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Laboratory Studies of Steam Stripping of LNAPL-Contaminated Soils

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ABSTRACT: Bench-scale laboratory experiments were conducted to evaluate the effectiveness of steam injection for *in situ* remediation of soils contaminated by light nonaqueous-phase liquids (LNAPLs). Several parametric studies were performed with various combinations of soils, LNAPLs, and steam injection conditions.

An increase in steam injection pressure produced a significant increase in LNAPL recovery efficiency. An increase in steam injection pressure from 12.4 to 44.8 kPa resulted in increased LNAPL recovery efficiency from 86 to 95% after one pore volume of steam injection. Higher steam injection pressure yielded maximum LNAPL recovery efficiency in significantly less time and required a smaller amount of steam than at low pressure.

An increase in soil grain size or an increase in grain-size-distribution slope resulted in increased LNAPL recovery efficiency. The final LNAPL residual saturation was approximately 0.5% for coarse-grained soils and 1.8% for soils with finer grain sizes. Soils with finer grains required more time for treatment than soils with coarser grains.

Steam injection experiments with No. 2 heating oil and with jet fuel showed no significant variation in steam front propagation, temperature profile, and maximum LNAPL recovery efficiency. The LNAPL residual saturation after steam injection was essentially independent of the starting LNAPL saturation.

KEY WORDS: steam stripping, soil remediation, contaminated soils.

I. INTRODUCTION

During the past few years, several *in situ* remediation technologies have been developed for cleanup of soils contaminated by nonaqueous-phase liquids (NAPLs) consisting of petroleum hydrocarbons and other organic solvents. Contamination occurs as a result of accidental surface spills, intentional dumping at disposal sites, or leakage from underground storage tanks and landfills. Existing remediation techniques include vapor extraction, radio frequency heating, and steam stripping, as well as other biological/chemical/physical methods. Among these various *in situ* technologies, steam injection (steam stripping), which is commonly used for oil recovery, is being investigated as a potential method for remediation of NAPL-contaminated soils. Extensive studies of steam injection have been reported in the oil recovery literature, but applications to soil remediation have been very limited.

Some of the knowledge and techniques developed in petroleum engineering for enhanced oil recovery by steam injection (e.g., Willman *et al.*, 1961) are useful to the problem of steam stripping for remediation of NAPL-contaminated soils. However, there is a distinct difference between these two applications. In enhanced oil recovery, the objective is to remove the maximum amount of oil from the reservoir for as long as it is economically feasible. Small amounts of oil left in the formation are usually ignored. In contrast, the purpose of remediation efforts is to remove as much of the contaminant as possible until cleanup levels are achieved.

The process of steam injection for subsurface remediation involves several complex interacting phenomena at the pore level that are not considered in petroleum reservoir engineering (Hunt *et al.*, 1988a; Falta *et al.*, 1992a). It is characterized by heat and mass transfer in multiphase flow (gas, water, NAPL) in which the mass transfer of components between the phases is significant. Important mechanisms include gaseous-phase mass transfer and contaminant advection in the liquid due to large pressure gradients. These complexities limit the general application of analytical methods to steam injection problems.

Early exploratory experiments with steam injection for soil remediation were carried out in the Netherlands by Hilberts (1985). Hunt *et al.* (1988) performed laboratory experiments to study fundamental aspects and to demonstrate the feasibility of steam injection as an *in situ* remediation technique. They found in some cases that only one pore volume of fluid had to be displaced by steam injection to achieve cleanup standards. Simplified measurements of recovery efficiency of kerosene in one-dimensional experiments of vacuum-assisted steam stripping were conducted by Lord *et al.* (1988), who also performed observations of two-dimensional steam front movement. Their work was later extended to include additional experiments to measure the recovery efficiency of vacuum-assisted steam stripping of several single compound chemicals and of kerosene in soils containing various amounts of silt, clay, and organic material (Lord *et al.*, 1989, 1991).

