# Assessment, Field Testing, and Conceptual Design for Managing Dense Non-Aqueous Phase Liquids (DNAPL) at a Superfund Site

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## Abstract

Dense non-aqueous phase liquids (DNAPL) greatly complicate groundwater remediation because the heavy DNAPL will sink and follow topographic lows within an aquifer system, and because DNAPL is difficult to extract using conventional pumping methods. These problems are now being observed at the Motco Superfund Site near Houston, Texas, where DNAPL is present in a shallow surficial aquifer. The aquifer remediation program includes these elements:

- Detailed stratigraphic interpretation of the aquifer to find “sinks" of DNAPL in the complex sand-silt aquifer system.
- A pilot recovery test to determine the effectiveness of enhanced oil recovery technologies (EOR) for mobilizing DNAPL.
- A conceptual remedial design for extracting mobile DNAPL and for managing residual DNAPL and DNAPL dissolution products

DNAPL accumulations were observed in wells screened in low spots in the shallow transmissive zone. The 60 boring and well logs at the site were supplemented with an additional seventy-three cone penetrometer logs to generate a continuous and laterally extensive stratigraphic record of the shallow aquifer system. The data were used to develop detailed topographic maps of the base of the transmissive zone to find DNAPL accumulation and to design a pilot test for recovery of DNAPL and affected groundwater. Results of this investigation showed DNAPL to be moving through fractures and other secondary porosity features of the silt stratum, in general accordance with the base topography of the unit.

The pilot test compared three recovery technologies: pumping, water flooding, and vacuum-enhanced recovery. For the vacuum-enhanced pumping scheme, the downhole pump was augmented by a wellbore vacuum to increase the available drawdown and maximum yield of the recovery well. For the water flooding scheme, a freshwater injection well was operated at a distance of 100 ft from the pumping well to increase the hydraulic gradient. A three-week testing program demonstrated that some DNAPL could be removed by pumping alone, but that waterflooding and vacuum enhanced recovery greatly increased recovery rates.

A conceptual remedial design was developed for managing the mobile DNAPL fraction and the dissolved organic constituents in the aquifer. Waterflooding and well-bore vacuums can be used to induce a high artificial gradient and mobilize some fraction of the DNAPL. After the artificial gradient is removed, the residual DNAPL would be immobilized under background gradient conditions. Design of the DNAPL management system involves two key considerations: evaluation of fracture and capillary effects to estimate residual saturation in the

unit before and after gradient application, and analysis of DNAPL dissolution rates for predicting the concentration of the soluble organic constituents in the aquifer over time.

## Project Background and Objectives

The Motco Superfund Site is a former reclamation facility that operated in the vicinity of La Marque, Texas, during the period of 1958 to 1968. Reclamation efforts involved the collection and reprocessing of petrochemical residues within an 11-acre system of earthen pits. Pit contents included styrene tars, refinery tank bottoms, and chlorinated solvents. Following abandonment of the site by the property owners, environmental investigations were commenced in 1980 by the EPA and industrial parties. At the present time, site remediation activities involve the removal and incineration of the surface pit source materials.

A principal concern of the Motco study is control of both dissolved and free-phase organic compounds detected within shallow water-bearing strata underlying the site. Hydrogeologic site investigations have shown this area to be underlain by a surface deposit of interbedded sands, silts, and clays designated the Transmissive Zone. The Transmissive Zone, extending from ground surface to a depth of approximately 50 ft below grade, is composed of four discrete stratigraphic units:

1) A surface deposit of low to high plasticity clay, extending to approximately 25 feet below ground surface,
2) A silty sand layer, designated as stratum TZ-2, extending from approximately 25 to 35 feet below grade,
3) A high-plasticity clay layer of variable thickness, termed the TZ-2/TZ-3 clay stratum, and
4) A zone of interbedded silt and silty clay layers, designated as stratum TZ-**3**, extending from approximately 40 to 50 feet below grade.

A stiff, high-plasticity clay layer, termed the UC-1 Clay, forms the base of the Transmissive Zone. Previous investigations have shown this clay unit to have an average thickness of approximately 34 feet, separating the Transmissive Zone from the underlying Upper Chicot aquifer. An idealized geologic cross-section is presented on Figure 1. As shown, the on-site pits penetrate the upper 20 feet of the Transmissive Zone.

The TZ-2 and TZ-3 strata comprise the principal conduits of shallow ground-water movement beneath this site. Water quality investigations have detected the presence of dissolved compounds in both TZ-2 and TZ-3 within the near vicinity of the pits. In addition, dense non-aqueous phase liquids (DNAPL) have been detected within these shallow water-bearing strata, typically occurring near the base of the TZ-3 permeable unit, perched atop the underlying clay layers. Due to their relatively high density and low water solubility, DNAPL fluids accumulating at the base of the TZ-3 unit appear to migrate laterally atop the underlying UC-1 Clay surface, in a general downslope direction.

In April, 1989, a DNAPL Pilot Recovery Program was commenced to evaluate the feasibility of pumped withdrawal of DNAPL fluids from shallow permeable strata underlying the Motco Site. Specific project objectives included:

- Preliminary delineation of the distribution of DNAPL fluids within both the TZ-2 and TZ-3 water-bearing units,
- Installation and testing of three alternative enhanced oil recovery (EOR) schemes for capture and removal of DNAPL fluids, and

- Development of a conceptual remedial design for integrated recovery of both dissolved and free-phase organic compounds from the Transmissive Zone strata.

The procedures and results of this design investigation are reviewed below.

## Field Investigation Program

### Cone Penetrometer Survey, Soil Borings, and Well Installation

To define potential pathways of DNAPL migration beneath the Motco Site, an extensive cone penetrometer survey was conducted to characterize the continuity and base topography of the TZ-2 and TZ-3 water-bearing units in the immediate vicinity of the waste pits. Within complex geologic environments similar to that of the Motco Site, the electric cone penetrometer has proven a cost-effective tool for such detailed stratigraphic analysis. At each sampling location, the cone yields a continuous log of minor silt, sand, and clay units without generating drill cuttings or fluids (see Figure 2). The presence or absence of perched hydrocarbon within this stratigraphic column can then be determined by means of discrete-depth soil cores or borehole fluid samples.

During March 1989, a total of 73 cone penetrometer tests were completed in the vicinity of the Motco Site at the locations shown on Figure 3. At each test location, cone tip resistance and sleeve friction were recorded continuously with depth, providing a detailed log of sand, silt, and clay units through the full thickness of the Transmissive Zone. As an indication of DNAPL presence, the return flow of grout tremied into each completed cone borehole was inspected for evidence of an oil sheen or visible oil content.

