Capillary Pressure and/or Mass Flux used in conjunction with Primawave is Patent Pending

Mobilizing Residual Non-Aqueous Phase Residual Contamination Using Pressure Pulse Technology

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Introduction

A small electrical substation in the Northeastern United States operated from 1925 until 1985 when it was decommissioned and all electrical equipment removed, leaving a level, gravel-covered surface and concrete pads. The pads supported transformers and electrical equipment containing dielectric fluid that leaked into the subsurface. Testing indicated that the mineral oil-based dielectric fluid was a light non-aqueous phase liquid (LNAPL) with a specific gravity of 0.90. The dielectric fluid served as a heat moderating medium that contained polychlorinated biphenyls (PCBs). Groundwater monitoring wells installed in 1996 as part of a site investigation displayed varying thicknesses of LNAPL. PCB concentrations in the LNAPL measured 1.1, 163, 214, and 328 mg/kg.

Nature of Issue

A subsurface investigation found the bulk of the LNAPL in the smear zone near the water table and within the capillary fringe, approximately 15 (4.6 meters) to 19 feet (5.8 meters) below grade. This left separate phase LNAPL and residual non-aqueous phase liquid (R-NAPL) as the issues driving remediation. The regulatory agency wanted the PCB-containing LNAPL and R-NAPL removed to prevent off-site migration, reduce groundwater impacts, and to remove as much of the PCB mass as feasible. Nearby residences were potential receptors.

Removing separate phase LNAPL is accomplished using a variety of conventional methods, but conventional removal leaves the bulk of the NAPL behind as an immobile residual. Wilson and Conrad 1984 recognized the difficulties posed by residual NAPL: "The trapped hydrocarbon remains as pendular rings, and/or isolated, essentially immobile blobs. Residual hydrocarbons act as a continual source of contaminants as, for example, water coming into contact with the trapped immiscible phase leaches soluble hydrocarbon components." In all but the most permeable soils R-NAPL movement cannot be effectively achieved because of the large hydraulic gradients required (Wilson and Conrad 1984).

Wiedemeier et al. 1999, as adapted from Wilson and Conrad 1984, note the difficulty in mobilizing residual NAPL and indicate that in porous media with a hydraulic conductivity of 10^{-3} cm/sec a hydraulic gradient of approximately 40 ft/ft is necessary to mobilize the residual. The required gradient increases linearly with further reductions in hydraulic conductivity, making R-NAPL mobilization all but infeasible using conventional approaches. Viscous fingering exacerbates the difficulty, but this is beyond the scope of this paper.

The first step in removing separate phase product at the former substation was to obtain an estimate of the LNAPL available for recovery. The second step was to remove the R-NAPL. An earlier estimate of recoverable separate phase LNAPL, using a conventional volume estimation approach (LNAPL thickness in wells x volume of impacted soil x porosity), yielded a recoverable LNAPL volume of 2,725 gallons (10.3 m^3).

LNAPL recovery began with hand bailing, but a product-only recovery system was eventually installed in May 2001 that operated for 15 months. The product-only recovery system removed

approximately 37 gallons (0.14 m³) of separate phase LNAPL, but was discontinued because of low recovery. Subsequently, monthly vacuum enhanced fluid recovery (VEFR) began in September 2002 in an attempt to more aggressively remove LNAPL. VEFR continued, intermittently, until October 2005, when it was terminated, again because of insufficient recovery.

After several years of hand bailing, skimming, and vacuuming, it became clear that LNAPL recovery reached diminishing returns and that the bulk of the product remained immobilized as residual. The estimated total recovered LNAPL volume by all conventional means, after four and a half years, was 90 gallons (0.34 m³), compared with the original estimate of 2,725 gallons (10.3 m³).

The owner reviewed the proposed treatment methods and concluded that pump-and-treat would need to continue for years and would ultimately be ineffective; and pump-and-treat would also fail to remove residual LNAPL, leaving the bulk of the contaminant behind. Excavation would be effective, but it would be time consuming, very expensive, and complicated as shoring and dewatering were required and space was severely limited. Major excavation constraints were that LNAPL occurred at depth and residences bordered the site.[1]

Purpose and Scope

In the search for a more viable and cost effective alternative, the owner considered Primawave™ (Primawave) formerly known as Pressure Pulse Technology. Primawave has been proven in the field in various scenarios since 2000, but remains a relatively underutilized technology that appears promising because it can promote faster and less cumbersome remediation. The advantages of Primawave are that it is an *in situ* process using wells or direct-push technology, thus eliminating excavation; it is potentially quick, a few days, weeks, or months of treatment, versus months, years, or decades of conventional treatment; Primawave can increase product recovery; and it can potentially mobilize R-NAPL for removal and/or treatment. Primawave was also potentially far less expensive than excavation. Considering the potential benefits, the owner decided to pilot test Primawave with several objectives in mind.

