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Effects of Capillarity on DNAPL Thickness in Wells and in Adjacent Sands

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EFFECTS OF CAPILLARITY ON DNAPL THICKNESS IN WELLS AND IN ADJACENT SANDS

by

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EFFECTS OF CAPILLARITY ON DNAPL THICKNESS IN WELLS AND IN ADJACENT SANDS

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Physical model experiments were used to investigate the behavior of dense non-aqueous phase liquids (DNAPLs) in various geologic media.

The objectives of the laboratory investigations were to (a) compare DNAPL thickness in wells to thickness in adjacent sands, (b) observe and interpret dyed DNAPL migration in unsaturated and saturated sands, and (c) study DNAPLs' effects on clay layers.

Two cylindrical glass columns fitted with various well screens were filled with sand, clay layers, water, and dyed DNAPLs in four experiments. Columns were packed with fine or coarse sand and clay layers. Coarse hydrophobic sand was also used.

At equilibrium, DNAPL thickness in wells exceeds that in sands. The finer the sand, the greater the difference. The thickness difference equals the DNAPL-water capillary fringe height, which varies with grain size. DNAPL thickness in the hydrophobic sand exceeds that in wells due to DNAPL capillary rise. Wells serve as conduits for vertical DNAPL migration.

ACKNOWLEDGEMENTS

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Effects of capillarity on DNAPL thickness in wells and in adjacent sands

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CHAPTER I

INTRODUCTION

Many halogenated solvents, halogenated benzenes, phthalate esters, and polychlorinated biphenyls (PCBs) are included in a group of organic chemicals that can be categorized as dense non-aqueous phase liquids (DNAPLs). Approximately one quarter of the organic chemicals on the United States Environmental Protection Agency (USEPA) List of Priority Pollutants are DNAPLs (Feenstra and Cherry 1988).

Descriptions of the physical properties of DNAPLs have long been documented, however, their potential to cause immediate and extensive contamination of an aquifer is only recently being uncovered. DNAPLs are typically more dense and less viscous than water and possess relatively low solubilities. DNAPLs are relatively nonsorbing (non-wetting) and therefore quite mobile under normal horizontal hydraulic gradients. However, because of its low solubility, DNAPL residual will not rapidly dissolve under normal groundwater flow. In laboratory experiments, groundwater in contact with DNAPLs acquires dissolved concentrations approaching the solubility of the DNAPLs within minutes causing a dissolved DNAPL plume to develop (Schwille, 1988).

A DNAPL's relatively low solubility, low viscosity and high density enable it to penetrate downward through unsaturated and saturated porous media as an immiscible liquid phase. Many DNAPLs are also very volatile. DNAPL vapor may migrate away from a liquid phase source, spreading contamination in the unsaturated zone (Schwille 1988). Below the water table, small quantities of DNAPLs can become incorporated in the groundwater flow regime by dissolution. Most DNAPLs have a relatively low solubility in water, and therefore may continue to dissolve in groundwater for extended periods of time.

Villaume (1985) attributed the distribution of liquid DNAPLs in a porous media to capillary pressure, gravitational forces, and viscous forces. In a saturated porous material, DNAPLs move downward under the influence of gravity. Capillary forces, which can restrict a DNAPL's downward movement, are dependent upon the pore structure of the porous material. A DNAPL's viscosity can also restrict downward movement especially in water saturated porous media.

Palombo and Jacobs (1982) examined the important considerations when monitoring DNAPLs in groundwater. Standardized groundwater and soil monitoring procedures may have to be altered where DNAPLs are present.

DNAPLs may accumulate to a greater thickness in the

well if the well is installed through the barrier where DNAPLs have accumulated. In a finer grained material, the capillary forces of the media restrict the migration of DNAPLs; however, a slotted well in this material essentially contains no capillarity and more DNAPL product will occupy the well instead of the small water-filled pore spaces in a fine grained media. Such a well could be used to recover DNAPLs if a sufficiently impermeable layer occurred below the well. If water were removed from such a well, the DNAPLs would seek the hydrostatic level outside the well. This would also give a false indication of actual DNAPL thickness (Villaume 1985).

The ever-increasing number of sites found to be contaminated with DNAPLs is forcing groundwater hydrologists to consider the controlling factors that govern the behavior of DNAPLs in the subsurface. Locating and removing pools of DNAPLs in aquifers is difficult but important in remediating this contamination. Location and removal depend upon understanding the interactions of DNAPLs in porous media and wells.

Conventional remedial methods for the removal of lighter than water non-aqueous phase liquids (i.e., petroleum hydrocarbons) such as pump and treat systems and collection wells may not be effective for the removal of DNAPLs because the migration of DNAPLs is not solely controlled by the groundwater flow pattern. It has been

found that only small quantities of DNAPLs can be removed with a recovery well which intersects pooled DNAPLs (Feenstra and Cherry 1988).

One approach to understanding these interactions is to physically model subsurface conditions in which DNAPLs may be present and observe their behavior when introduced under controlled conditions.

Physical models were used to examine the thickness differences between DNAPLs measured in a well and the adjacent porous media outside the well. A clay layer was introduced to determine a DNAPL's ability to structurally alter a clay. Finally, each step of a DNAPL's migration through unsaturated and saturated media was photographed and compared with the DNAPL's physical properties.

CHAPTER II

MATERIALS AND METHODS

Materials

Two PYREX glass cylindrical columns (Column A and Column B), measuring 58 cm tall and 28 cm in internal diameter, were fitted with 5-cm-diameter stainless steel, PFTE (Teflon), and fiber-reinforced epoxy (fiberglass) well screens. Various well screen materials were used to evaluate the compatibility between the well material and the DNAPLs. The screens were cut in half lengthwise and attached to the inside walls of the columns using a silicone vacuum grease or a bentonite powder/water paste.

The columns were filled with various geologic materials, including 0.41-mm median grain size (fine) well sorted sand; 0.77-mm median grain size (coarse) well sorted sand (Figure 1); clay layers made of a 25% bentonite powder/75% poorly sorted medium grained sand; coarse gravel; and a hydrophobically-treated volume of the (coarse) well sorted sand. The sands were distributed through a meshed sieve screen to allow for even horizontal stratification in the columns.

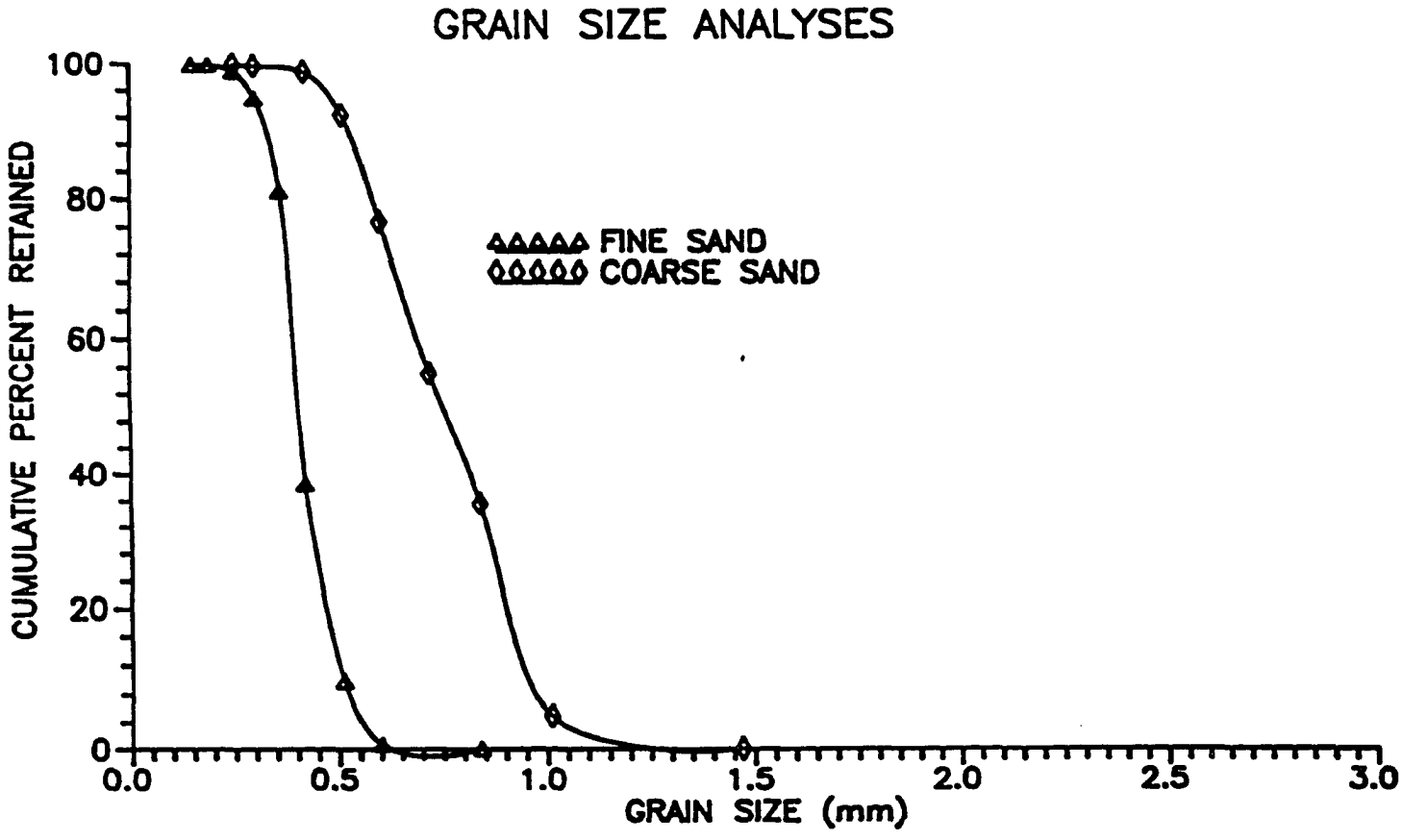

Figure 1. Grain Size Analysis for Fine and Coarse Gravel Pack Sand.

The columns were packed differently for each of the four experiments in order to examine DNAPL migration under different geologic boundary conditions. The first two experiments utilized both glass columns packed with the fine sand and clay layers. The third experiments compared DNAPL migration in the coarse sand under normal hydrophilic (3) and altered hydrophobic (3A) conditions. No clay layers were used. The fourth experiment examined DNAPL migration in a non-capillary media (coarse gravel).

Once the well screen and column packings were set, the water table and capillary fringe were established by adding water through the well screen. Dyed DNAPLs were then injected at the surface of the sand or gravel.

Two DNAPL mixtures were used during these experiments. Most experiments used blue-dyed perchloroethylene (PER). The blue dye, which was added at a concentration of 2 gm/L, was Kriegrosol Supra Blue Concentrate Powder from Special T Chemicals, in Hollywood, California. A red-dyed chlorobenzene and aniline mixture (CAM), composed of equal volumes of each substance, was also used in Experiments 1 and 2. The red dye, added at 2 gm/L, was Oil Red EGN Solvent from Aldrich Chemicals, in Milwaukee, Wisconsin. These DNAPLs were selected in order to compare and contrast migration of DNAPLs that have different physical properties. The physical properties of the selected DNAPLs are listed in Table 1.

Table 1

Physical Properties of DNAPLs

DNAPL	Density (g/ml)	Absolute Viscosity (centipoise)	Solubility (mg/l)
Perchloroethylene	1.63	0.9	200
Chlorobenzene	1.11	0.8	488[a]
Aniline	1.02	3.7	20,000

[a]Value measured at 25°C.
Note: Temperature of measurement is 20°C unless otherwise noted.

Experiment 1

The objectives of the first experiment were not well known. Comparisons were to be made between thickness in the well versus the thickness in the sand as well as evaluating the clay layers reaction to DNAPL introduction. The experiment served as a guide for improving the design of the future experiments.

Column A was fitted with Teflon and fiberglass well screens. The screens were set on a clay layer at the base of the column. The column was then packed with 10 cm of fine sand, another 1-cm-thick clay layer, and 33 cm of fine sand (Figure 2). Once a water table and capillary fringe were established, blue-dyed PER was injected at the surface of the sand at a rate of approximately 1 liter/minute.