On the basis of preliminary geologic cross-sections and structure maps developed from cone penetrometer data, 15 soil boring locations were selected to confirm the presence or absence of perched DNAPL at the base of the TZ-2 and TZ-3 permeable units. Based on these soil core analyses, several wells were installed in an area of known DNAPL accumulation (see Figure 3). Recovery well RW-1 and injection well IW-1A were screened over the depths of both the TZ-2 and TZ-3 permeable units. In addition, three nested pairs of 4-inch diameter observation wells, screened within TZ-2 and TZ-3, respectively, were installed at approximate distances of 25 feet, 100 ft, and 200 ft from the pilot recovery well.

### Description of TZ-2 and TZ-3 Units and Groundwater Flow Patterns

Results of this geologic investigation confirmed the presence of two discrete horizons of permeable soils within the Transmissive Zone, corresponding to the TZ-2 and TZ-3 units. However, the cone penetrometer data demonstrated considerable variability in the thickness and continuity of these water-bearing strata beneath the study area. The TZ-2 sand layer was found to be absent beneath much of the Pit Area, occuring as a 2 to 10-foot thick, silty sand deposit only under the eastern edge of the Motco Site. The TZ-3 stratum is significantly less permeable but more laterally continuous than TZ-2. The net permeable thickness of the TZ-3 silt stratum averages 2 ft beneath the full Pit Area, thickening gradually in an eastward direction. The principal TZ-3 soil facies are comprised of silty clay and clayey silt with numerous silt seams and partings, as well as slickenside fractures. As shown on Figure 4, the base structure of TZ-3 is characterized by numerous trough features, some of which extend beneath the Pit Area.

Potentiometric data from wells screened within the TZ stratum show both the TZ-2 and TZ-3 units to be saturated and confined, with static water levels rising above overlying clay confining layers to within 5 feet of ground surface. Groundwater flow in both TZ-2 and TZ-3 is to the southeast at average flow gradients of 0.0045 and 0.0035 feet/foot, respectively.

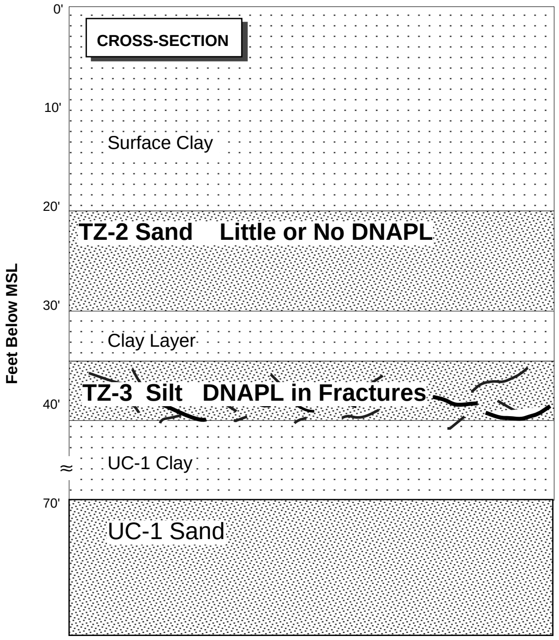


Figure 1. Idealized Cross Section of Motco Site

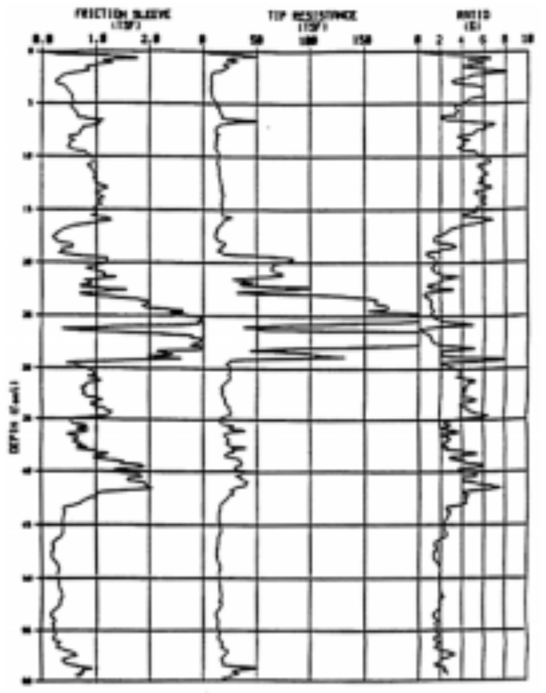


Figure 2. Cone Penetrometer Log

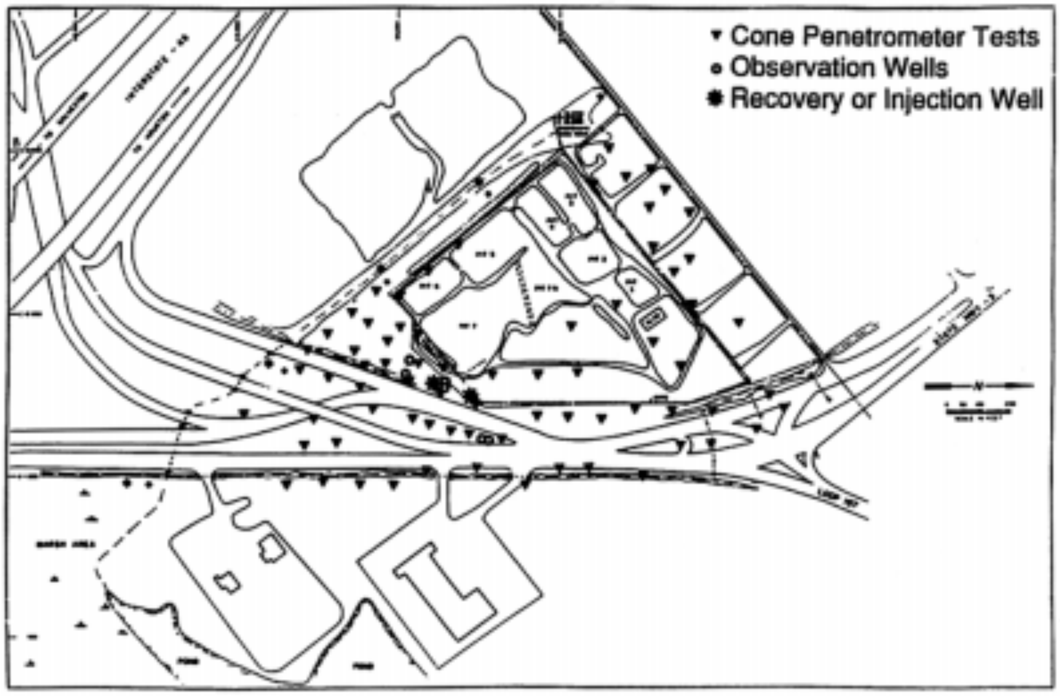


Figure 3. Base Map of Motco Site, Showing Location of Cone Penetrometer Borings and Pilot Test Well Locations

DNAPL Distribution Within TZ Units

The presence of DNAPL fluid within the Transmissive Zone extends beneath the Pit Area and includes a broad area immediately east of the Motco Site. Analysis of soil cores shows the principal pathway of this DNAPL migration to be the TZ-3 silt layer. DNAPL saturation in soil samples from the TZ-2 sand was limited to the immediate vicinity of the Pit Area. In contrast, DNAPL was observed in soil cores obtained from the TZ-3 unit at numerous boring locations spread over a significantly wider area (see Figure 5). Vertical penetration of the underlying UC-1 Clay by DNAPL was not observed to exceed 2 feet at any drilling location.