Several field demonstration projects related to soil remediation by steam stripping were conducted (Baker *et al.*, 1986; Lord *et al.*, 1987; Udell and Stewart, 1989b; and DePercin, 1991). Udell and Stewart (1989b) performed field measurements to identify the dominant mechanisms responsible for displacement and recovery of NAPLs from soils, using combined steam injection and vacuum extraction. In a field demonstration study of steam and hot air injection, under the U. S. Environmental Protection Agency (EPA) Superfund innovative technology evaluation (SITE) program, DePercin (1991) found that more than 85% of the volatile organic compounds were recovered by steam and hot air injection.

In all the studies reported so far, the effects of steam injection conditions and soil type have not been studied systematically. The main objective of the present study was to conduct laboratory experiments of steam injection for various combinations of soils contaminated by light nonaqueous-phase liquids (LNAPLs) to investigate the effects of various parameters on LNAPL recovery efficiency. These parameters include: (1) steam injection pressure, (2) soil-grain-size distribution, and (3) type of LNAPL.

II. APPROACH

Laboratory-scale column experiments were designed to evaluate the mobilization and recovery of LNAPLs by steam flooding. Initial phases of the experimental approach included soil preparation and packing, and evaluation of soil properties.

In the present work, the selected soils were characterized by their grain-size distribution. The tested soil types were poorly graded soils of uniform grain size and well-graded soils in which several grain sizes were mixed to obtain different grain-size distribution slopes.

The soils were sieved into several different grain sizes (U.S. standard sieve sizes). The soil mean grain size is specified by its D_{50}, which is the size corresponding to 50% finer. In Figure 1a, grain-size distributions are shown for four soils having the same grain-size-distribution slope but different mean grain size. The grain-size-distribution slope is defined by the relation

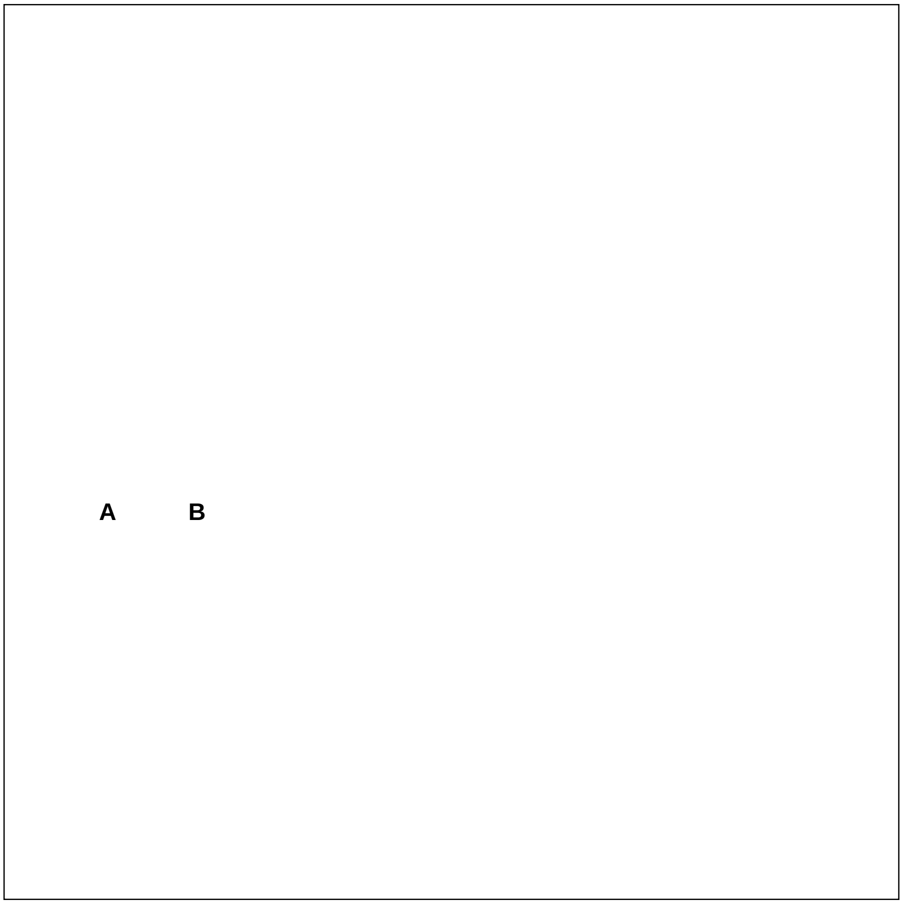
$$S = (F_2 - F_1)/(\log D_2 - \log D_1) \tag{1}$$

where F_1 and F_2 are the percentages finer at two points on the grain-size-distribution curve and D_1 and D_2 are corresponding grain sizes for the same two points. Four soils having different grain-size-distribution slopes but the same mean grain size were selected, as illustrated in Figure 1b.

