

EXECUTIVE SUMMARY

A. OBJECTIVE

Steam injection, combined with soil vapor extraction, was demonstrated in situ at Operable Unit One (OU-1), Hill Air Force Base (Hill AFB), Utah. The purpose of this research was to evaluate steam injection technology for the removal of non-aqueous-phase liquid (NAPL) contamination from the subsurface. This experiment was part of a cooperative research effort funded by the United States Environmental Protection Agency (USEPA) and the Strategic Environmental Research and Development Program (SERDP). The results of this research were used to evaluate eight innovative remediation technologies for the removal of NAPL and to evaluate these technologies for their potential inclusion in the Record of Decision (ROD) for the OU-1 site. Applied Research Associates, Inc. (ARA) and Praxis Environmental Technologies, Inc. demonstrated the utility of steam injection combined with soil vapor extraction as a remediation technique. In addition, the experiment included the use of a partitioning tracer test, which was employed to estimate the quantity and distribution of the NAPL prior to and immediately following the steam treatment.

B. BACKGROUND

Subsurface contamination by NAPLs, such as hydrocarbon fuels and halogenated organic solvents, is a serious environmental problem facing the Department of Defense and industry in general. Once the NAPLs migrate into the subsurface environment, significant quantities of the liquid become trapped in the soil by capillary forces, providing a continuous source of groundwater contamination. Complete removal of these contaminants by conventional technologies is difficult, time-consuming and expensive. Historically, technologies such as pump-and-treat and soil vapor extraction have been used with moderate success, but in general, they are inefficient and costly technologies to achieve the desired clean-up goals. Recent studies have demonstrated the utility of using steam injection and subsequent vacuum extraction of steam to remove NAPL contamination from in situ soils.¹

The use of steam injection to remediate NAPLs and saturated zone contamination is an innovative application of a recently developed remedial technology. Many of the technology principles have been tested extensively in analogous field applications (e.g., enhanced oil recovery). However, steam injection has been applied only recently to the remediation of shallow subsurface contamination where required recovery rates are much higher. Most of this recent experience applies to soil above the water table and these efforts were not instrumented adequately for understanding the process. Hence, this project will be a carefully monitored and documented effort to advance the understanding and the state of design of steam injection.

C. SCOPE

This document presents and analyzes the findings of the steam injection/vapor extraction treatability experiment conducted at the OU-1 site located at Hill AFB, Ogden, Utah. Section I is

¹ Stewart and Udell, 1987, and Olsen et al., 1991.

an introduction to the technology and includes a brief literature review, description of the site, and the project objectives. Section II presents an overview of the methodology followed during the course of the study and includes descriptions of the test cell construction, leak testing, and pre- and posttreatment cell characterization. It also includes a conceptualized narrative of the steam injection/vapor extraction system. Section III includes detailed descriptions of the processes and procedure followed during the test execution for all phases of the experiment. This section includes discussions about both the fluorescein dye and the partitioning interwell tracer tests, the steam injection process equipment and finally, the implementation of the steam injection experimental phase's. The results of the experimentation are presented in Section IV and finally the conclusions and recommendations are presented in sections V and VI, respectively.

D. METHODOLOGY

To achieve the goals of this experimental research, the project was divided into two phases. Phase I consisted of the cooperative development of a workplan by all of the individual research groups, the EPA, and Hill Air Force Base. It also involved some preliminary bench scale testing by the researchers to aid in the experimental design. Preliminary field investigations were also conducted during Phase I to collect site characterization data to assist with cell placement. Finally, Phase I included the installation of the eight individual experimental cells.

Phase II consisted of several subtasks. First, an extensive characterization effort was conducted for each of the individual cells. This characterization included the collection and logging of soil samples, and subsequent chemical analysis of these samples. These data provided an estimate of the pretreatment NAPL saturation and distribution, and served as a baseline to compare to the posttreatment results. Coinciding with the cell characterization activities, was the installation of the multilevel sampling points, steam injection/extraction wells, and piezometers.