Careful inspection of soil cores from the TZ-3 unit found DNAPL to be preferentially concentrated within the slickensides, fractures, and silt partings of the predominately silty clay soil matrix, rather than uniformly distributed throughout the soil mass - a phenomenom likely related to the interfacial tension of the DNAPL fluid and the fine pore size of the silt unit. Within several TZ-3 soil cores, such DNAPL concentrations were observed perched above minor clay seams. On a macroscopic level, lateral migration of DNAPL does appear to be strongly influenced by the topography/structure of the UC-1 Clay layer which forms the base of the TZ-3 unit. Specifically, the point of maximum lateral transport as seen in Figure 5 corresponds to a significant structural trough in the base of TZ-3.

The relatively limited lateral extent of DNAPL migration within TZ-2 as compared to TZ-3 is most likely a result of 1) the density forces driving DNAPL downwards through TZ-2 sand and the slickenside fractures of the TZ-2/TZ-3 Clay, 2) the relatively low permeability and low effective porosity of the UC-1 Clay, hindering downward migration of DNAPL below the base of TZ-3, and 3) the greater lateral continuity of permeable TZ-3 strata beneath the Motco pits.

Summary of Significant Findings

- Methodology: The cone penetrometer provided a cost-effective means of defining permeable thickness and base structure of water-bearing strata within a complex alluvial environment. Furthermore, the presence or absence of an oil sheen within the return flow of grout tremied into each penetrometer hole correlated perfectly with occurrence of DNAPL, as determined by subsequent soil core analyses.

- DNAPL Migration: The distribution of DNAPL fluids within the Transmissive Zone strata suggest the principal factors in DNAPL migration to be the downward fluid density gradient and the secondary porosity features of the fine-grained sediments underlying the site. DNAPL has seeped downward from the source pits, migrating laterally via fractures, partings, and other secondary porosity features of the TZ-3 silt stratum, in general accordance with the surface topography of the underlying UC-1 Clay, a relatively low permeability, massive clay deposit.

## Pilot Recovery Test

Objectives

To evaluate the feasibility of pumped withdrawal of perched DNAPL, a pilot recovery well system was installed at the Motco Site and operated to determine the potential groundwater and DNAPL yield under three alternative operating conditions:

- Case 1: Continuous pumping only
- Case 2: Continuous pumping augmented by a wellbore vacuum
- Case 3: Continuous pumping augmented by a wellbore vacuum and freshwater injection.

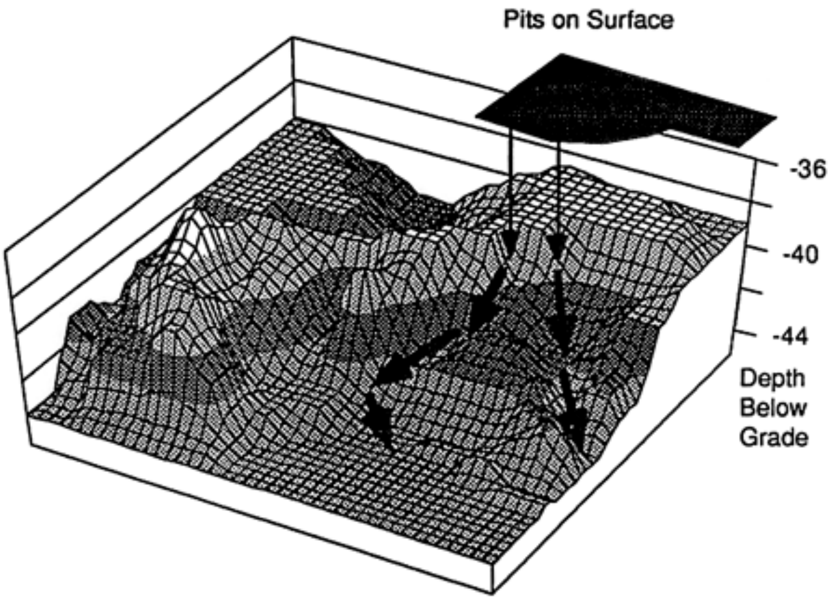


Figure 4. Surface Map of Top of Clay Unit, Showing Movement of Dense Non-Aqueous Phase Liquids (DNAPLs) Moving Down Topographic "Valleys" in TZ-3 Unit