The soils were packed in the steel column according to ASTM-D558 standard procedure (American Society for Testing and Materials, 1986). The soils were carefully placed into the column to avoid any segregation, density variation, or channeling within the column. At both ends of the column, a layer of gravel was included for better filtration and to ensure uniform axial flow conditions.

The hydraulic conductivity was measured using the falling-head permeameter method (Bear, 1972). The direct method was used to measure the porosity. The volume of the void space (V_v) was determined by volumetric analysis following water flooding, and the bulk volume (V_b) inside the column was calculated from measurements of the cross-sectional area and length of the soil column. The porosity was then determined simply as

$$n = V_v / V_b \tag{2}$$



A

FIGURE 1. Representation of soil-grain-size distribution: (A) soils with different grain size; (B) soils with different grain-size-distribution slope.

Physical properties of the selected soils are listed in Tables 1 and 2.

Steam injection experiments were conducted in an instrumented one-dimensional soil column, as illustrated in Figure 2. The column was 91 cm long and 7.6 cm in diameter and was packed uniformly with a soil of selected grain-size distribution. Two high-accuracy pressure gauges were placed at both ends of the soil layer, and two additional ones were used at the inlet and outlet of the column. Several copper-constantan thermocouples were inserted into the column, spaced at equal intervals, to measure the column centerline temperature. Two additional thermocouples were placed on the column outside wall and within a thick layer of insulation that covered the entire column in order to minimize radial heat losses. The thermocouples were connected to an auto-

FIGURE 1B

matic signal scanner, and the temperature readings were displayed on a digital thermometer. Air-free saturated steam was piped from the steam generator to the core face in insulated lines; steam traps were used to remove any condensate formed in the lines. During steam injection, column effluent was passed through a condenser and was collected in a graduated cylinder in which LNAPL separated from water, allowing separate measurements of LNAPL and water quantities.

The major steps involved in the experiments were as follows. The column was packed with the selected soil sample and was saturated with water. The permeability and porosity of the soil were measured. One pore volume of LNAPL was then injected into the column. Initially, water flooding was conducted to obtain a volumetrically measured LNAPL saturation level. The LNAPL saturation established after waterflooding was fixed at 23% for all the experiments except for the

TABLE 1
Physical Properties of Soils with Uniform Grain Size

U.S. std. sieve no.	Mean grain size (D_{50}) (mm)	Slope	Hydraulic conductivity (cm/s)	Porosity
10–20	1.20	265.4	0.764	0.39
20–40	0.61	265.4	0.114	0.36
40–60	0.31	265.4	0.0665	0.33
60–100	0.22	265.4	0.0166	0.31

TABLE 2
Physical Properties of Well-Graded Soils

Slope	Mean grain Size (D_{50}) (mm)	Hydraulic conductivity (cm/s)	Porosity
265.4	1.20	0.764	0.39
95.0	1.20	0.0097	0.37
55.6	1.20	0.00255	0.37
41.3	1.20	—	0.21

experiments with varying grain-size distribution slope, for which the initial LNAPL saturation was fixed at 48%.