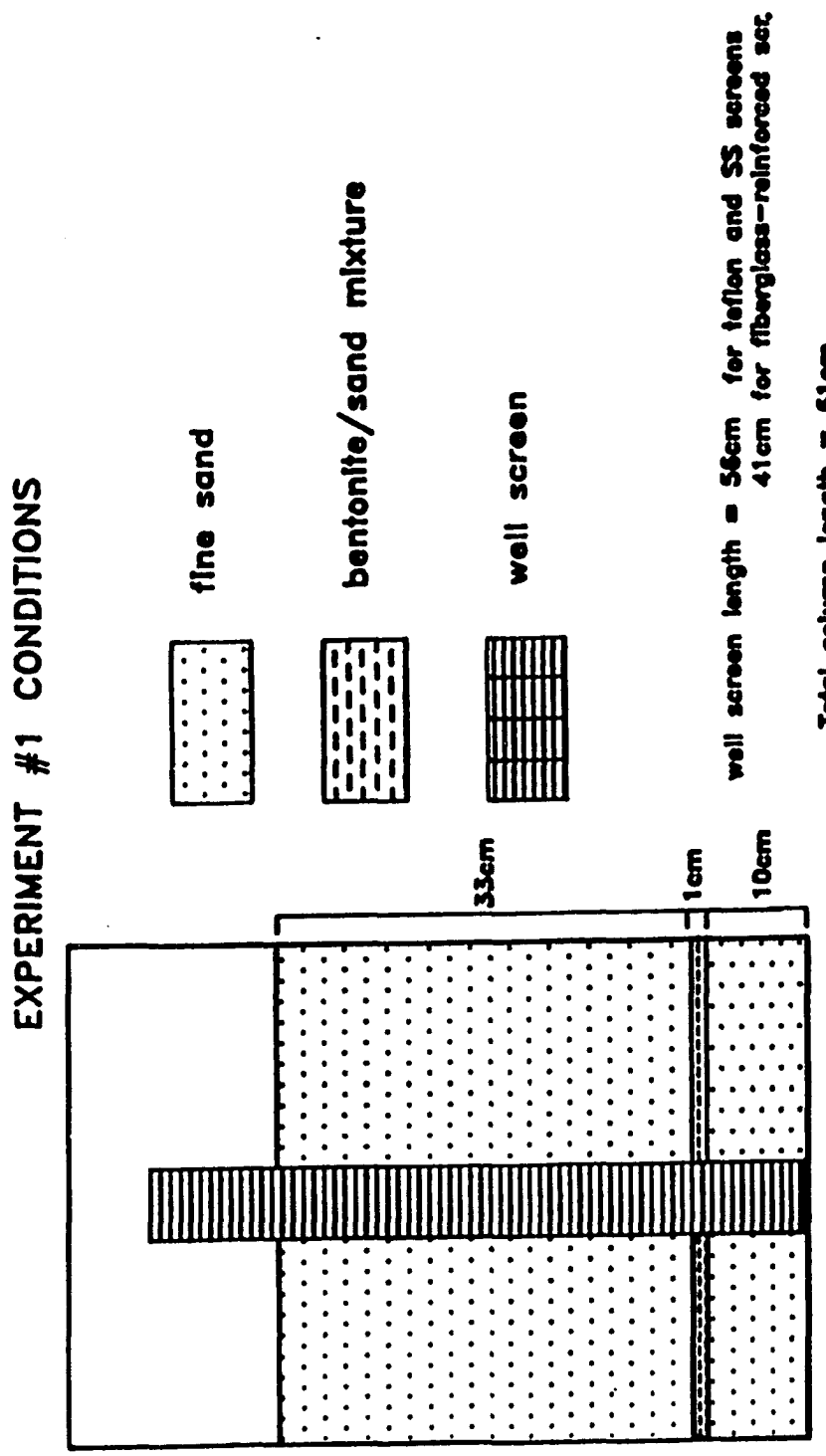

Figure 2. Experiment #1: Initial Conditions.

The stainless steel well screen was set to the base of Column B. The column was packed in the same manner as Column A. The well screen was filled with granular bentonite to the top of the upper clay layer to prevent migration through the well into the lower sand layer. Once a water table and capillary fringe were established, CAM was injected at the surface of the sand.

Both columns were monitored and photographed until migration ceased (about 3 weeks). DNAPL thickness measurements and observations were recorded and measurements between the two columns were compared. The results of Experiment 1 are shown in Tables 2 and 3.

Experiment 2

The objectives of the second experiment were to better evaluate the effect of pooled DNAPLs on the clay layer by placing the well screen on top of the clay layer. In Experiment 2, one Teflon and one stainless steel well screen per column were set on top of a 2-cm-thick clay layer with fine, well sorted sand above and below the clay (Figure 3). Blue-dyed PER and red-dyed CAM were injected at the sand surface in the respective columns after a water table and capillary fringe had been established. DNAPL migration was photographed and monitored for 1 month. These results are shown in Tables 4 and 5.

Table 2

Experiment #1: PER Thickness in Wells vs. Time Column A

Comments	Time (days)	Thickness in Wells (cm) #1	#2
Add 500 ml PER	0.00	0.0	0.0
	0.04	5.8	6.2
	0.06	10.1	6.6
	0.10	13.9	7.8
Add 250 ml PER	0.13	--	--
	0.15	16.3	12.3
	0.19	18.7	16.0
	0.28	20.0	19.3
	0.37	20.9	20.8
	0.97	21.4	21.3
	1.16	21.1	21.2
	2.00	21.3	21.4
	2.92	20.3	20.2
	3.16	20.4	20.3
	3.57	20.4	20.4
	4.13	19.9	19.6
	5.00	19.4	19.5
	6.00	19.0	18.8
	7.00	18.8	18.7
	8.00	18.5	18.3
	9.00	18.5	18.3
	10.00	18.8	18.7
	11.00	18.9	18.7
	13.00	18.1	18.0
	15.00	18.1	18.0
	16.00	18.2	18.0
	18.00	18.1	18.0
	21.00	17.9	18.0
	23.00	18.5	18.3

Well Screen #1 = 2-inch-diameter fiberglass-reinforced epoxy; 41 cm in length.

Well Screen #2 = 2-inch-diameter Teflon; 56 cm in length.
-- = no measurement

Table 3

Experiment #1: CAM Thickness in Well vs. Time Column B

Comments	Time (days)	Thickness in Well (cm)
Add 750 ml CAM	0.00	0.0
	0.08	0.0
Add 250 ml CAM	0.10	0.0
	0.96	0.0
Add 500 ml CAM	1.16	0.0
	1.20	0.5
	1.83	16.3
	2.08	19.9
	2.50	20.0
	3.05	20.0
	4.00	20.0
	5.00	19.9
	6.00	19.8
	7.00	19.8
	8.00	19.6
	9.00	19.8
	10.00	20.0
	12.00	18.4
	14.00	19.2
	15.00	19.4
	17.00	19.2
	20.00	19.1
	22.00	19.5

Well Screen = 2-inch-diameter wire-wrapped stainless steel, 56 cm in length.

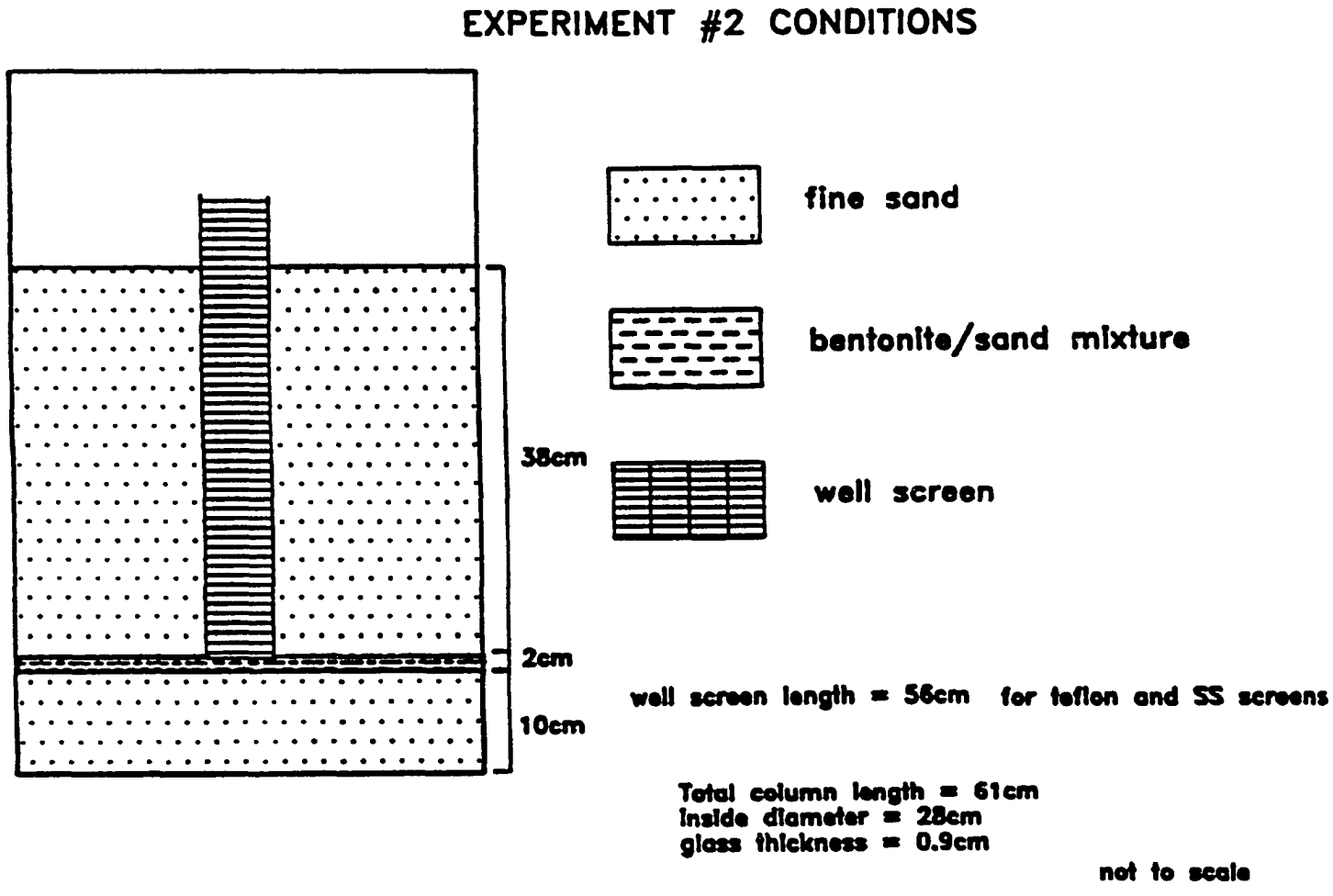

Figure 3. Experiment #2: Initial Conditions.

Table 4

Experiment #2: PER Thickness in Well vs. Time Column A

Comments	Time (days)	Thickness in Well (cm)
Add 100 ml PER	0.00	0.0
	0.08	2.2
	0.10	3.2
	0.15	8.0
	0.33	15.0
	0.75	17.2
	1.25	17.2
	1.88	17.4
	2.30	17.4
	2.80	17.4
	4.00	17.2
	5.00	17.2
	6.00	17.3
	7.00	17.1
	9.30	16.3
	10.00	16.7
Add 500 ml PER	10.88	16.8
	10.89	17.0
	10.90	17.3
	10.91	17.5
	10.92	18.4
	10.96	19.8
	11.00	19.9
	11.08	20.4
	11.29	20.2
	11.79	20.0
	12.29	19.9
	12.90	20.0
	14.00	19.7
	15.00	19.6
	17.00	19.5
	18.00	19.6
	21.00	19.7
	25.00	19.4
	33.00	19.7
	42.00	17.8
	55.00	17.1
	105.00	16.2

Well Screen = 2-inch-diameter Teflon, 56 cm in length.

Table 5

Experiment #2: CAM Thickness in Well vs. Time Column B

Comments	Time (days)	Thickness in Well (cm)
Add 930 ml CAM	0.00	0.0
	0.08	0.0
	0.10	0.0
	0.15	0.0
	0.33	0.0
	0.75	0.0
	1.25	0.0
	1.88	0.0
	2.30	0.0
	2.80	0.0
	4.00	0.0
	5.00	0.0
	6.00	0.0
	7.00	0.0
	9.30	0.0
	10.00	0.0
Add 100 ml CAM	10.88	0.0
	10.89	1.0
	10.90	2.2
	10.91	2.9
	10.92	3.5
	10.96	6.9
	11.00	8.5
	11.08	11.3
	11.29	15.0
	11.79	16.4
	12.29	16.5
	12.90	16.8
	14.00	16.8
	15.00	16.7
	17.00	16.7
	18.00	16.8
	21.00	17.0
	25.00	20.5
	33.00	20.5
	42.00	19.5
	55.00	20.6
	105.00	25.0

Well Screen = 2-inch-diameter wire-wrapped stainless steel, 56 cm in length.