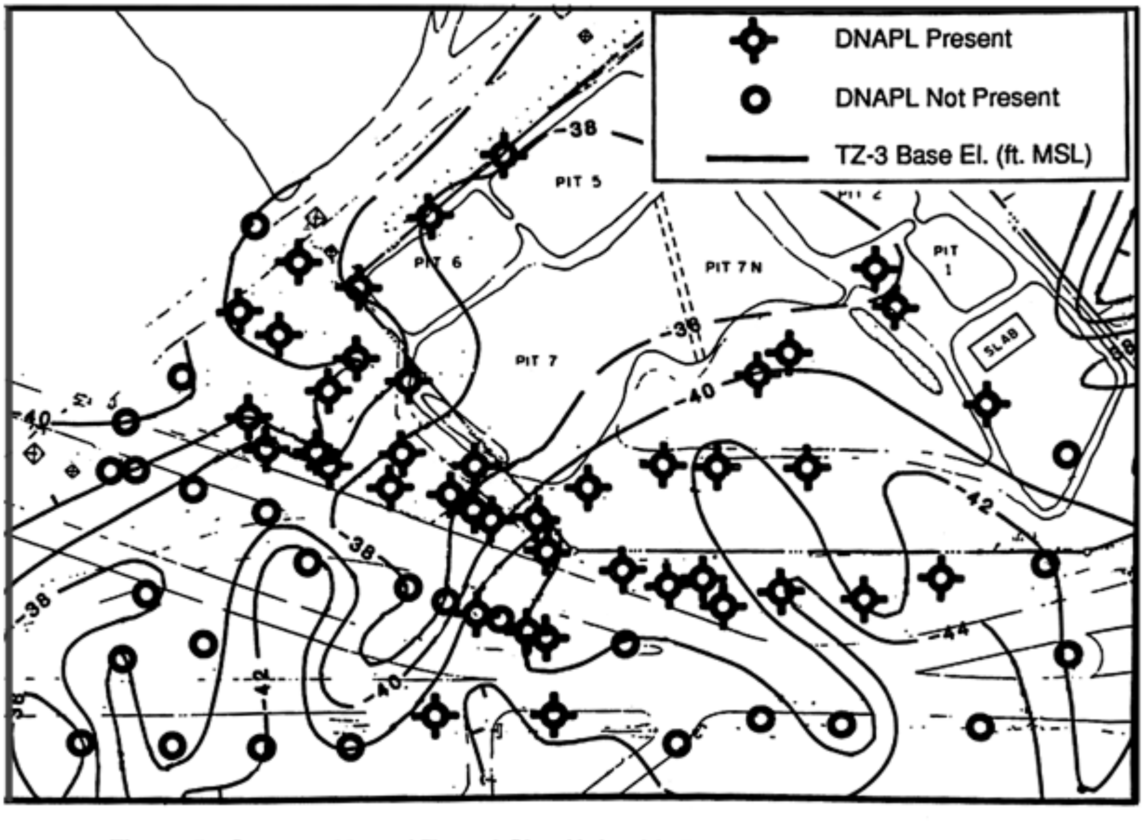


Figure 5. Contour Map of Top of Clay Unit with Range of DNAPL Occurence, Showing Correlation of DNAPL Location to Topographic Features in TZ-3 Unit

During the period of May to June, 1989, a 12-day pilot test was performed, with each operating condition being evaluated for four continuous days of operation. Results of this pilot test have been analyzed to define the critical hydraulic properties of the TZ water-bearing units and determine the optimal pumping scheme for control of DNAPL and groundwater plume migration. Test procedures and results are summarized below.

### Pilot Plant Installation

For this pilot study, one recovery well (RW-1) and one pilot injection well (IW-1A) were installed approximately 100 feet apart in an area of known DNAPL accumulation (see Figur 3). For combined pumping of groundwater and DNAPL, the recovery well was fitted with a submersible positive-displacement pump with discharge routed to two 4000-gallon holding tanks to permit measurement of oil/water percentages on 12-hour batch samples. For application of a wellbore vacuum, the suction intake of a 5 HP vacuum pump was piped directly to the recovery well casing. General piping and instrumentation design for this skid-mounted pilot plant are shown on Figure 6.

To facilitate continuous injection of freshwater to the TZ-2 and TZ-3 permeable units, a skid-mounted standpipe assembly was installed adjacent to the injection well. The standpipe unit was designed to maintain a relatively constant injection head over a pressure range of 1-13 ft $H_2O$ above ground surface.

### DNAPL Recovery Pilot Test Procedures

In May, 1989, a continuous, 12-day pilot test was commenced to determine recovery system production under the three alternate operating conditions. Groundwater pumping rates, vacuum levels, and injection well flowrates employed for each of the three operating conditions are summarized on Figure 7. Throughout the test period, DNAPL accumulation at the base of the recovery well holding tanks was measured at 12 to 24-hour time intervals. Static water level variations within the observation wells were monitored continuously using an electric pressure transducer network. To detect DNAPL flow within the TZ-2 and TZ-3 units, DNAPL accumulation at the base of each observation well was checked at maximum 1-day intervals using weighted cotton cord.

### Evaluation of Aquifer Hydraulic Characteristics

Table 1 summarizes the aquifer transmissivity, storage, and hydraulic conductivity values calculated on the basis of pumping test and slug test data. Representative T and S values determined for the TZ-2 sand stratum are 500 gpd/ft and $5\text{x}10^{-4}$, respectively, corresponding to a soil hydraulic conductivity of approximately $3\text{x}10^{-3}$ cm/sec. For the TZ-3 unit, test results indicate average T and S values of 5 gpd/ft and $1\text{x}10^{-4}$, with the hydraulic conductivity of the silt soils averaging approximately $1\text{x}10^{-4}$ cm/sec.

### DNAPL Production Data

Throughout the 12-day test, recovery well RW-1 produced oily groundwater with a strong organic odor. The oil content of well discharge varied in proportion to the well flowrate, ranging from minor oil droplets at a pumping rate of 1 gpm to a significant oil fraction at a pumping rate of 10 gpm. Measurements in the DNAPL holding tanks indicated that the oil fraction in recovery well discharge averaged approximately 1-2% over the pumping range of 1 to 3 gpm. Observation well data indicates that oil produced by the pumping well came primarily from the TZ-3 stratum. Pumping test results show that the TZ-3 unit contributed only 5% of the total fluid flow from well RW-1. Consequently, the 1-2% oil fraction measured in the

DNAPL Recovery Pilot Test
Motco Site, LaMarque, Texas

**Pump Test Summary**

| Well | Zone | Q (gpm) | Δs (ft) | r (ft) | b (ft) | S | **K (ft/day)** | **K (cm/sec)** | **T (gpd/ft)** | **T (ft2/day)** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P-RW1 | Both | 2.5 | 6.77 | 1 | 9.5 | 4.E-03 | 1.4 | 4.8E-04 | 97 | **13** | * |
| P-IW1A | Both | 2.5 | 0.88 | 112 | 10.0 | 5.E-04 | 10.0 | 3.5E-03 | 750 | **100** | |
| GW-1S | TZ-2 | 2.375 | 1.63 | 27.5 | 9.5 | 7.E-04 | 5.4 | 1.9E-03 | 385 | **51** | |
| GW-2S | TZ-2 | 2.375 | 1.16 | 100.1 | 10.0 | 6.E-04 | 7.2 | 2.5E-03 | 541 | **72** | |
| GW-3S | TZ-2 | 2.375 | 0.76 | 198.3 | 9.0 | 3.E-04 | 12.3 | 4.3E-03 | 825 | **110** | |
| | | | | | | Average TZ-2 Wells: | **8.3** | **2.9E-03** | **583** | **78** | |
| GW-1D | TZ-3 | 0.125 | 10.69 | 25.5 | 1.5 | 2.E-04 | 0.3 | 9.7E-05 | **3.1** | **0.4** | |
| GW-2DA | TZ-3 | 0.125 | 4.58 | 98.4 | 1.0 | 7.E-05 | 1.0 | 3.4E-04 | **7.2** | **1.0** | |
| GW-3D | TZ-3 | 0.125 | 0.88 | 203.7 | 5.0 | 3.E-05 | 1.0 | 3.5E-04 | **37.5** | **5.0** | ** |
| | | | | | | Average TZ-3 Wells: | **0.7** | **2.6E-04** | **15.9** | **2.1** | |