Steam, at a selected pressure (and corresponding temperature), was then injected beyond the point of steam breakthrough. The amount of LNAPL removed and the axial temperature profile in the column were monitored periodically. Steam injection was stopped when the condensed liquid was free of LNAPL. The final LNAPL residual saturation and the corresponding LNAPL recovery efficiency were determined by mass balance. The residual saturation was defined as the fraction of void space occupied by LNAPL that could not be recovered by steam injection of additional pore volumes. The LNAPL recovery efficiency was calculated as

$$\%\ \text{LNAPL recovery efficiency} = \frac{\text{Total volume of LNAPL recovered}}{\text{Initial volume of LNAPL in the soil}} \tag{3}$$

The experiments were conducted with two LNAPLs (No. 2 heating oil and jet fuel), four soils with different mean grain size, and four soils with different grain-size-distribution slopes. Three steam injection pressure (gauge) settings (44.8, 24.1, and 12.4 kPa) were selected. Steam flow rate and recovered volume of LNAPL were determined from the amount of liquid collected in the graduated

FIGURE 2. Schematic diagram of the experimental setup.

cylinder. At the end of steam injection, one pore volume of water was injected into the column to obtain the final effluent water sample for analysis.

III. MECHANISMS OF LNAPL RECOVERY BY STEAM INJECTION

Before discussing the results obtained in the present study, an overview of the mechanisms involved during steam injection in LNAPL-contaminated soils is presented.

Several mechanisms are responsible for LNAPL recovery by steam injection (Willman *et al.*, 1961; Hunt *et al.*, 1988a; Stewart and Udell, 1988; Udell and Stewart, 1989a; Falta *et al.*, 1992a). Primary mechanisms include evaporation in the steam zone, vaporization in the hot water zone, and large pressure gradients at the condensation front that result in increased capillary number. The effectiveness of steam injection as a remediation technique depends on the ability to enhance the above mechanisms.

During steam injection, high volatile components having high vapor pressure and a boiling point below the steam condensation temperature vaporize as the steam front approaches. The LNAPL vapor is subjected to local gaseous-phase mass transfer mechanisms, which in a steam injection process are dominated by the large convective flux of the steam, and the LNAPL is carried along as hydrocarbon components in the gas phase. Thus, any generated vapors are advected toward the cooler region, where condensation of both the steam and the vaporous contaminant occurs. A bank of liquid distillate develops ahead of the condensation front. If the contaminant is completely vaporized at a temperature less than the steam condensation temperature, complete removal of the LNAPL is possible.

The LNAPL components remaining in the steam zone that do not completely vaporize (semivolatile components) evaporate at an enhanced rate due to increased temperature and increased liquid-phase molar fractions (Udell and Stewart, 1989a). In the oil recovery literature, the term *steam distillation* is commonly used to describe the two different phenomena: vaporization and evaporation. Hence, the principal recovery mechanism for LNAPLs is steam distillation.

The third major mechanism is due to high pressure gradients that occur in the steam zone close to the condensation front and that facilitate displacement of LNAPL ganglia into the condensation zone, where they are transported by the liquid bank. Furthermore, the steam-water thermodynamic equilibrium constraint at the pore level in conjunction with the high steam-water interfacial tension, compared with the LNAPL-water interfacial tension, produces an additional pressure increment at the upstream end of a ganglion extending through the steam condensation zone (Hunt *et al.*, 1988a).

Recently, a simple criterion was derived by Falta *et al.* (1992b) that provides a necessary condition for the optimal removal of LNAPLs from porous media by steam injection. They showed that the efficiency of the steam displacement process depends on the LNAPL-saturated vapor pressure at the steam temperature. The results of Falta *et al.* (1992b) indicated that LNAPLs having boiling points lower than about 175°C may be efficiently removed as a separate phase by steam injection. Although the steam displacement of LNAPLs with boiling points above 175°C may not be as efficient, the rate of removal is still much larger than that of other remediation techniques, including air injection and vapor extraction. The applicability of this criterion was demonstrated through several numerical simulations using various LNAPLs.

IV. **RESULTS**

Several aspects of the obtained results, such as steam front propagation and temperature profile in the column during steam injection, were compared with previously reported results (Hunt *et al.*, 1988b, Lord *et al.*, 1990; and Falta *et al.*, 1992b). Comparison of the temperature profiles, as shown in Figure 3, indicates

FIGURE 3. Comparison of measured temperatures with the experimental data of Hunt *et al.* (1988b).

that good agreement exists between the present results and the experimental results of Hunt *et al.* (1988b). These profiles were recorded when the condensation front was at 64 cm from the column inlet. Discrepancies between the two profiles are due mostly to slightly lower steam injection pressure and higher ambient temperature in the experiments conducted by Hunt *et al.* (1988b).