At the completion of Experiment 2, an extraction experiment was conducted on both columns in order to observe the re-release of DNAPLs into the well from the adjacent sand. PER and CAM that had accumulated in the wells in Columns A and B, respectively, were extracted using a hand-operated pump. Product recovery in the wells was monitored for 2 days as the DNAPL from the adjacent sands reoccupied the wells. Recovery data for both compounds is summarized in Tables 6 and 7, respectively.

Experiment 3

The coarse sand was used in the third set of experiments in order to observe DNAPL migration in a coarser grained sand compared to the fine sand used in Experiments 1 and 2.

Only one column was utilized for Experiment 3. The Teflon well screen was set to the base of the column, which was packed with coarse, well sorted sand (Figure 4). No clay layers were used. The water table and capillary fringe were established by adding water to the column through the well screen. Blue-dyed PER was injected at the surface of the sand. Product thickness measurements in the well and sand are presented in Table 8.

Experiment 3A was conducted using the same column setup and boundary conditions that were used in Experiment 3. However, the lower half of the coarse sand was made

Table 6

Extraction Experiment: PER Recovery in Well vs. Time Column A

Comments	Elapsed Time (minutes)	Thickness in well (cm)
Extract 16.2 cm PER accumulated in well	0.0	0.0
	0.2	3.0
	0.5	8.0
	1.0	10.5
	2.0	10.9
	4.0	11.0
	8.0	12.4
	16.0	12.6
	32.0	12.6
	120.0	12.5
	720.0	14.0
	1,440.0	14.8
	2,880.0	14.9

Table 7

Extraction Experiment: CAM Recovery in Well vs. Time Column B

Comments	Elapsed Time (minutes)	Thickness in Well (cm)
Extract 25.0 cm CAM	0.0	0.0
	0.2	0.0
	0.5	0.0
	1.0	0.0
	2.0	0.0
	4.0	0.0
	8.0	0.0
	16.0	0.0
	32.0	0.0
	120.0	0.0
	720.0	2.0
	1,440.0	2.5
	2,880.0	2.5

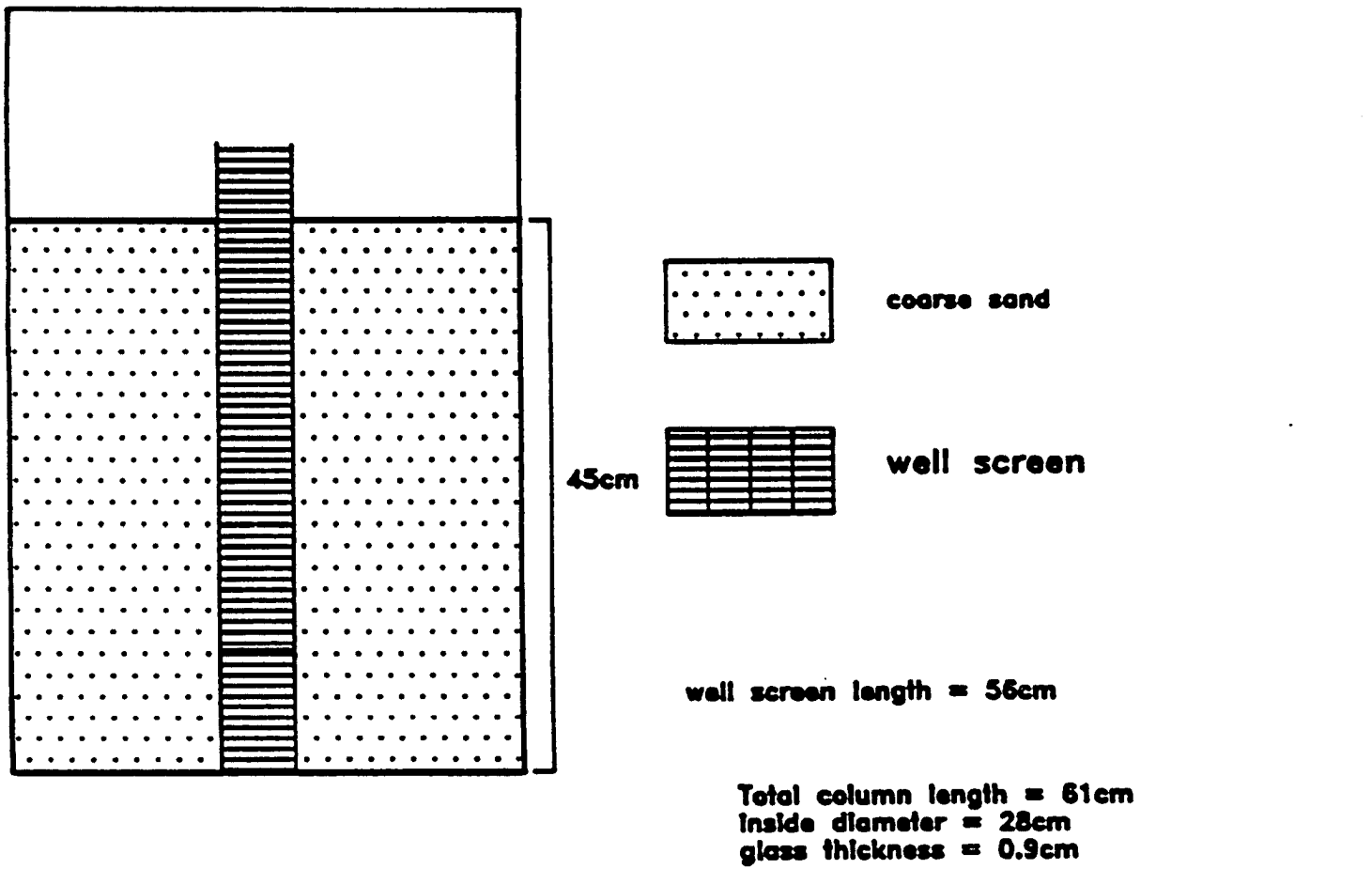

Figure 4. Experiment #3: Initial Conditions.

hydrophobic to observe the effects of capillarity on DNAPL distribution.

Table 8

Experiment #3: PER Thickness in Well and Sand vs. Time Coarse Sand

Comments	Elapsed Time (days)	Thickness in Well (cm)	Thickness in Sand (cm)
Add 1,500 ml PER	0.000	0.0	0.0
	0.006	6.0	2.0
	0.008	7.0	2.3
	0.014	7.3	4.0
	0.020	7.5	5.0
	0.042	10.5	5.2
	0.083	12.0	5.5
	0.300	12.0	5.5
	0.830	12.2	6.0
	2.000	12.0	6.2
	6.000	11.1	6.5
	7.000	11.1	6.4
	8.000	11.1	6.5

Hydrophobic alteration of the sand required several steps. First the sand was dried in an oven to evaporate any moisture on the sand grains. A 10% siliconizing solution was prepared by mixing 100 ml of dimethyl-dichlorosilane (DMDCS) with 1,000 ml of A.C.S.-grade acetone. Acetone served as a soluble dilutant for the DMDCS siliconizing fluid. The 1,100 ml, 10% solution was poured on the sand to make it hydrophobic and the wet sand was placed under an exhaust hood while chlorine gas evolved. The sand was dried in an oven at 140 degrees fahrenheit for 24 hours to evaporate the remaining siliconizing solution.

When the sand was dry, it was packed in the column (Figure 5). Untreated coarse sand was used for the upper portion (approximately 54%) of the profile. Blue-dyed PER was injected at the surface of the sand after a water table and capillary fringe had been established. The results of the experiment were compared with the results from Experiment 3. Thickness measurements in the sand and well over time are shown in Table 9.

Table 9

Experiment #3A: PER Thickness in Well and Sand vs. Time Using Hydrophobically Treated Coarse Sand

Comments	Elapsed Time (days)	Thickness in Well (cm)	Thickness in Sand (cm)
Add 1,500 ml PER	0.000	0.0	0.0
	0.001	0.5	0.0
	0.003	0.5	2.0
	0.006	2.0	3.5
	0.101	2.8	4.0
	0.020	2.9	4.0
	0.042	3.4	4.0
	0.292	3.6	4.5
	0.500	3.4	4.2
	1.000	4.0	4.2
	2.000	4.0	4.2
	4.000	3.9	4.3
	6.000	3.9	4.3

Experiment 4

Experiment 4 utilized a non-capillary media to show the ideal case of equal DNAPL distribution in the well and adjacent media. A coarse gravel was packed in the column

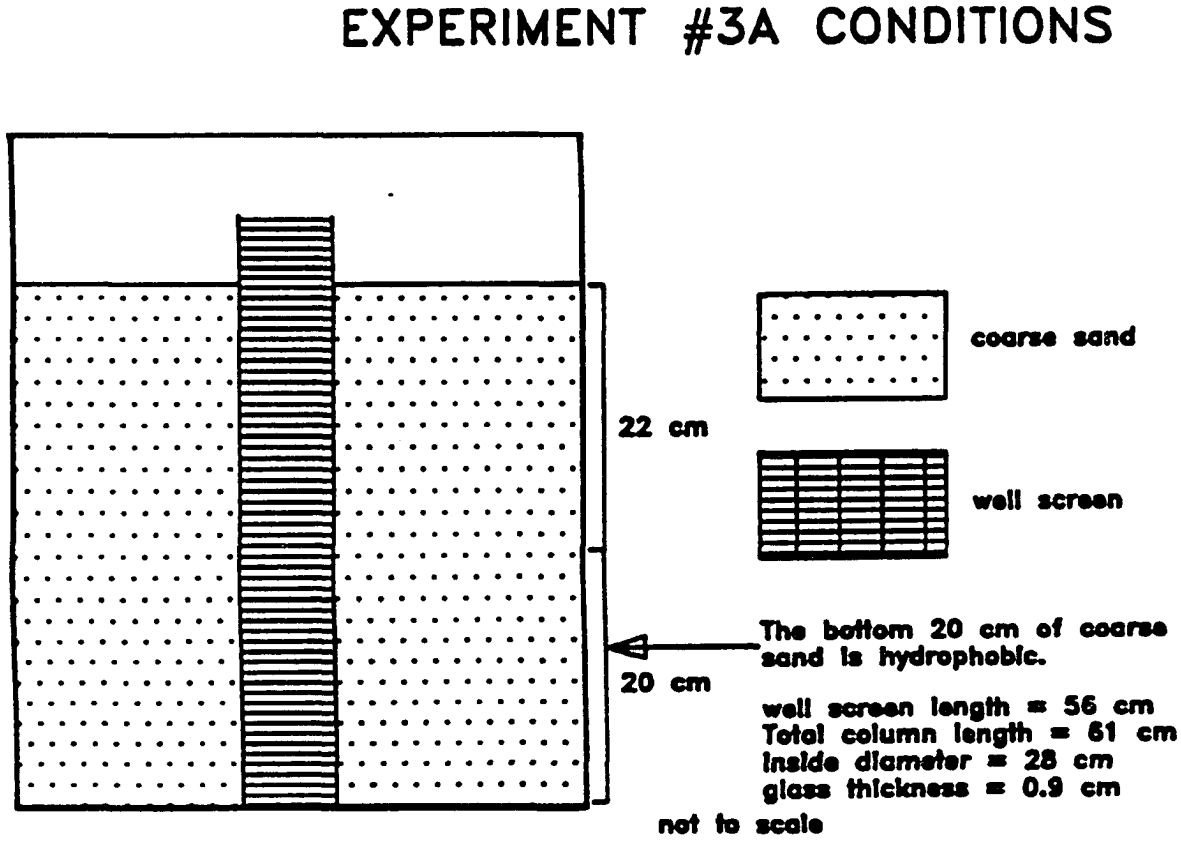

Figure 5. Experiment #3a: Initial Conditions.

for Experiment 4 after the stainless steel well screen was attached to the column (Figure 6). Blue-dyed PER was injected at the surface of the gravel after the water level had been established.

At the completion of each experiment, the columns were excavated from top to bottom and DNAPL migration routes were observed and photographed. The columns were then washed with Alconox detergent and water and rinsed with water and isopropyl alcohol. The contaminated sand, water, and solvents were drummed and disposed of by the Western Michigan University Department of Environmental Health and Safety.