Assuming 95% Flow from TZ-2
* Possible Well Efficiency Effects
** Possible Combined TZ-2 and TZ-3 Effects

**Slug Test Summary**

| **Well** | **R (ft)** | **Ro/R** | **b (ft)** | **Δt (secs.)** | **H1** | **H2** | **K (ft/day)** | **K (cm/sec)** | **T (gpd/ft)** | **T (ft2/day)** |
|---|---|---|---|---|---|---|---|---|---|---|
| GW-1S | 0.168 | 200 | 9.5 | 167 | 0.4 | 0.1 | 5.6 | 2.0 e-3 | 400 | **53** |
| GW-2S | 0.168 | 200 | 10.0 | 239 | 0.7 | 0.2 | 3.4 | 1.2 e-3 | 253 | **34** |
| GW-3S | 0.168 | 200 | 9.0 | 144 | 0.7 | 0.1 | 9.7 | 3.4 e-3 | 651 | **87** |
| | | | | | | Average TZ-2 Wells: | **6.2** | **2.2 e-3** | **435** | **58** |
| GW-1D | 0.168 | 200 | 1.5 | 11600 | 0.9 | 0.5 | 0.2 | 7.7 e-5 | 2 | **0.3** |
| GW-2DA | 0.168 | 200 | 1.0 | 9750 | 0.9 | 0.6 | 0.3 | 9.6 e-5 | 2 | **0.3** |
| GW-3D | 0.168 | 200 | 5.0 | 1164 | 0.9 | 0.7 | 0.3 | 9.8 e-5 | 10 | **1.4** |
| | | | | | | Average TZ-3 Wells: | **0.3** | **9.0 e-5** | **5** | **0.7** |

R= Radius of Well
b = Permeable Thickness at Well
Δt = time from Slug Test Plot
H1 = Head Ratio 1 from Slug Test Plot
H2 = Head Ratio 2 from Slug Test Plot

From Design Manual 7.1 - NAVPAC
Horslev Method of Field Permeability Tests
Shape Factor 3, Table 15  Fully Penetrating Well

Table 1.  Pump Test and Slug Test Results

recovery well discharge represents a 20-40% oil concentration in groundwater produced from TZ-3. At an average pumping rate of approximately 2 gpm, total oil production at recovery well RW-1 ranged from approximately 30-60 gallons/day throughout the 12-day test

Plots of daily DNAPL level measurements within the primary observation wells show a significant increase in DNAPL accumulation within TZ-3 wells immediately following recovery well start-up, with a continued increase occurring throughout the full 12-day test period (see Figure 8 In fractured, fine-grained soil deposits such as the TZ-3 silt stratum, heavy oil levels accumulating within monitoring wells do not represent the actual depth of DNAPL saturation within the formation but more directly correspond to “sump" drainage of the various secondary features intersected by the well screen. Under pumped conditions, DNAPL levels within such observation wells can therefore be expected to increase at a rate proportional to the induced oil flow in the aquifer.

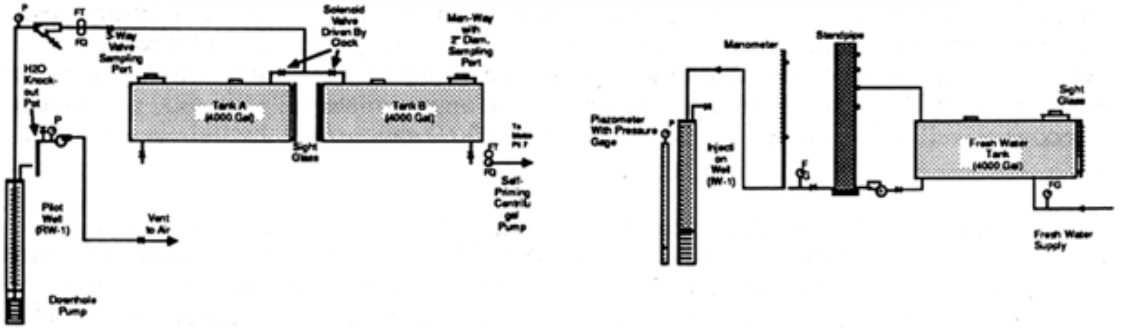
### Relative Performance of Alternative Pumping Schemes

Pumping rate and water level drawdown data collected during the 12-day test were analyzed to compare the relative hydraulic performance of the three alternative pumping schemes employed in this pilot test. In the absence of vacuum application or water injection, recovery well RW-1 could be pumped at a maximum continuous flowrate of approximately 1.7 gpm. Within such low-yield aquifer units, vacuum application can significantly improve the pumping capacity of a recovery well by artificially raising the pumping water level within the wellbore. For each foot $H_2O$ of vacuum applied, the water level in the well is raised by 1 foot, providing additional “available drawdown" and a proportional increase in the well pumping capacity. At recovery well RW-1, test results show the maximum long-term well yield under a 20 ft $H_2O$ wellbore vacuum to be approximately 2.5 gpm, a 50% increase over pumping alone. To test the additional influence of waterflooding on recovery well yield, injection well IW-1A was activated during the final phase of the 12-day pilot test. Continuous freshwater injection at the rate of 1.5 gpm was found to increase the vacuum-enhanced pumping capacity of well RW-1 to approximately 3.4 gpm, doubling the initial maximum yield of the recovery well.

Throughout the 12-day pilot test, the total oil content of well RW-1 discharge averaged approximately 1-2% of the total fluid volume. No significant variation in the fraction of DNAPL produced was detected among the three alternate modes of operation. Consequently, daily DNAPL production increased in direct proportion to the maximum yields determined for Cases 1, 2, and 3. In addition to an increased rate of oil production, the ultimate degree of DNAPL removal from the TZ units can be expected to improve under the vacuum-enhanced and waterflooding modes of operation. Hydraulic flow gradients induced within the TZ-3 stratum over the course of the pilot test ranged from 40 to 60 times the normal flow gradient measured in this water-bearing unit. For long-term operation of the recovery well system, an increased flow gradient should mobilize a larger fraction of the free oil present within the TZ permeable strata, resulting in a lower residual DNAPL concentration within TZ-3 soils.

### Significant Findings

- Feasibility of DNAPL Recovery: Results of the pilot test demonstrated that mobile DNAPL could be recovered from the Transmissive Zone strata by means of groundwater pumping. As evidenced by DNAPL accumulation within nearby observation wells during recovery well operation, hydraulic gradients 40 to 60 times greater than normal are capable of overwhelming density forces and inducing DNAPL flow within the aquifer.