After validation of the experimental technique used in the present study, several experiments were performed in a systematic way to correlate the effects of steam injection pressure, soil-grain-size distribution, and LNAPL properties on the LNAPL recovery efficiency. Measurements of the temperature gradients in the radial direction at several axial positions along the pipe were performed in order to evaluate the heat losses from the system. The results showed that the total heat loss varied from 0.35% of the total energy input when steam was injected into coarse-grained soils (D_{50} = 1.2 mm) to 4.8% when soils with finer grain size

(D_{50} = 0.22 mm) were tested. These results indicate that the heat losses should have negligible effects on LNAPL recovery efficiency within the considered range of soils and steam flow rates.

A. **Effect of Pressure**

In this phase of the experiments, the column was initially packed with the coarse-grained soil. The experiments were conducted for three steam injection pressure settings of 44.8, 24.1, and 12.4 kPa. The experiments were performed without repacking the column to save time, because it was ensured that steam injection provided adequate cleaning between experiments (Hunt *et al.*, 1988b). Relevant data for these experiments are given in Table 3. The variation of steam flow rate with steam injection pressure is illustrated in Figure 4 for the selected soil-grain sizes, and it is shown that steam flow rate is directly proportional to steam injection pressure.

Steam injection pressure has a significant effect on LNAPL recovery efficiency, as illustrated in Figure 5a, where it is shown that LNAPL recovery efficiency increases with increasing steam injection pressure. Higher steam injection pressure results in higher steam flow rate and a correspondingly increased rate of energy input, which produce more rapid cleaning. High injection pressure also results in increased velocity of the condensation front, which results in improved LNAPL displacement. In Table 3, it is shown that when the grain size is decreased from 1.2 to 0.61 mm, the effect of steam injection pressure on LNAPL recovery efficiency is reduced due to reduced increase in steam flow rate for the same increase in steam pressure, as in the previous case (Figure 4).

An increase in steam injection pressure yields faster LNAPL recovery and requires a smaller amount of steam (number of pore volumes) to achieve minimum LNAPL residual saturation (Figure 5b). More detailed analysis of the

TABLE 3
Data for Experiments with No. 2 Heating Oil as LNAPL for Various Pressures and Soils of Uniform Grain Size

Mean grain size (mm)	Steam inlet pressure (kPa)	Inlet temp. (°C)	Flow rate (ml/min)	Recovery eff. after 1 PV (%)	Max. recovery eff. (%)
1.20	44.8	110.0	116.6	95.0	99.8
1.20	24.1	105.0	66.6	89.0	99.0
1.20	12.4	102.2	33.3	86.0	98.7
0.61	44.8	110.0	41.6	90.9	99.4
0.61	24.1	103.9	20.2	88.2	99.0
0.31	44.8	110.0	12.8	87.2	99.3
0.22	44.8	110.0	7.7	82.8	98.2

FIGURE 4. Variation of steam flow rate with steam injection pressure and soil grain size.

results in Figure 5b revealed that the amount of time needed to complete one pore volume of steam (condensed) decreased linearly with increasing pressure. Figure 5b shows that it takes about five times longer to establish minimum residual saturation with low-pressure (12.4 kPa) than with high-pressure steam (44.8 kPa).

B. **Effect of Grain Size**

To study the effect of grain size, experiments were conducted with No. 2 heating oil and four soil types having uniform grain size (Figure 1a). The relevant properties of these soils are listed in Table 1. The steam injection pressure was fixed at 44.8 kPa.

Figure 6a shows that as mean grain size decreases, the LNAPL recovery efficiency decreases significantly. For a fixed steam injection pressure, as the soil-grain size is decreased, the soil permeability decreases, leading to reduced steam flow rate (Table 3 and Figure 4). This reduces the rate of energy input as well as the effective capillary number, which results in reduced recovery of the LNAPL.

A B

A

FIGURE 5. Effect of pressure on LNAPL recovery efficiency: (A) recovery efficiency vs. pore volumes; (B) recovery efficiency vs. time.