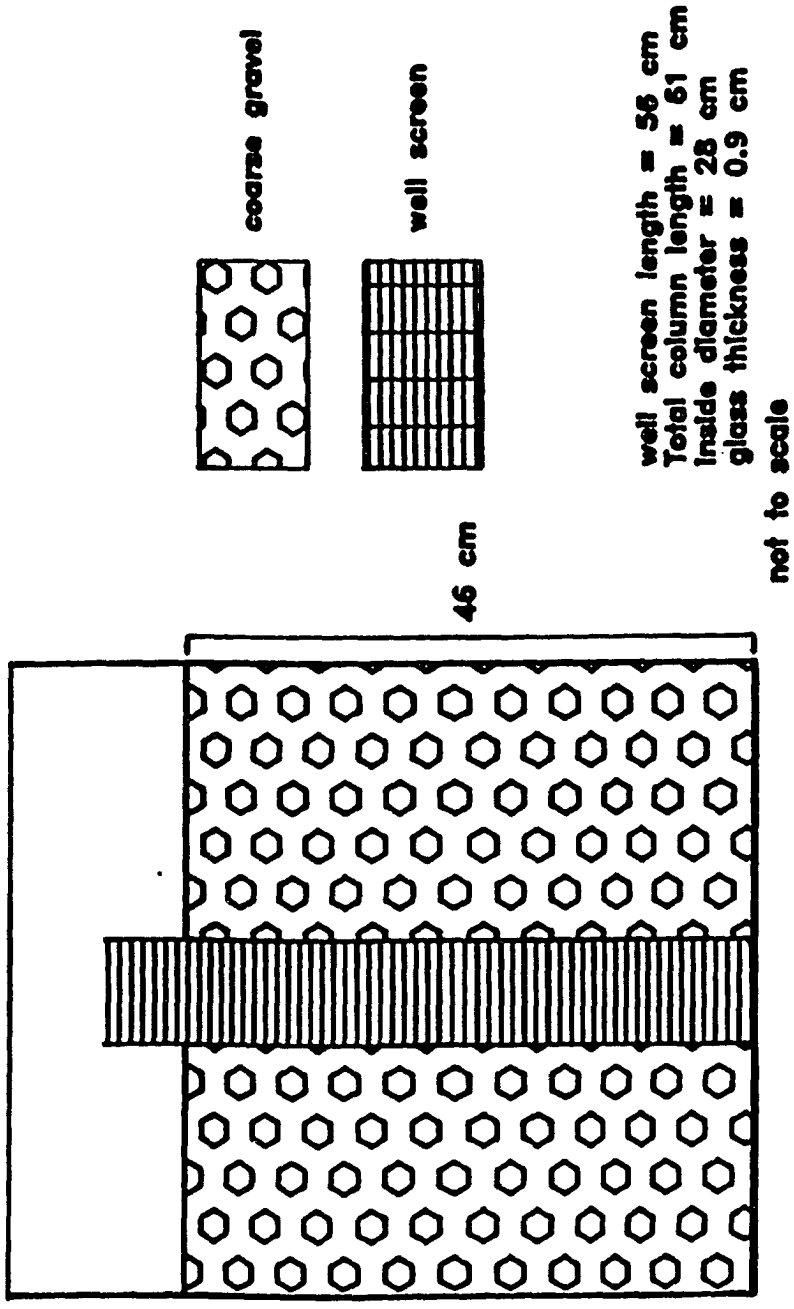

Figure 6. Experiment #4: Initial Conditions.

CHAPTER III

RESULTS AND DISCUSSION

Experiment 1

In Experiment 1, several phenomena were observed. PER was trickled onto the fine sand away from the well screens. The DNAPLs moved rapidly in a vertical direction through the unsaturated sand under gravity and spread horizontally along the capillary fringe until it intersected the wells. It migrated vertically downward along the well screens and soon began to accumulate at the base of the wells. Eventually, most of the PER accumulated in the screens and only a small amount remained in the coarser sand. Figure 7 shows that, at equilibrium, the PER thickness in both wells was equal. The PER thickness over time in both wells is shown in Figure 8.

CAM infiltration in Experiment 1 contrasted sharply with PER infiltration. CAM accumulated for hours above the capillary fringe without penetrating it. The original CAM volume of 750 ml was doubled before CAM penetrated the saturated sand and entered the well (Figure 9). The slow rate of CAM infiltration into the column in contrast with PER infiltration is caused by its lower density and higher

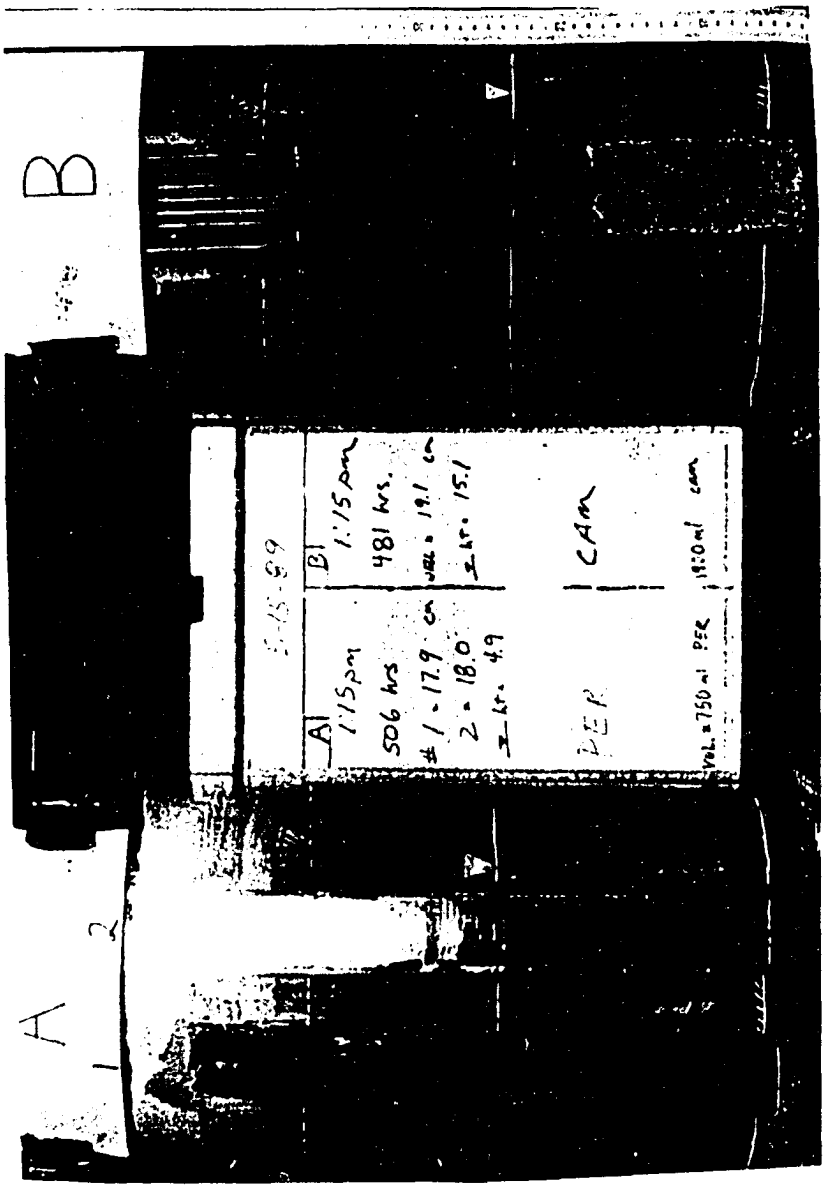

Figure 7. Experiment 1: Conditions in Columns A and B Comparing PER and CAM Migration and Thickness.

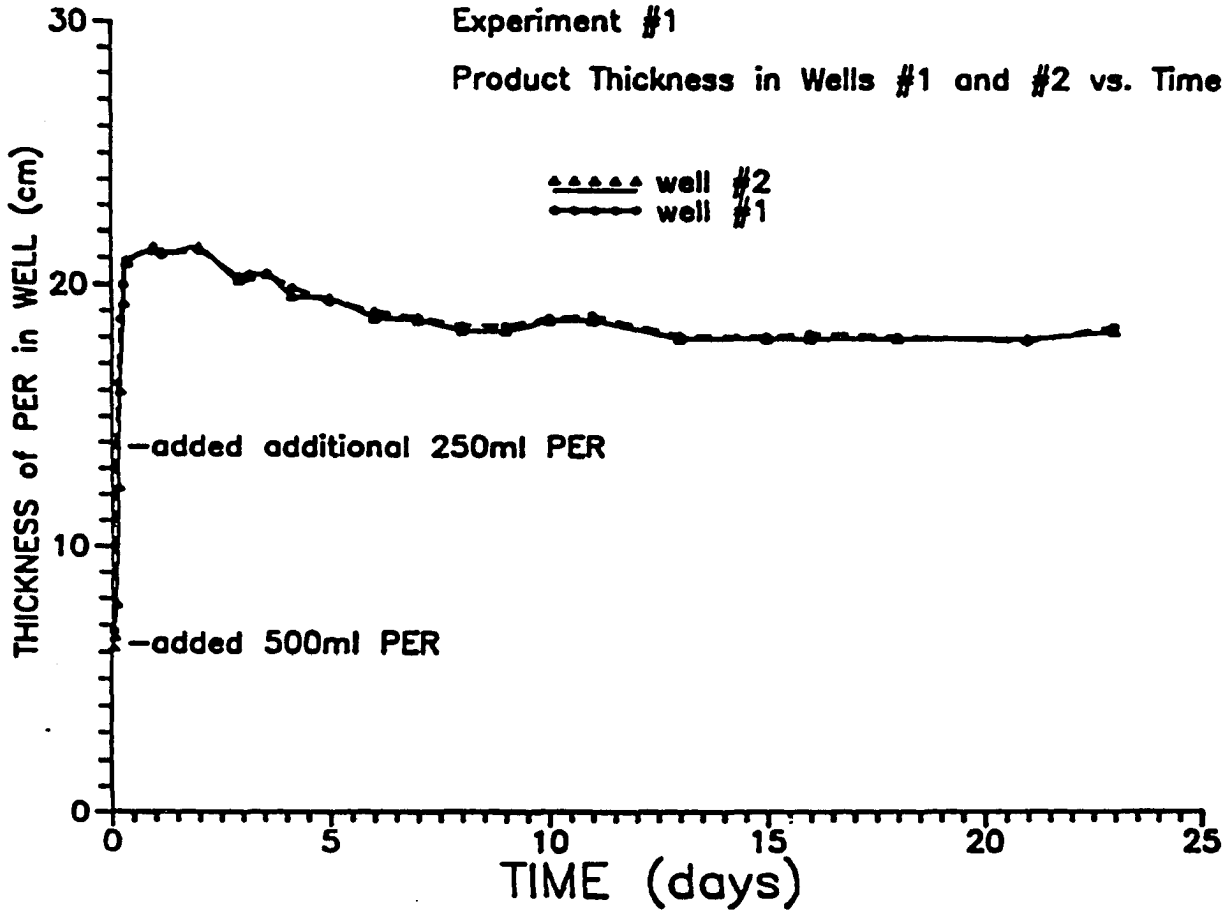

Figure 8. PER Thickness in Wells 1 and 2 in Column A During Experiment 1.

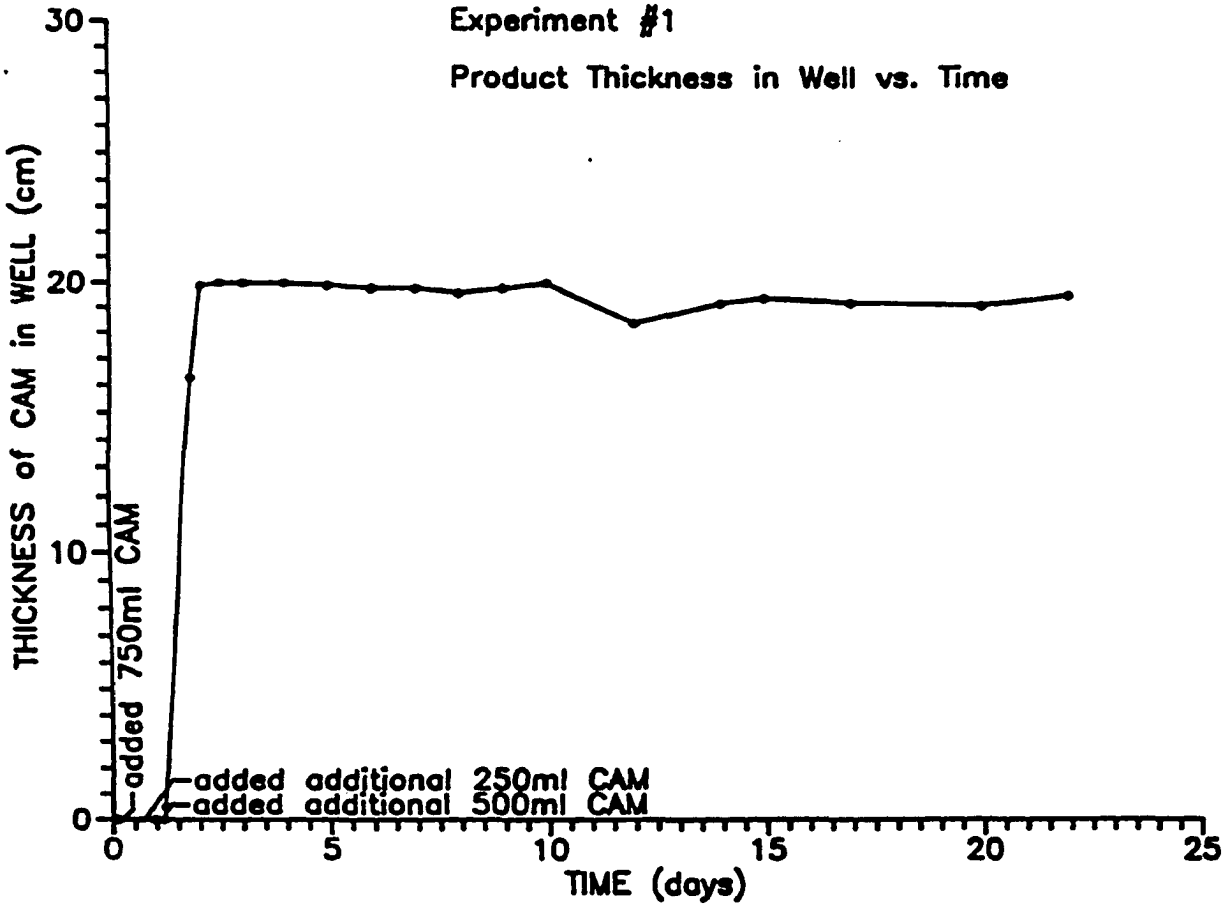

Figure 9. CAM thickness in Well in Column B During Experiment 1.

viscosity. CAM leaked through the plugged well screen or perhaps down its side into the lower sand layer below the clay.