Once cell construction activities were completed, a partitioning interwell tracer test (PITT) was conducted as an additional method to estimate the saturation and distribution of the NAPL within the cell prior to steam treatment. Groundwater samples were collected before and after the PITT to determine the static and dynamic equilibrium concentrations of the target analytes in the groundwater.

Following the characterization efforts, the steam treatment activities commenced, consisting of five individual stages: (1) dewatering the cell, (2) pre-steam-injection soil vapor extraction, (3) steam injection, (4) post-steam-injection soil vapor extraction, and (5) reflooding the cell and cooling.

Once the cell cooled to the pretreatment in situ temperature, a posttreatment PITT was conducted to estimate the residual saturation of the NAPL within the cell. These data were used as a secondary method to estimate the efficiency of NAPL removal from the cell. As with the pretreatment PITT, groundwater samples were collected under dynamic (prior to the PITT) and static (after the PITT) conditions.

Finally, the posttreatment characterization was conducted to collect soil samples for chemical analysis and to further define the lithology of the cell. All of the data associated with this experiment is presented in this report with the exception of postdemonstration PITT analysis. This analysis was conducted by others and was not complete as of this date.

E. TEST DESCRIPTION

1. Partitioning Interwell Tracer Test (PITT)

The PITT test consists of the simultaneous injection of a slug of dilute concentrations of both partitioning and non-partitioning tracers into the test cell under constant flow conditions. The tracer solution is subsequently sampled through the MLS sampling grid and extraction wells. The non-partitioning tracers flow through the cell unimpeded by the NAPL, behaving much like a particle of water. The partitioning tracers interact with the NAPL, moving in and out of the NAPL solution at a rate proportional to the NAPL/tracer partitioning coefficient. The net result of this interaction is that the partitioning tracers are retarded with respect to the non-partitioning tracers. By plotting concentration breakthrough curves for each tracer and comparing the first moments (mean residence time) of each, an estimate of the magnitude and distribution of NAPL can be determined.

2. Steam Injection / Vapor Extraction Treatment

The steam injection/vapor extraction test consisted of injecting steam into vertical injection wells placed within the region of contamination and subsequent removal from the extraction wells placed within and around this region. First, relatively high pressure gradients develop in the steam zone due to the high vapor velocities. These pressure gradients force the effective displacement of original water and contaminant in place. Liquids that are "pushed" into the well are removed via pumps until steam breakthrough occurs. Application of a vacuum to the recovery wells during the injection of the steam aids in directing flow of steam toward the extraction wells through the vadose zone, and contaminant recovery is identical to that of soil vapor extraction technology until steam breakthrough. After breakthrough, the steam vapor behaves like air during soil venting, only now the soil is at an elevated temperature. The vapor pressures of typical organic compounds increase by factors from 25 to 40 over those at ambient soil temperatures. This greatly accelerates evaporation rates and reduces remediation duration.

F. RESULTS

Based on visual descriptions of the soil corings collected during the pre- and posttreatment characterization activities, a detailed three-dimensional model of the soil stratigraphy was developed. The model shows clearly that there are four distinct stratigraphic sections within the cell consisting of three interbedded soil types; (1) poorly graded sands, (2) well-graded gravelly sand mix, and (3) clay. Chemical analyses of the soil core samples show elevated concentrations of all of the target analytes within the cell with the highest levels located at about (18-20 feet) below grade. This coincided with the lithologic section with the highest hydraulic conductivity.

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Data analysis of the pre-steam injection PITT using the method of moments technique indicates an average NAPL saturation of about 5 percent and an estimated 469 liters (124 ± ? gallons) of NAPL in the saturated zone of the test cell. The results from the method of inverse modeling support the results obtained using the method of first temporal moment analysis. Both methods indicate that the average NAPL saturation in the test cell is approximately 5 percent. However, due to a slightly different cell geometry assumed for the method of inverse modeling, the volume of NAPL estimated was 394 liters (104 gallons).