Pumping Well and DNAPL Collection System

Injection Well and Standpipe System

**Figure 6. Pilot Test Equipment Schematic Showing Piping and Instrumentation**

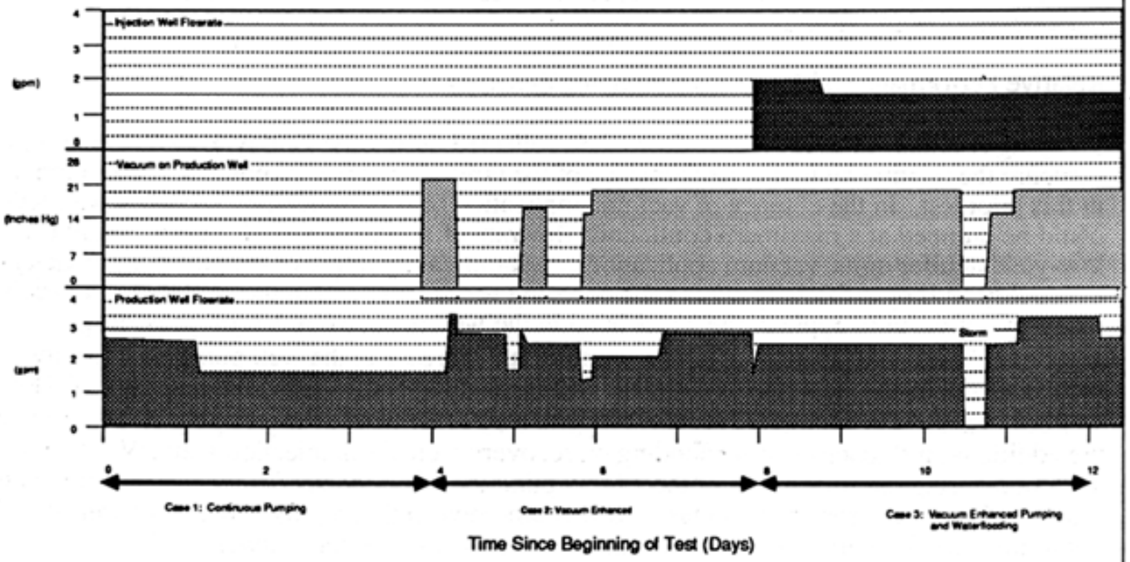


**Figure 7. Pilot Test Operating Conditions: Pumping Rate, Wellbore Vacuum, and Injection Well Flowrate**

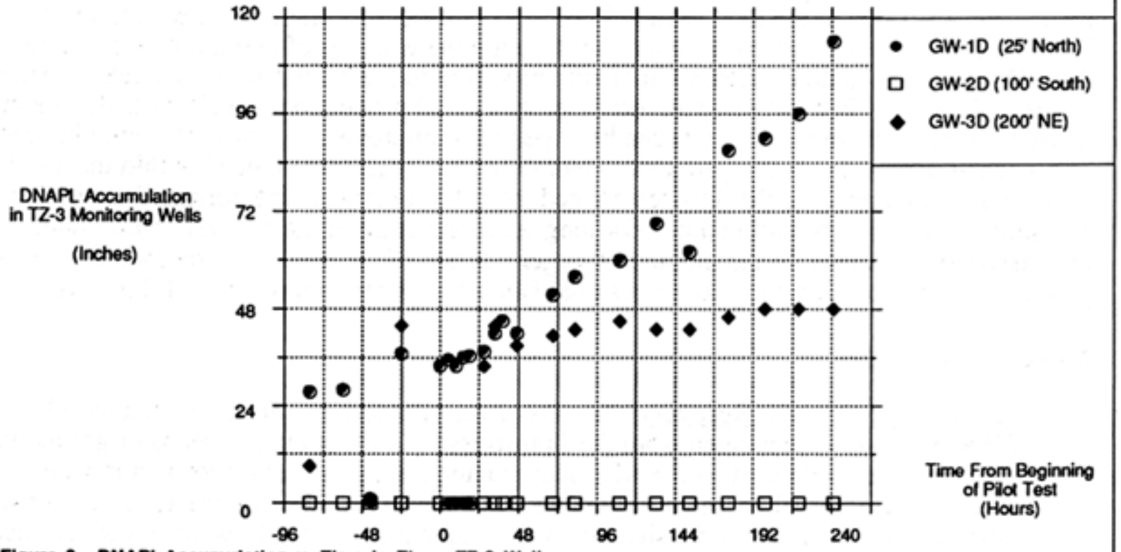


**Figure 8. DNAPl Accumulation v. Time in Three TZ-3 Wells**

- Optimal Pumping Scheme: Test results indicate that either of the three pumping schemes should prove effective for groundwater recovery from TZ-2 and groundwater/DNAPL recovery from TZ-3. However, due to improved well yield and higher induced flow gradients, vacuum-enhanced pumping (Case 2) and waterflooding (Case 3) offer significant advantages in terms of the rate and potential degree of DNAPL removal.

## Conceptual Design for DNAPL Recovery

### Theoretical Considerations

Hydrogeologic studies performed to date at the Motco Site have detected the presence of dissolved organics within TZ unit groundwater over an area extending southeast of the Motco pits, in the direction of natural groundwater flow. In addition, DNAPL is present near the base of the TZ-3 stratum, migrating laterally atop the underlying clay stratum, in general accordance with clay surface topography. To prevent further migration of dissolved and free-phase organics within the local groundwater flow regime, the recovery well system should be designed to control fluid flow over the full plume area.

Pumped withdrawal of the dissolved organic plumes can be designed on the basis of conventional advection-dispersion-adsorption equations, providing continuous reduction of solute concentrations over time until an appropriate aquifer restoration standard is achieved. However, the ultimate degree of DNAPL recovery from these water-bearing units will be limited by the effect of capillary forces acting on the viscous hydrocarbon fluid. Commonly, following pumped removal of free hydrocarbons, 10-50% of the initial hydrocarbon mass remains immobilized within the pores and fractures of the aquifer media. The water-soluble fraction of this residual DNAPL can serve as a long-term source of dissolved organic release to local groundwater. Pumped removal of the mobile portion of the DNAPL does reduce the potential for continued migration of free-phase material. Nevertheless, long-term management of the DNAPL plume should address potential dissolution products from the DNAPL residual. Proper design of a DNAPL recovery well system requires careful consideration of the mechanisms of hydrocarbon flow and capillary retention.