Experiment 2

The same infiltration behavior of Experiment 1 was also observed in Experiment 2. Figure 10 shows PER fingering through the sand, while the more viscous CAM spread along the capillary fringe before penetrating it. The lower white line on the columns delineates the pre-injection water table position.

In contrast to their divergent infiltration behavior, the final DNAPL thickness in both columns in Experiment 2 was strikingly similar. Figure 11 shows that the DNAPL-water interface in the Teflon well screen is slightly higher than in the stainless steel screen. The interface is harder to distinguish in the latter screen because it is darker, but is just above the white line marking the original water table. The water level is higher in Column B because more DNAPL was added than in Column A. The PER thickness in the sand in Column A was continuous around the base of the column, but was difficult to measure accurately. The small amount of CAM observed in the sand outside the well was in irregular blobs. So, although the thickness of CAM in the sand could not be accurately

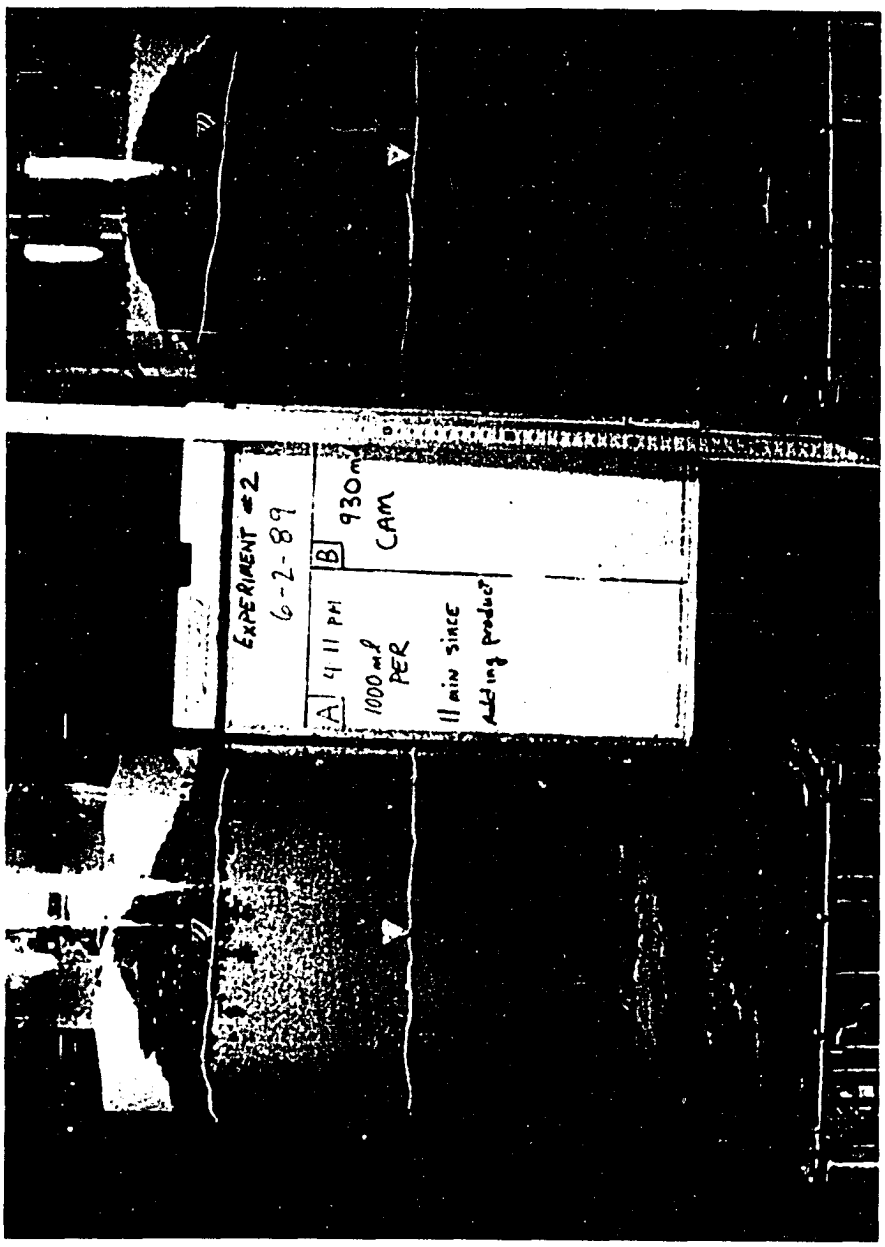

Figure 10. PER and CAM in Columns A and B, Respectively, 11 Minutes After Injection in Experiment 2.

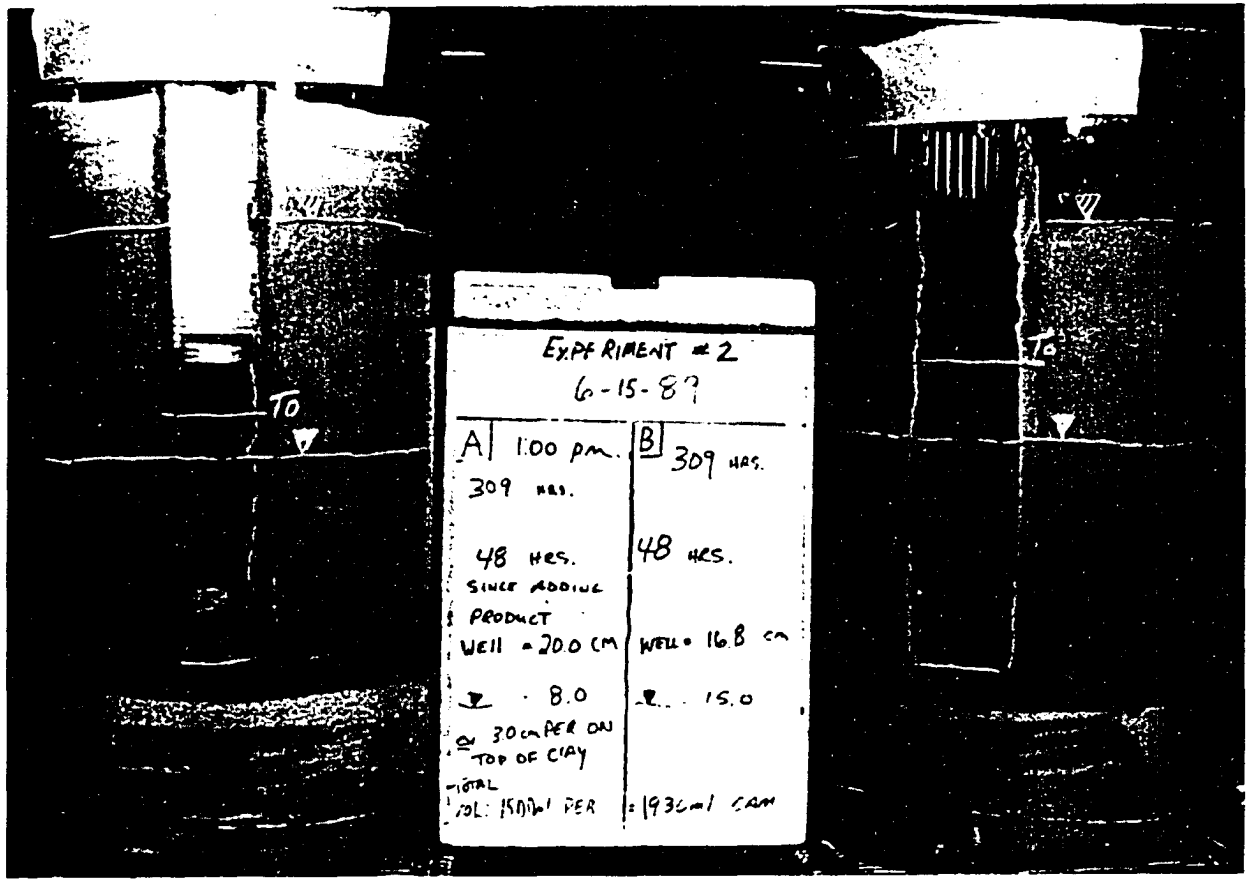

Figure 11. PER and CAM Thicknesses in Wells and Sand 48 Hours Into Experiment 2. Note thickness difference between PER and CAM in well and adjacent sand.

determined, it was small. Figures 12 and 13 show the temporal distribution of PER and CAM thicknesses, respectively, in the wells.

The well contents were extracted in columns A and B at the completion of Experiment 2. Water and DNAPL recoveries were measured in the respective wells. Figures 14 and 15 show that PER recovered in the well more quickly than CAM. Its lower viscosity enabled PER to reoccupy the well more quickly than CAM.

Experiment 3

PER migrated more easily through the coarse sand in Experiment 3. In contrast to Experiments 1 and 2, PER was not held above the capillary fringe in Experiment 3 (Figure 16). A measurable PER thickness was present in the sand compared to the thickness of PER in Experiments 1 and 2. There was less PER thickness difference between the well and sand. Figure 17 shows these thicknesses over the duration of Experiment 3.

Conditions in Experiment 3 were duplicated in Experiment 3A. However, the lower half of the sand was hydrophobic in order to reverse the effects of capillarity. In Figure 18, the DNAPL capillary rise above the DNAPL-water interface is marked by the lower white line. As a result the DNAPL thickness in the sand was difficult to

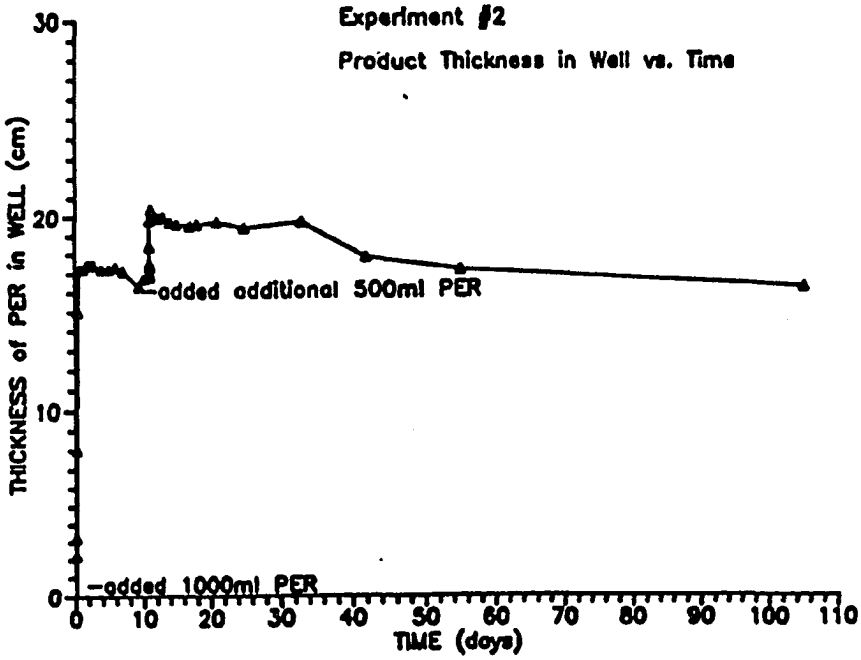

Figure 12. PER Thickness in Well in Column A During Experiment 2.