Furthermore, soils with finer grain sizes have lower porosity, which reduces the total amount of steam occupying the pore volume, leading to reduced heat transfer rate between the steam and the LNAPL ganglia. The final LNAPL residual saturation was approximately 0.5% for coarse-grained soils and 1.8% for soils with finer grain sizes (Table 3).

Remediation by steam injection is achieved much more rapidly in coarser than in finer soils. Also, in coarser soils, a smaller amount of steam is needed to establish minimum residual saturation than in finer soils. Figure 7b shows that the soil with a mean grain size of 1.2 mm yielded maximum LNAPL recovery

FIGURE 5B

efficiency in approximately 1.5 h, whereas >30 h was required to achieve maximum LNAPL recovery efficiency in the soil with a mean grain size of 0.22 mm.

C. **Effect of Grain-Size-Distribution Slope**

Four soil types have grain-size-distribution slopes as shown in Figure 1b were tested with No. 2 heating oil as the contaminant. The properties of these soils are listed in Table 2. In all these experiments, the steam injection pressure was fixed at 44.8 kPa (with corresponding temperature of 110°C) and the LNAPL saturation established after water flooding was 48%. Pertinent data for these experiments are presented in Table 4.

From Figure 7a, it is clear that by decreasing the slope, the LNAPL recovery efficiency is decreased. As the grain-size-distribution slope decreases, the soil

A B

A

FIGURE 6. Effect of soil-grain size on LNAPL recovery efficiency: (A) recovery efficiency vs. pore volumes; (B) recovery efficiency vs. time.

becomes poorly sorted (or well graded) and is characterized by a mixture of very coarse and very fine grains. It is an established fact that well-graded soils have lower porosity and lower permeability than well-sorted soils. Therefore, for a fixed steam injection pressure, as the slope is decreased the steam flow rate decreases, leading to diminished LNAPL recovery mechanisms, as indicated in the previous section. Cementation among the soil particles can also be an important factor that reduces the permeability of well-graded soils (Means and Parcher, 1963). In Figure 7a, a large gap is observed between the slopes of 55.6 and 95.0, and the effect of slope is more pronounced in this range.

Figure 7b shows that soils having lower grain-size distribution slope take longer time to reach minimum LNAPL residual saturation. Among the four types of soils tested, the soil with highest slope (265.4), reached minimum residual saturation in 1 h and 10 min, while the soil with lowest slope (41.3) attained residual saturation after 67 h and 30 min.

FIGURE 6B

D. **Effect of LNAPL**

Results from steam injection experiments with No. 2 heating oil and with jet fuel are compared in Figure 8. These experiments were conducted with soils having uniform mean grain size of 1.2 mm, and the steam injection pressure was set at 24.1 kPa. Relevant data for these experiments are presented in Tables 3 and 5. Due to higher vapor pressure and lower boiling point (as listed in Table 6), jet fuel is more volatile than No. 2 heating oil. Therefore, LNAPL recovery by steam distillation is more significant in jet fuel during the injection of the first two pore volumes, as shown in Figure 8. After the majority of the light components of the two LNAPLs are vaporized, the important recovery mechanism is related to LNAPL displacement due to large nonwetting-phase pressure gradients directly behind the steam condensation front (Hunt *et al.*, 1988a). In this case, LNAPL recovery is slightly higher with No. 2 heating oil, which has a lower interfacial tension with water than jet fuel (Table 6). In order to verify this result, additional experi-

A B

A

FIGURE 7. Effect of soil-grain-size-distribution on LNAPL recovery efficiency: (A) recovery efficiency vs. pore volumes; (B) recovery efficiency vs. time.

ments were performed with a soil having a mean grain size (D_{50}) of 0.61 mm, using the same steam injection pressure of 24.1 kPa. The results showed the same trend in LNAPL recovery.