Under natural conditions, non-aqueous phase liquids migrate as a continuous separate phase under the influence of capillary, viscous, and gravity forces. However, once the source of the hydrocarbon has been eliminated, the continuous phase hydrocarbon mass breaks up, trapping some of the hydrocarbon fluid as “blobs" or “ganglia" within the aquifer pores. This interaction of residual hydrocarbons with the aquifer solids cannot be accurately characterized as an adsorption phenomenom (Hunt et al, 1988). Rather, residual saturation has been shown to be a function of the ratio of the capillary forces and viscous forces (i.e. groundwater flow) acting on the oil mass (Wilson and Conrad, 1984; Hunt et al, 1988). For a given aquifer system, residual saturation can be estimated by the capillary number, $N_C$, a dimensionless ratio of capillary and viscous forces, calculated as:

$$N_C = V * \mu_W / \sigma$$

where: $V$ = Darcy velocity (cm/min) = $K * i$
$K$ = aquifer hydraulic conductivity (cm/min)
$i$ = hydraulic flow gradient (cm/cm) of the aquifer fluids
$\mu_W$ = dynamic viscosity (gm/cm-sec) of water, and
$\sigma$ = interfacial tension (dyne-cm) of the oil/water media.

As shown on Figure 9, a characteristic curve defining the relationship of residual hydrocarbon saturation to capillary number can be established for a given aquifer/hydrocarbon system. Laboratory research indicates that hydrocarbon blobs or ganglia held within the soil pores will begin to mobilize once the capillary number exceeds a threshold value $N_C*$, and that nearly all of the residual hydrocarbon will be displaced if the capillary number exceeds an upper value of $N_C**$ (Larson et al, 1981; Chatzis and Morrow, 1981; Wilson and Conrad, 1984). As suggested by the above equation, the effective capillary number for any aquifer system can be varied by adjusting the hydraulic flow gradient acting on the area of concern.

Application of this idealized flow mechanism to the design of a DNAPL recovery system is illustrated on Figure 9. Following removal of continuous phase hydrocarbon, residual DNAPL can be mobilized if the effective capillary number is increased to a value $N_C'$, exceeding the threshold value $N_C*$ required for mobilization of trapped ganglia. Once residual saturation has approached equilibrium under this artificial gradient, the recovery system may be scaled down, allowing the aquifer flow gradient and capillary number to return to near background conditions. At that time, the factor of safety against further migration of free DNAPL fluid within the aquifer may be estimated as the ratio of the induced flow gradient to the maximum future flow gradient likely to occur within the aquifer.

Following this stabilization of DNAPL fluid within the aquifer pore space, dissolution of water-soluble constituents from the residual DNAPL mass may serve as a continued source of organic release to local groundwater. Potential dissolution rates can be estimated on the basis of continuous mass transfer from the cumulative ganglia surface area to passing groundwater (Hunt et al, 1988). As noted earlier, DNAPL migration beneath the Motco Site occurs primarily via fractures, partings, and other secondary porosity features of the TZ-3 silt stratum. At present, soil core analyses are underway to estimate the capillary effects and effective porosity of this fracture network.

### Conceptual Design for DNAPL Management at the Motco Site

As shown by the DNAPL recovery pilot test, mobile DNAPL fluid can be removed from the Transmissive Zone strata by means of groundwater pumping. Under long-term operating conditions, DNAPL production at each recovery well location can be expected to attenuate as the mobile fraction of the DNAPL is drained from the TZ-3 stratum. As illustrated on Figure 10, the conceptual DNAPL management program would consist of three distinct phases: 1) removal of continuous phase DNAPL fluid, 2) reduction of DNAPL residual below background concentrations, and 3) containment of DNAPL dissolution products. Phase 1 and 2 would require installation of a sufficient number of recovery wells to adequately reduce DNAPL concentrations within the desired operating period. As depicted on Figure 10, the total DNAPL yield of this recovery system will ultimately diminish to a negligible percentage of the initial production rate, indicating effective recovery of mobile DNAPL within the zone of influence of the pumping system. Phase 3 of the DNAPL management program may then involve the continued operation of selected wells for the purpose of hydraulic gradient control.

An integrated system for management of both the dissolved and free-phase organic plumes detected beneath the Motco Site is shown on Figure 11. To prevent further plume migration, this conceptual pumping scheme has been designed to 1) control lateral hydraulic gradients over the affected area of the TZ-2 sand stratum, 2) control lateral hydraulic gradients and recover DNAPL from the TZ-3 silt stratum, and 3) alleviate hydraulic potential for downward solute migration from the affected area of TZ-3 to the underlying UC-1 sand unit. Based on the results of the pilot test, recovery wells equipped with simple submersible pumps should be adequate to control flow within the TZ-2 sand layer. However, vacuum-enhanced pumping wells augmented by freshwater injection wells will likely prove necessary to maintain hydraulic