Based on the results of the pre- and posttreatment groundwater chemical analyses, the average percent recoveries of the target analytes ranged from 88 percent removal (1,1,1-trichloroethane) to 28 percent removal (TCE). Concentrations of several of the less volatile compounds increased significantly (88 percent increase for 1,2-dichlorobenzene). This result occurred because of changes in the NAPL makeup. As the more volatile compounds are stripped out, the less volatile compounds, such as 1,2-DCB are left at a higher mole fraction. The higher mole fraction then yields a higher equilibrium groundwater concentration despite significant removal of the compound. Yet, only two of 15 target compounds (TCE and 1,2-DCB) were above drinking water standards at the end of the test.

The mass of target compounds removed during the pre-steam SVE, steam injection and poststeam SVE tests was estimated from the measured extraction rate and the measured concentrations. These results are summarized below:

Phase	Extracted Volume of Air (m ³)	Extraction Period (hours)	Average Total Target Compound Concentration (mg/m ³)	Total Mass Removed (kilograms)
Pre-Steam SVE	2030	47	445	0.9
Steam Injection	3194	100	1900	6.0
Post-Steam SVE	24,260	356	106	2.6

Analysis of the posttreatment PITT results is being conducted by others and is currently not available. This analysis, along with a discussion comparing the results to the chemical analytical results of the soil cores, will be included as an addendum to this document upon receipt.

G. CONCLUSIONS

$$\frac{124}{2460} = \frac{.0504}{1} = \frac{V_n}{V_s} ; \begin{matrix} V_n = \text{Vol of NAPL} \\ V_s = \text{tracer-swept Volume} \end{matrix}$$

The total NAPL volume estimated from the method of first moment analysis was determined to be approximately 469 liters (124 gallons). This value was obtained by tracer data extrapolation up to 16 days. It represents the NAPL volume in the saturated zone of the entire test cell, which corresponds to an estimated tracer-swept volume of 9.3 m³. Because of the irregularly shaped boundary of the test cell, the simulation grid for the inverse modeling technique only represents the rectangular portion of the test cell between the rows of the injection and extraction wells. The estimated volume of NAPL within this region is 394 liters (104

$$9.3 \text{ m}^3 \times \frac{1000 \text{ L}}{\text{m}^3} \times \frac{9.54}{3.78 \text{ L}} = \underline{\underline{2460 \text{ gallons}}}$$

gallons). Assuming a porosity of 0.28, this contains a pore volume of 8.19 m³. For both scenarios, the ratio of volume of NAPL to volume of pore space is approximately 50 liters/m³. The NAPL is nonuniformly distributed in the test cell ranging from 0 to 10 percent in saturation. The average NAPL saturation is higher in the intermediate layers of the test cell.

The vapor concentrations of the more volatile compounds such as 1,1,1-trichloroethane (1,1,1-TCA) and heptane in the waste stream during the initial ambient soil vapor extraction (SVE) were initially high and exhibited the exponential decay characteristic of long-term SVE. For moderately volatile compounds such as toluene and nonane, the vapor concentrations appeared to decrease slightly during the tests. Concentrations of compounds with relatively low volatility, such as 1,2-dichlorobenzene (1,2-DCB) and undecane, were erratic and did not appear to decrease during the SVE testing.

Careful examination of the results from the SVE and steam injection portions of the remediation indicate disequilibrium of the NAPL (i.e., a nonuniform mixture) that would result from weathering of the NAPL over time or the presence of two distinct NAPL layers. The site usage history indicates two NAPL sources: one NAPL was the result of hydrocarbon usage for fire training, while the other NAPL resulted from chemical disposal pits that included the release of solvents. Approximately 34 kg (75 pounds) of NAPL were removed from the cell through the vapor stream during the course of the experiment. Assuming a unit weight of 0.75 g/cm³ for the NAPL, this equates to about 45.5 liters (12 gallons). An additional 9.5 liters (2.5 gallons) were recovered in the NAPL/water separator.