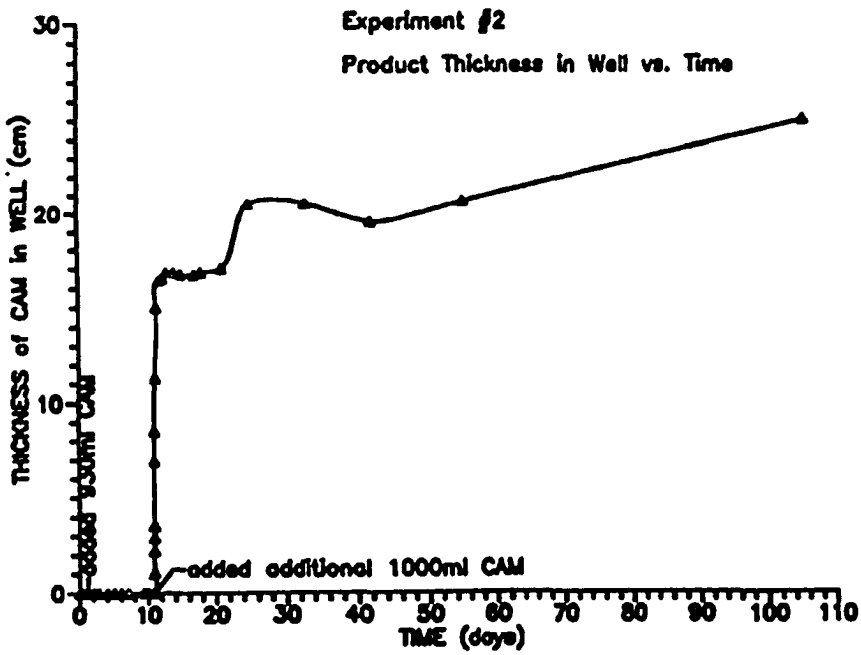

Figure 13. CAM Thickness in Well in Column B During Experiment 2.

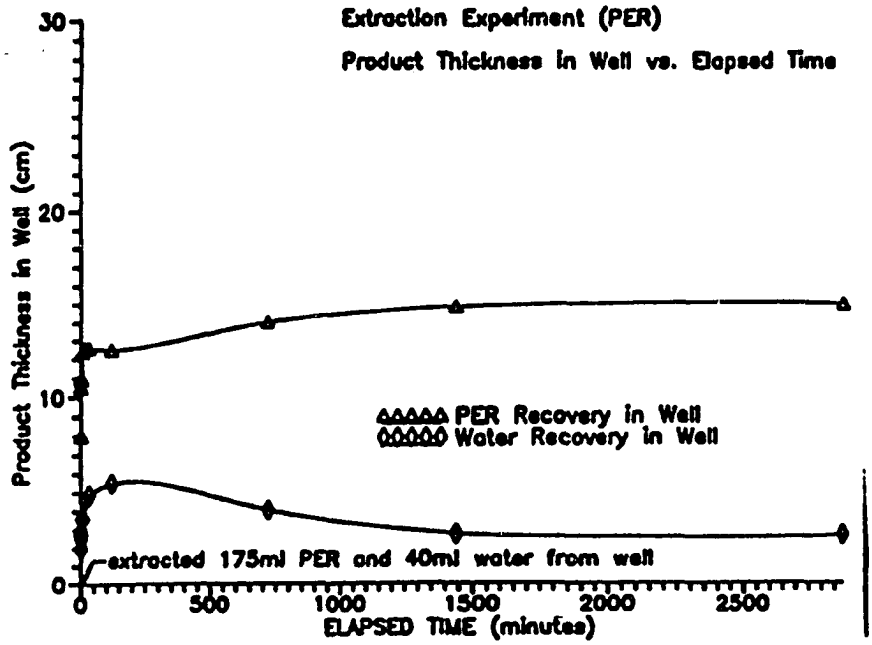

Figure 14. PER and Water Recovery After Extracting PER and Water From Column A Well.

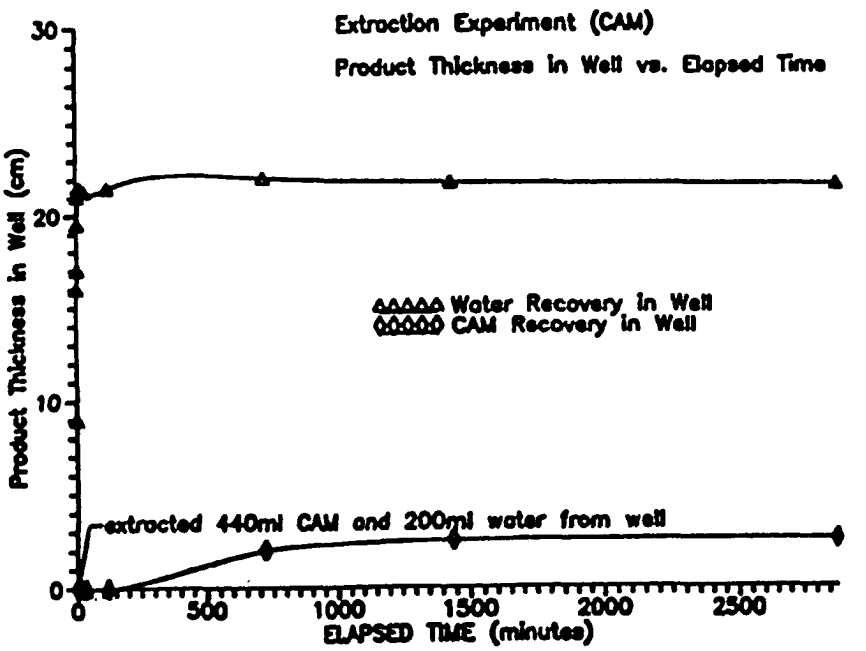

Figure 15. CAM and Water Recovery After Extracting CAM and Water From Column B Well.

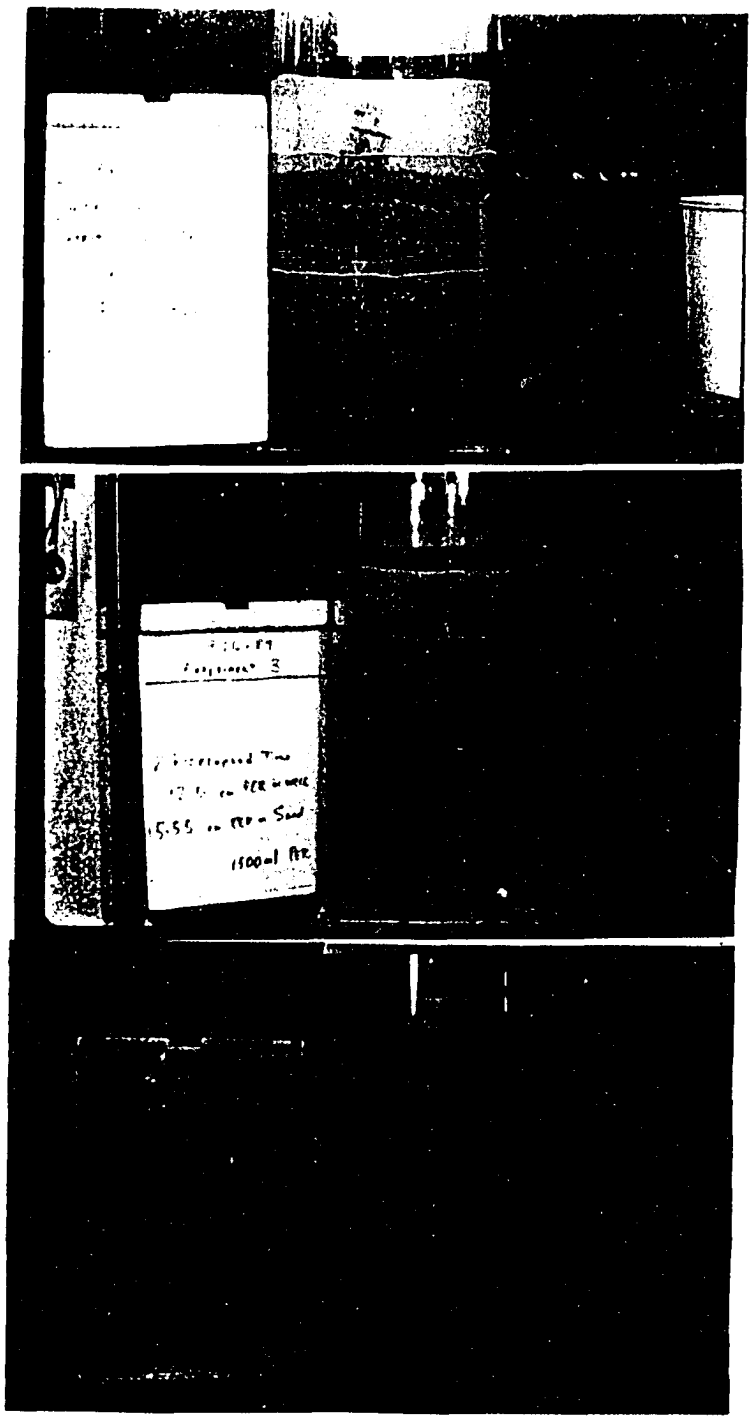

Figure 16. PER Migration Through Coarse Sand During Experiment 3. a) 5 minutes after injection. b) 2 hours. c) 190 hours.

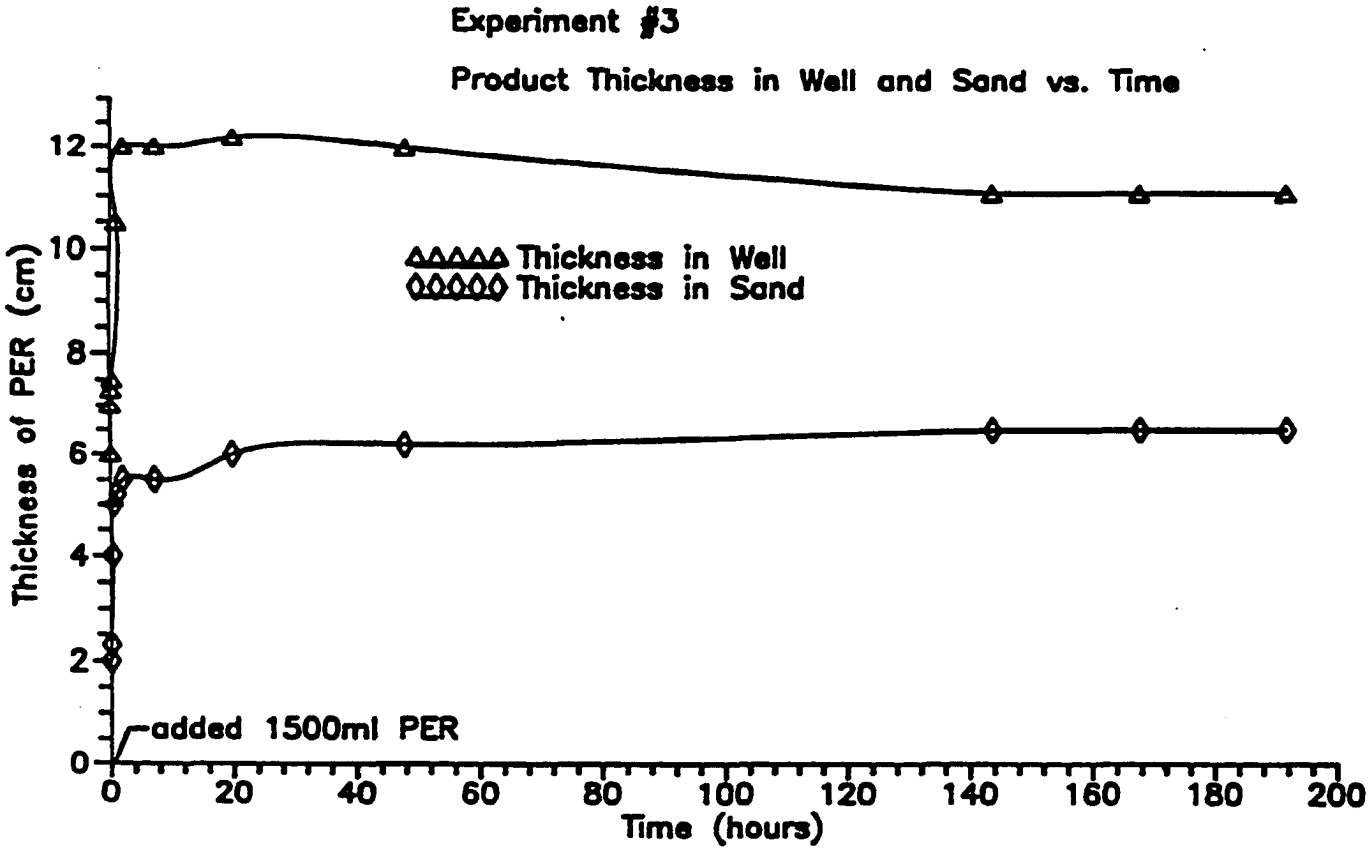

Figure 17. PER Thickness in Well and Sand During Experiment 3.