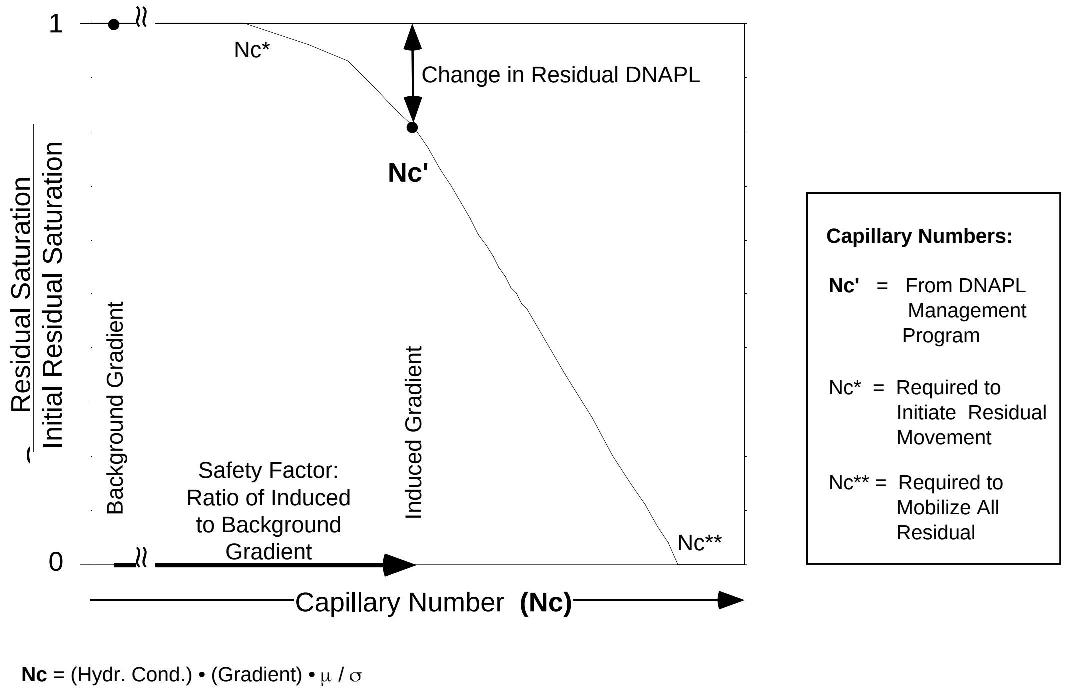


**Figure 9. Capillary Number vs Residual DNAPL**

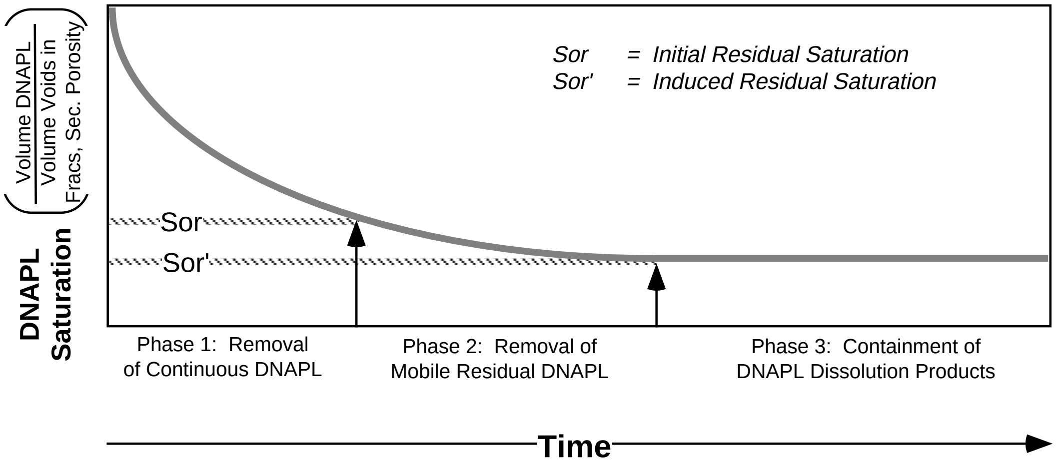
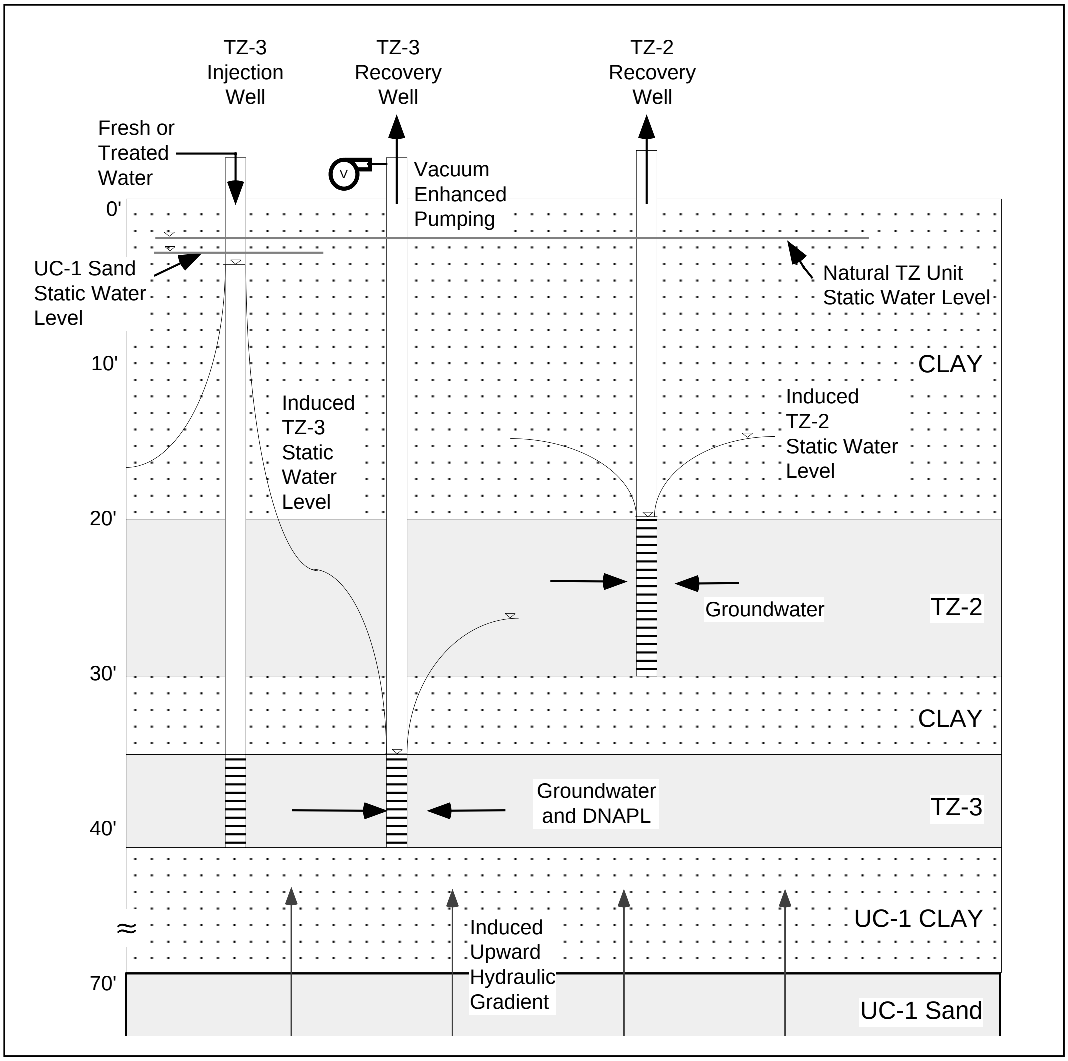


**Figure 10. Conceptual Design Phases: DNAPL Production vs. Time**



**Conceptual Design Criteria:**

- **TZ-2 Unit:**
  1). Hydraulic Gradient Control of TZ-2 Groundwater Plume
- **TZ-3 Unit:**
  1). Hydraulic Gradient Control of TZ-3 Groundwater Plume
  2). Recovery of Mobile DNAPL
- **UC-1 Sand:**
  1). Induce Upward Hydraulic Gradient from UC-1 Sand to TZ Unit

**Figure 11. Conceptual Recovery System Design for TZ-Units**

flow gradients sufficient for DNAPL displacement from the TZ-3 silt stratum. The potential for downward solute transport through the UC-1 clay layer can be alleviated by balancing hydraulic head pressures at TZ-3 pumping and injection wells to maintain an upward flow gradient from the UC-1 sand.

Final design specifications for this proposed recovery system are presently being developed using the OASIS groundwater flow modeling system, calibrated to the aquifer hydraulic conditions measured during the pilot recovery test (Newell, Haasbeek, and Bedient, 1990).

## Biographical Sketches

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