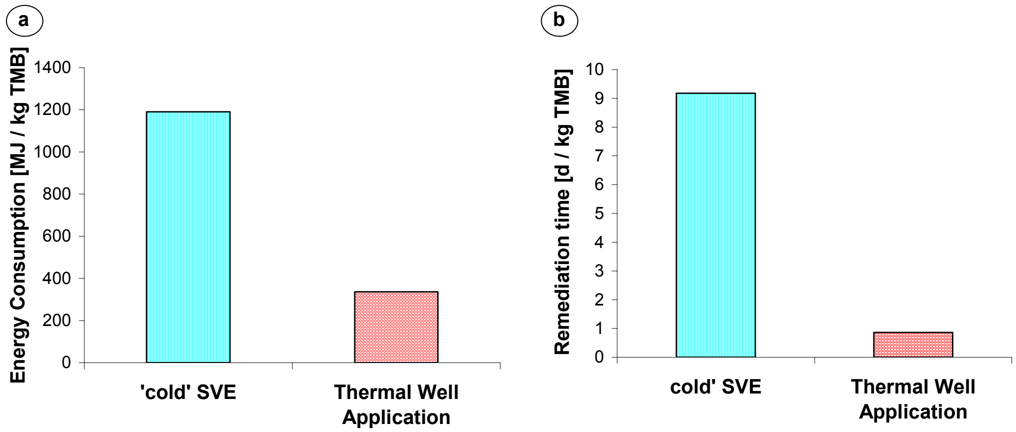

FIGURE 5: Comparison between 'cold' SVE and SVE with additional thermal well application: a) Energy Consumption per kg TMB-extraction, b) remediation time per kg TMB Extraction.

The predicted remediation efficiency for the removal of the remaining 23.6 kg TMB with the 'cold' SVE was overestimated through the linear extrapolation. This resulted in an underestimated remediation time estimate of eight additional months for the 'cold' SVE. At least, a further 8.8MWh would have been necessary with this method. The THERIS method, on the other hand, consumed only 2.2MWh within 20 days.

The remediation time, calculated in plant operation days per kg removed contaminant, could be reduced by applying thermal wells by more than a factor of ten (Figure 5b). The same factor results from predicting the remediation time of the 'cold' SVE for the removal of the remaining 23.6kg TMB by a linear extrapolation. A replacement of the most optimistic linear extrapolation by a more realistic extraction function including a decrease of the contaminant concentration in the extracted soil vapor results for the remediation time higher differences than a factors of 10.

The 'cold' SVE with longer operation times has also a disadvantage in regards to energy demand. This experimental investigation emphasized the time- and energy-saving aspect of thermal treatment, as has already been demonstrated from life cycle assessments for steam-air-injections [HIESTER ET AL. 2003a].

Conclusions

This study successfully demonstrated that the use of thermal wells as a thermally enhanced remediation technique led to an efficient removal of the contaminant Trimethylbenzene (TMB) (boiling point 169˚C) from a soil layer of low permeability in the unsaturated zone. In detail, the following can be concluded:

- The contaminant concentrations in the extracted soil vapor during the thermal well operation were ten times higher compared to the former 'cold' soil vapor extraction. The remediation time was decreased by at least a factor of ten.
  The 'contaminant and site specific' remediation time for the 'cold' SVE was more than 9 days per kg TMB. The THERIS method needed less than 21 hours per kg TMB.
- The contaminant removal was completed by achieving an average temperature within the center zone of about 100˚C. The application of thermal wells resulted in energy savings of up to 75% compared to the 'cold' soil vapor extraction technique, proving that the application of thermal methods does not necessarily result in higher energy costs. Thermal wells can even be considered an 'energy saving' remediation technology.
- The radius of influence of the thermal wells was not limited to the central area, though this was the area of highest efficiency. The increase of vapor pressure, Henry-coefficient and gaseous permeability ensured a quick remediation.

Acknowledgements

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