$$12 + 25 = \frac{14.5}{124} = 11.7\% \text{ NAPL Removal}$$

The final soil and groundwater concentrations in the test cell were significantly reduced from the pre-test concentrations. Estimates of mass removed based on soil concentrations before and after steaming reveal over 90% removal for volatile compounds, 80 to 90% removal for moderately volatile compounds and 70 to 80% for semi-volatile compounds. In addition, soils swept directly by the steam exhibited excellent cleanup and the soils which were not swept showed reductions but not as profound. The steam swept soils were cleaned of the target compounds by over 94% including the semi-volatile compounds. A deeper steam sweep was not possible in this field test because the groundwater pump inlets could not be placed deeper than 6 m. It is expected the same high levels of removal would have been achieved in the lower soils if deeper screen and pump placement had been possible.

A bank of NAPL preceding steam breakthrough was considered possible; yet, only about 9.5 liters (2.5 gallons) of NAPL were recovered in the NAPL/water separator after steam breakthrough. This indicates the steam injection was not effective at driving the residual NAPL out of the cell. This occurred because the viscosity of the NAPL was too high and the saturation too low to allow the formation of a stable NAPL bank ahead of the steam condensation front. Theory predicting the maximum NAPL viscosity which allows a stable NAPL bank to mobilize was developed and suggested the maximum NAPL viscosity allowing stable displacement by steam injection at OU-1 is about 2.5 centipoise (cP). The NAPL at Operable Unit One has a viscosity significantly higher than 2.5 cP.

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Value = ?

H. RECOMMENDATIONS

Based upon the results obtained during the course of this project several recommendations can be made. The results from this study showed steam injection to be very effective in distilling contaminants from the mixed NAPL at OU-1, Hill AFB. Yet, the increase in vapor concentrations of the moderately volatile compounds was not as high as expected based upon the vapor pressures of these compounds at the elevated temperature. Further study is warranted to evaluate the reasons for this lack of increase. In particular, the role which liquid water may play in this process needs more investigation because further understanding could lead to substantial improvements in the technology implementation. Additionally, a substantial bank of NAPL was not pushed ahead of the steam condensation front in this demonstration. Theory was presented suggesting a relatively low limiting viscosity for such a push to occur. This theory requires additional laboratory and field studies for validation because of the potential impact this result could have on how the technology is applied to heavier hydrocarbons. Also, the evaluation of the technology for other contaminants and soil types should be pursued.

Any of these additional studies should also comment on the costs of using steam injection as a remediation technology. For coarse, gravelly soils, such as those at Hill, the injection and extraction wells can be relatively far apart, whereas for fine grained soils, more wells per unit area may be required, driving the cost higher than experienced during this study. These costs need to be considered when performing a complete evaluation of steam injection remediation for a site. In addition, the feasibility of using pushed wells for injection and extraction of the steam should be studied. This well installation procedure has the potential to be faster, cheaper, and more informative without any loss in performance.

A second recommendation is to further enhance and develop the Partitioning Interwell Tracer Test (PITT). Although this test was very useful in determining the pre- and post-contaminant locations and saturation levels, performing the test was relatively expensive and very labor intensive. Additional methods to reduce the costs of performing these tests would greatly assist in increasing the utility of these tests. A new approach would still use partitioning tracers, but rather than collect samples over a 10-day period (over 2,000 samples were collected and analyzed for each PITT test during this demonstration), a monitoring system could be used to monitor the partitioning in-situ. This would require a sensor network to be installed and different tracers to be selected that matched with the sensing technology chosen for the network. One sensing technology that should be investigated is fluorescence techniques. If partitioning fluorescence sensors can be selected, then a network of simple fluorescence probes could be used to monitor the experiment. Since the sample collection rate would not be limited by actual sample collection time, more detailed results can be collected at low additional cost. A Cone Penetrometer fluorescence sensor version can be used to monitor the tracers in an open field condition, under a lower gradient. These approaches effectively reduce costs and allow more flexibility in the tracer flow field.