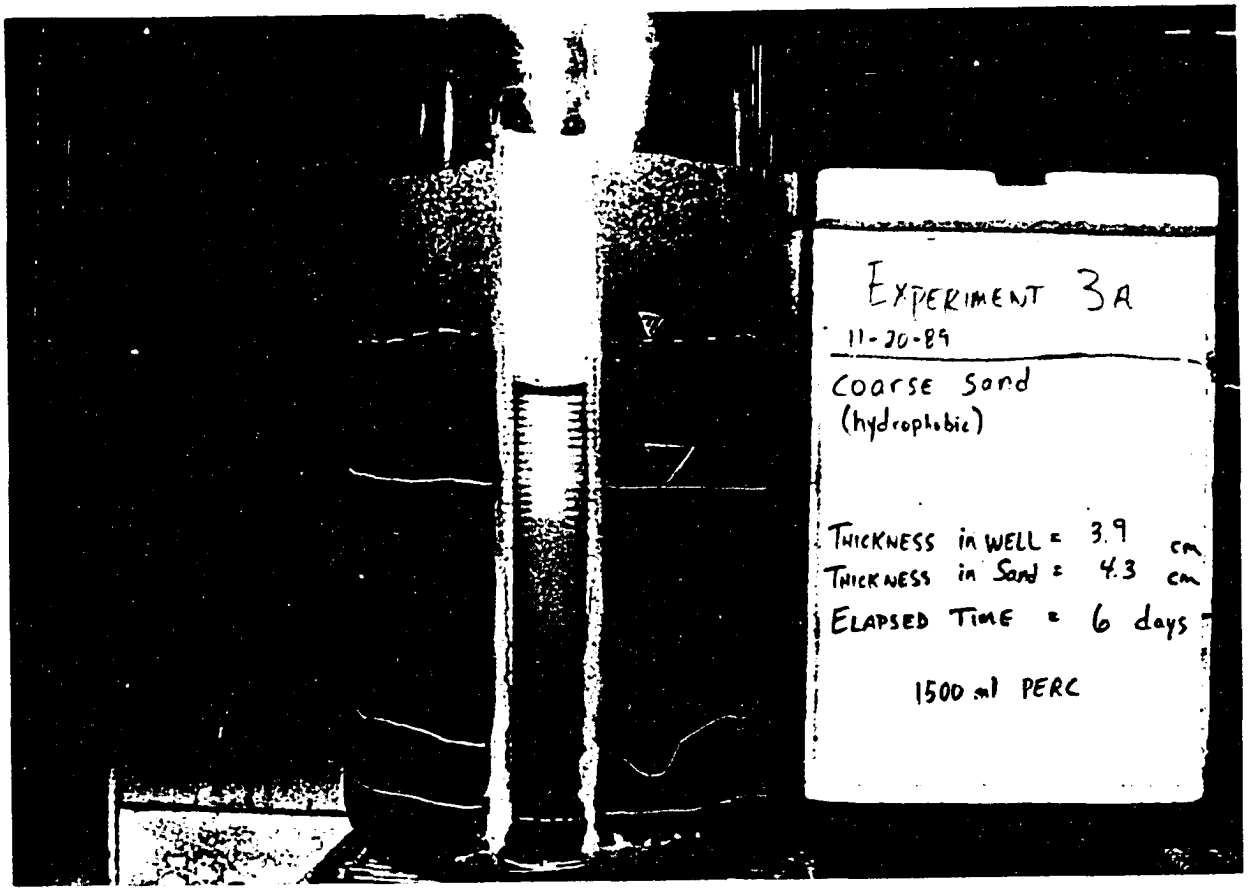

Figure 18. DNAPL Capillary Rise Above the DNAPL-Water Interface in Hydrophobic Sand; Experiment 3a.

measure. The results are presented in Figure 19.

Experiment 4

Coarse gravel was packed in the column for Experiment 4 to eliminate the capillary effects. Stringers of PER globules were observed to migrate through the large pores in the gravel. Equilibration of equal PER thicknesses in the well and sand occurred within a few minutes (Figure 20).

The results of Experiments 1, 2, and 3 indicate that DNAPL thickness in the wells exceeded DNAPL thickness in the adjacent sand. The thickness difference was greater in the fine sand than in the coarse sand. The thickness difference equals the DNAPL-water capillary fringe height, which varies with grain size of the media. The smaller the grain size, the greater the height of the DNAPL-water capillary fringe.

PER and CAM were retained at the capillary fringe boundary until they could reach the critical capillary pressure and migrate downward. Villaume (1985) suggests that the only way displacement below the water table can occur is for the DNAPLs to attain enough mass to overcome the capillary pressure by agglomerating into vertical globule stringers along interconnected pore spaces. These stringers were observed during Experiment 4 and in

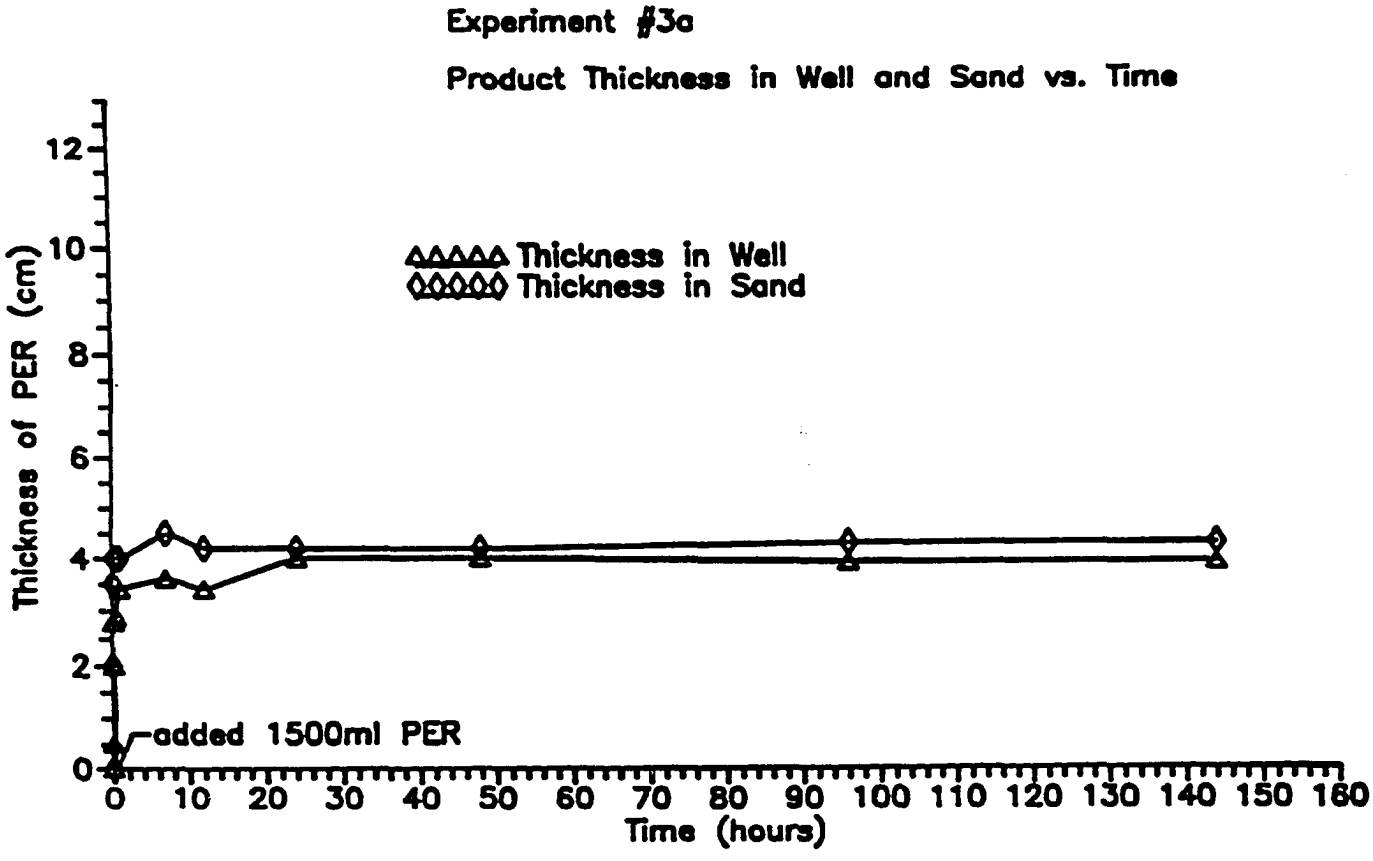

Figure 19. PER Thickness in Well and Sand During Experiment 3a.

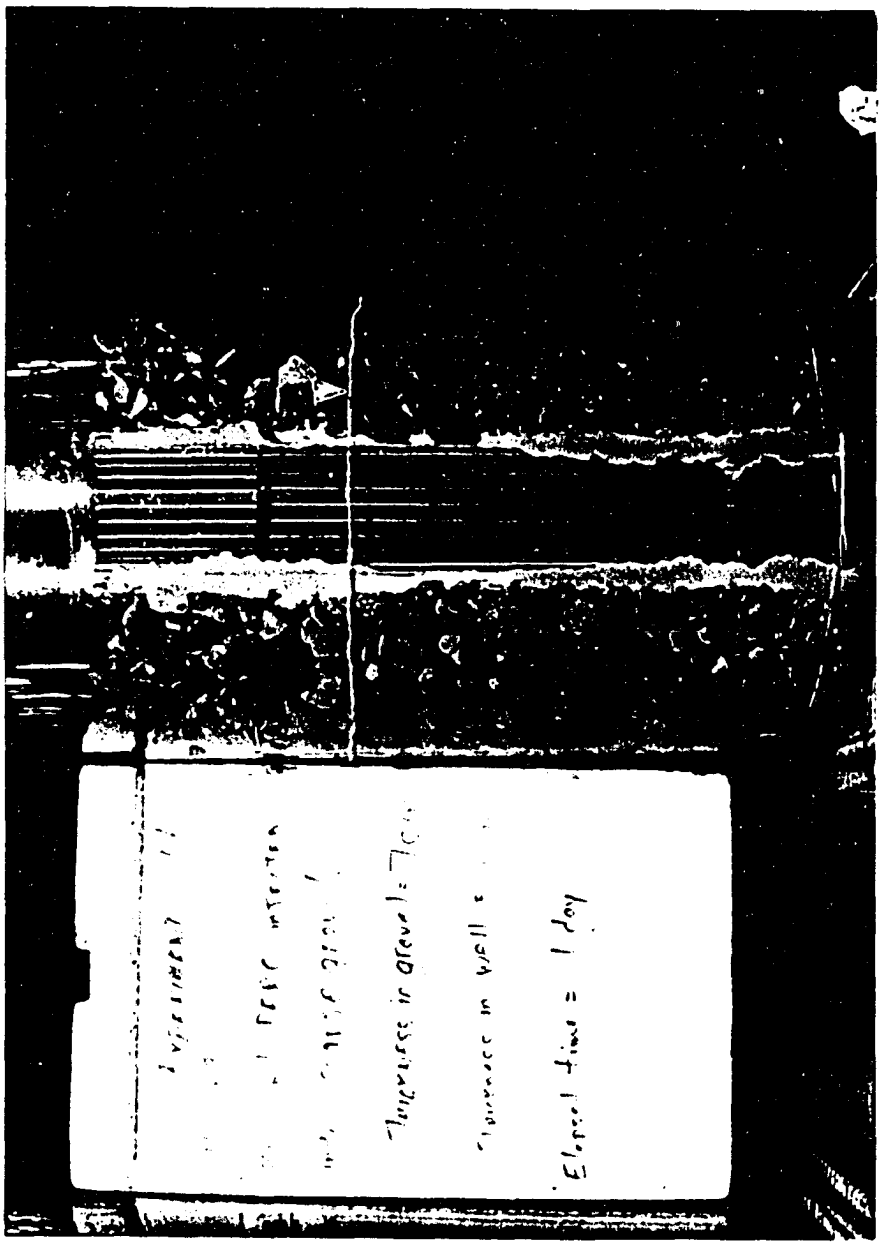

Figure 20. PER Thickness in the Well and Gravel During Experiment 4.

excavating the column packings of Experiments 1, 2, and 3. As the grain size of the media decreases, the capillary pressure increases, making it more difficult for downward migration of DNAPLs below the water table.