E. **Temperature Profiles**

Figure 9 shows the column centerline temperature profiles for the experiments conducted at a steam injection pressure of 44.8 kPa, with No. 2 heating oil as the contaminant, and with soils of different mean grain size. These profiles were recorded when the steam condensation front reached 51 cm from the column inlet. In the steam zone, the temperature decreases slowly, almost linearly, with

FIGURE 7B

increasing distance. In the vicinity of the condensation front, a large temperature drop occurs over a very small distance. Ahead of the steam front, the temperature decays exponentially with distance in agreement with the theory presented by Hunt *et al.* (1988a). In the coarse-grained soil, there is a sudden temperature drop at the condensation front due to high convective heat transfer, which is dominant in this case as a result of high steam flow rate. As the soil mean grain size is decreased, the temperature gradient across the steam condensation front decays gradually over a longer distance. In this case, due to lower steam flow rate, convective heat transfer at the condensation front is lower, and conduction becomes more significant, leading to a more gradual temperature gradient across the condensation front.

Experiments with No. 2 heating oil and with jet fuel showed no significant variation in the temperature profiles (Figure 10), indicating that steam front propagation through the one-dimensional soil column was insignificantly affected by the type of LNAPL. Hunt *et al.* (1988b) made the same observation from their experiments with trichloroethylene and with gasoline.

TABLE 4
Data for Experiments with No. 2 Heating Oil as LNAPL for Various Well-Graded Soils

Slope	Steam inlet pressure (kPa)	Inlet temp. (°C)	Flow rate (ml/min)	Max. recovery eff. (%)
265.4	44.8	110.0	122.7	99.6
95.0	44.8	110.0	56.5	99.1
55.6	44.8	110.0	4.0	97.3
41.3	44.8	110.0	2.8	96.8

FIGURE 8. LNAPL recovery efficiency with No. 2 heating oil and with jet fuel.

TABLE 5
Data for Experiments with Jet Fuel as NAPL for Various Uniform-Grain-Size Soils and Pressures

Mean grain size (mm)	Steam inlet pressure (kPa)	Inlet temp. (°C)	Flow rate (ml/min)	Recovery eff. after 1 PV (%)	Max. recovery eff. (%)
1.20	44.8	110.0	116.6	96.4	99.5
1.20	24.1	105.0	66.6	94.2	98.9
0.61	44.8	110.0	41.6	91.8	99.2
0.61	24.1	105.0	20.2	89.3	98.8

TABLE 6
Properties of No. 2 Heating Oil and Jet Fuel

NAPL	Vapor pressure (mmHg)	Boiling point (°C)	Interfacial tension with water (dyn/cm at 25°C)	Dynamic viscosity, (CP at 20°C)	Specific gravity
No. 2 Heating oil	<1 (20°C)	160–350	26.24	3.54	0.87
Jet Fuel	103—155 (38°C)	55–270	35.48	1.65	0.78

V. SUMMARY AND CONCLUSIONS

A series of one-dimensional soil column experiments were performed to evaluate the effectiveness of steam injection for efficient recovery of LNAPLs. Experiments were conducted with No. 2 heating oil and jet fuel. Different types of soils and steam injection conditions were selected. Important results are summarized as follows:

1. An increase in steam injection pressure results in a significant increase in LNAPL recovery efficiency, and a smaller amount of steam is required to achieve maximum LNAPL recovery efficiency. Higher steam injection pressure yields maximum LNAPL recovery efficiency in significantly less time than low-pressure steam.
2. An increase in soil grain size or an increase in grain-size-distribution slope results in increased LNAPL recovery efficiency. Soils with

FIGURE 9. Temperature profiles at 51 cm from column inlet for experiments with No. 2 heating oil at P = 44.8 kPa.

finer grains require more time for treatment than soils with coarser grains.

3. Steam injection experiments with No. 2 heating oil and jet fuel showed that during initial pore volumes, LNAPL recovery efficiency is higher in the more volatile jet fuel, and it is slightly higher with No. 2 heating oil during the later stages of steam injection.

4. No significant variation in steam front propagation and temperature profile was obtained during the experiments with No. 2 heating oil and jet fuel.

5. The LNAPL residual saturation after steam injection is essentially independent of the starting LNAPL saturation.

FIGURE 10. Temperature profiles for experiments with No. 2 heating oil and with jet fuel.

The results indicate that near complete recovery of volatile and semivolatile contaminants is possible for high-permeability soils; for low-permeability soils, steam stripping is highly competitive with other remediation technologies.

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