The pressure heads at the organic liquid-water interface will determine whether DNAPLs achieve equilibrium near the capillary fringe, near the water table, or at various depths below the water table (Cary et al., 1989).

When DNAPLs are introduced in a saturated hydrophilic medium, it is a non-wetting fluid that is immiscible with water (wetting fluid). DNAPLs can only occupy pore spaces in the saturated medium by displacing pre-existing water. As grain size decreases, permeability decreases and DNAPL transmission through the small pore spaces becomes more difficult. The well opening offers a less resistant (lower entry pressure) migration pathway. Figure 21 shows that the wells in Experiment 1 served as preferential conduits for vertical DNAPL migration. PER entered the well and migrated down its sides to the base of the well.

Cary et al. (1989) suggest that, as the DNAPL volume in the well increases, sufficient pressure head may develop to force it out through the bottom of the well. This is shown in Figures 8 and 12.

Experiments 1 and 2 showed that the clay layers remained impermeable to DNAPL migration over the time the

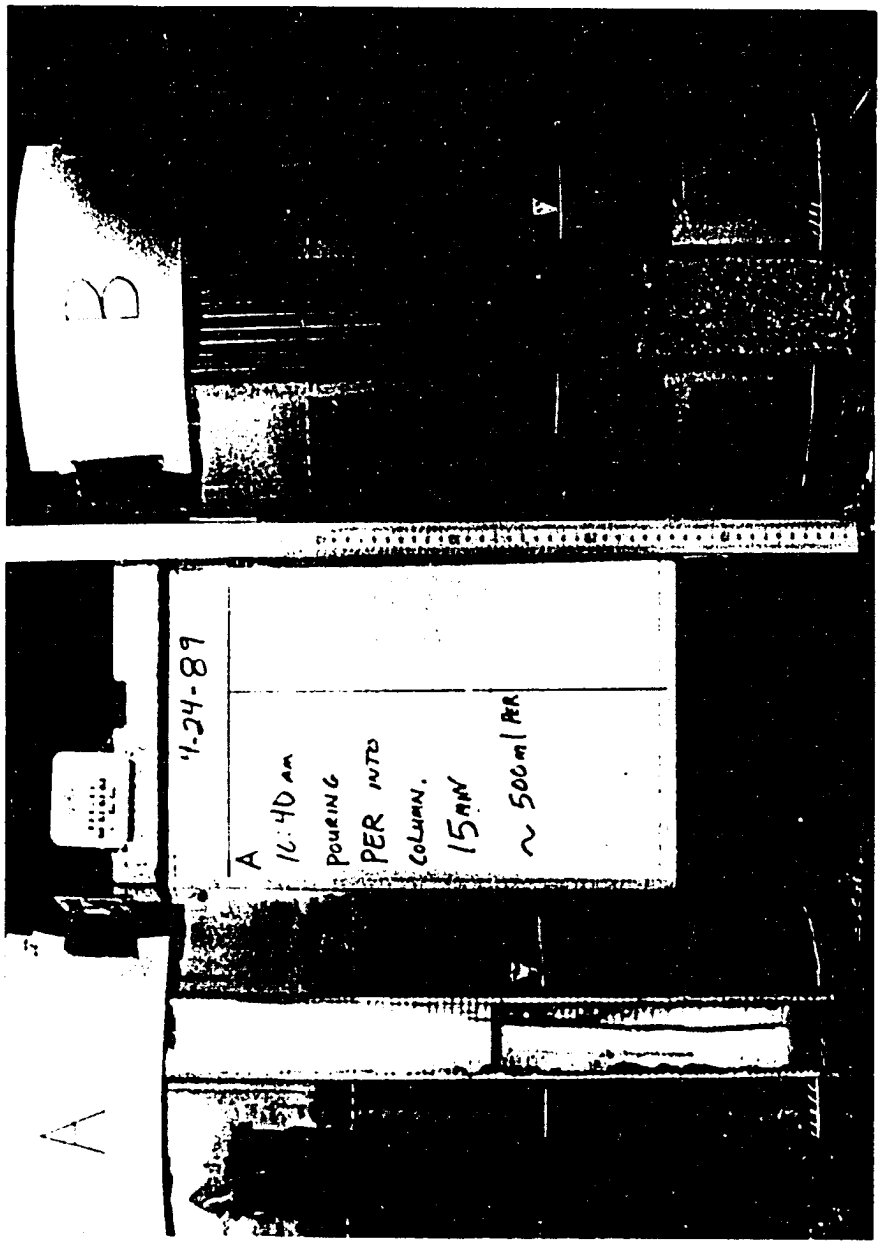

Figure 21. PER Migrating Down Well Screen in Column A During Experiment 1.

experiments were conducted. Based on observations made during the excavations, the dyed DNAPLs penetrated the 1- to 2-cm-thick clay layers approximately 2 to 3 mm.

In their 1982 study, Palombo and Jacobs mention the ability of some solvents to structurally alter a clay and make it more permeable.

Anderson et al. (1981) discovered that a clay treated with xylene (neutral non-polar compound) showed a two order of magnitude increase in permeability over a short time period.

The permeability of the clay used in Experiments 1 and 2 was not evaluated. However, the penetration of dyed-DNAPLs were evaluated over the duration of the experiments.

PER and CAM accumulated on the clay in Experiment 2 after additional volumes of each were added. However, no direct migration through the clay occurred.

The well screen materials remained unaffected by the DNAPLs used in the various experiments. No observable alterations to the well screens occurred over the short duration of the experiments.

CHAPTER IV

CONCLUSIONS

In most experiments, the DNAPL-water interface was much higher in the wells than in the adjacent sands, causing the DNAPL thickness in the wells to exceed that in the sands. The thickness difference was greater in the fine sand than in the coarse sand; there was no difference in the gravel. This thickness difference equals the height of the DNAPL-water capillary fringe, which varies with grain size. This fringe height also varies mainly with different DNAPLs and their interfacial tensions with water. DNAPL thickness in the hydrophobic sand was greater than in the well, because of the DNAPL capillary rise. Water-air-DNAPL thickness relationships observed in the experiments are summarized in Figure 22.

This study supported findings from several other studies. The experiments show that a DNAPL's migration depends upon its inherent physical properties as well as on grain size of the medium. Wells can serve as conduits for vertical DNAPL migration. The clay layers in Experiments 1 and 2 remained impermeable over the duration of these experiments.

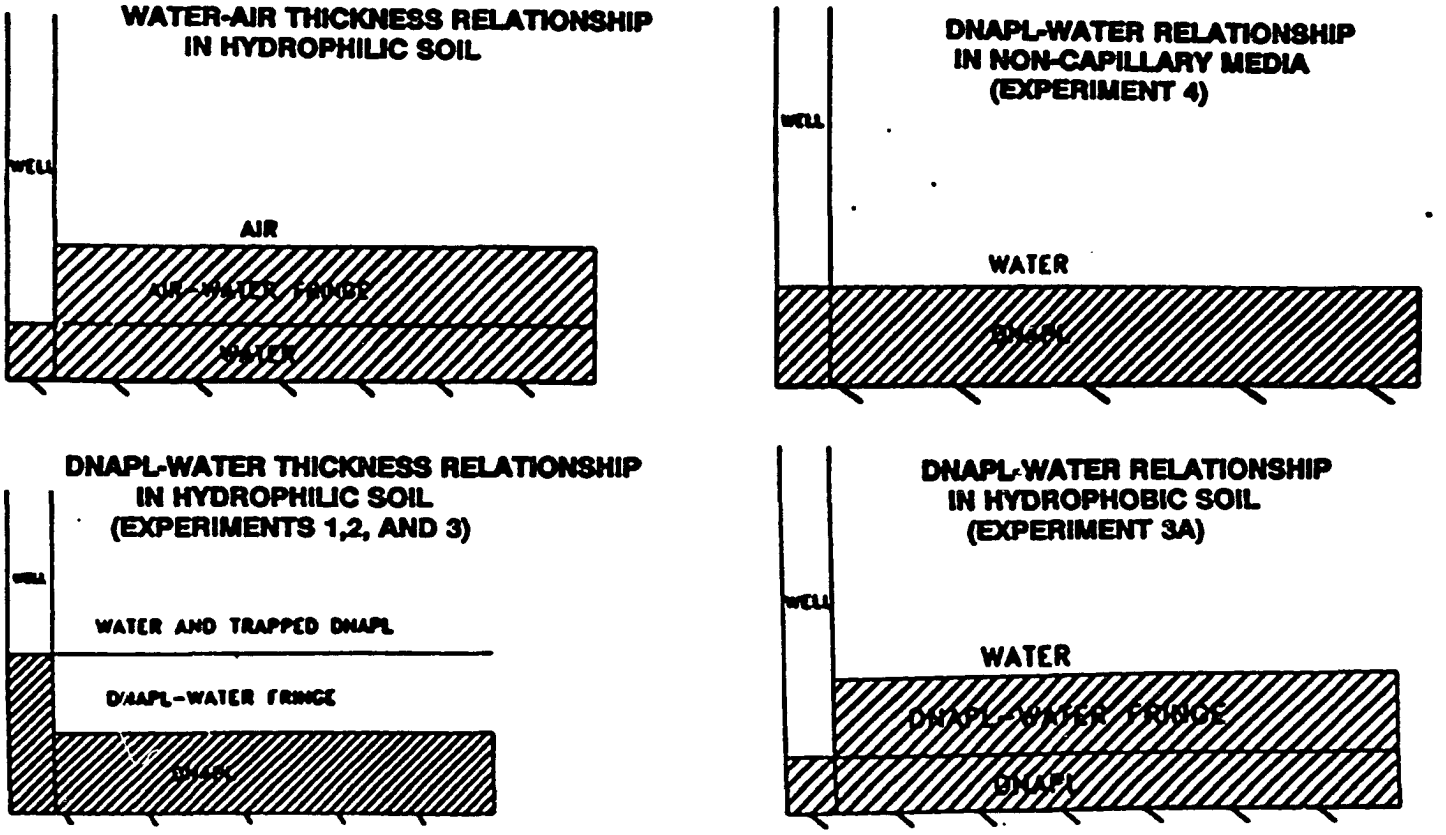

Figure 22. DNAPL-Water-Air Thickness Relatonships in Well and Adjacent Media.

BIBLIOGRAPHY

Anderson, D.C., Brown, K.W., and Green, J., 1981, Organic leachate effects on the permeability of clay liners, in Proc., Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C., Oct. 1981, 223.

Cary, C.R., McBride, J.R., and Simmons, C.S., 1989, Trichloroethylene residuals in the capillary fringe as affected by air-entry pressures: J. Envir. Quality 18:72-77.

Faust, C.R., 1985, Transport of immiscible fluids within and below the unsaturated zone: a numerical model: Water Resour. Res. 21:587-596.

Feenstra, S. and Cherry, J.A., 1988, Subsurface contamination by dense non-aqueous phase liquid (DNAPL) chemicals, in Proc: Int. Groundwater Symp. of the Int. Assoc. of Hydrogeologists, Halifax, Nova Scotia, May 1-5, 1988, 61-69.

Feenstra, S. and Kueper, B.H., 1990, Elimination of Dense Non-Aqueous Phase Liquids (DNAPLs) from fractured bedrock formations: Principles and potential remedial technologies: Prepared for ENSR Consulting and Engineering, Acton, MA.

Hampton, D.R. and Miller, D.G., 1988, Laboratory investigation of the relationship between actual and apparent product thickness in sands, in Proc: Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection, and Restoration, Houston, Texas, November 9-11, 1988, 157-181.

Palombo, D.A. and Jacobs, J.H., 1982, Monitoring chlorinated hydrocarbons in groundwater, in Proc.: Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Silver Springs, Maryland, 1982, 165-168.

Schwille, F., 1988, Dense chlorinated solvents in porous and fractured media-model experiments: Translated by J. F. Pankow. Chelsea, MI.: Lewis Publishers Inc.

Villaume, J.F., 1985, Investigations at sites contaminated with dense non-aqueous phase liquids (NAPLs): Ground Water Monitoring Review, 5(2):60-74.