Pilot Test Objectives

The pilot test focused on two key issues: (1) the volume of recoverable LNAPL and residual and (2) whether LNAPL recovery could be enhanced using Primawave. To address the first issue, the goal was to develop a reliable estimate of recoverable separate phase LNAPL. This was completed using the capillary pressure methodology developed by Farr, Houghtalen, and McWhorter 1990, and Lenhard and Parker 1990. To address the second issue, the pilot test was implemented to answer the following questions: (1) Can separate phase LNAPL be mobilized and recovery enhanced? (2) Can R-NAPL entrapped in soil be remobilized for recovery and to what extent? (3) How long does the process take? (4) What is the treatment distance or radius of influence?

Site Setting

The site is a trapezoidal-shaped parcel in a mixed commercial/residential area of the Northeastern United States. The site is level, occupies approximately 0.2 acres (0.08 hectares) and has the dimensions of approximately 160 feet (49 meters) by 65 feet (20 meters). The

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[1] Ultimately, the site was excavated because of concerns about PCBs in soils at depth. No LNAPL was observed during extensive excavation that went well below the water table and smear zone.

former substation service building (Facility) fronts the site on the south side, private homes border the site on the north side, and a street and secondary road border the site on the east and west sides, respectively. Figure 1 shows the site layout. There are no streams or water bodies on the site, but a creek lies 3,200 feet (975 meters) to the west.

Site Geology and Hydrogeology
The site is underlain by fill and natural sediments. Approximately 8 feet (2.4 meters) of clean fill replaced contaminated soil excavated in 1990. Below the clean fill the sediments are predominately yellow-brown, dark brown, grey, and orange-brown silty fine, medium, and coarse sands with trace gravel that range in compactness from medium dense to dense, but are occasionally loose to very dense. Depth to groundwater ranges from 15 (4.6 meters) to 19 feet (5.8 meters) below grade with an annual fluctuation of 2 feet (0.2 meters) to 4 feet (1.2 meters). Groundwater flow is to the west-southwest. The hydraulic gradient ranges from 0.0475 near the east side of the site to 0.0215 toward the center and western portions of the site where the gradient flattens.

A 24-hour pumping test centered on monitoring well MW-103A (4-inch [10.2 cm]-diameter). Results from the pumping test indicated that the water-bearing unit could sustain a continuous pumping rate of 0.25 gpm (0.95 liters/minute). Transmissivity estimates in five wells ranged from approximately 90 to 500 gpd/ft (1.1 to 6.2 m^2/day), with a median value of approximately 160 gpd/ft (2 m^2/day) and an average of approximately 220 gpd/ft (2.7 m^2/day). Hydraulic conductivity estimates ranged from 2 ft/day (7.1 x 10^{-4} cm/sec; 0.8 Darcy) to 11 ft/day (3.9 x 10^{-3} cm/sec; 4.6 Darcy).

Figure 1
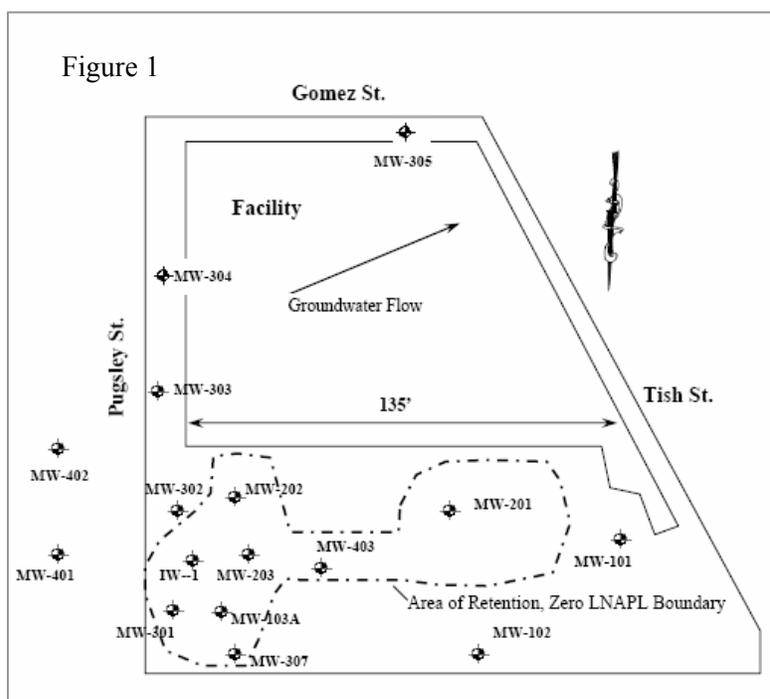
Site Conceptual Model
A site conceptual model is important for understanding contaminant movement and migration and the interaction between the contaminant and the hydrogeologic media. The conceptual model holds that the dielectric fluid release was relatively small, the total volume released being on the order of 400 gallons (1,514 liters) to 600 gallons (2,271 liters). Since the substation ceased operations in 1985, and this is the latest date at which there could be a continuing source of LNAPL, most of the LNAPL became immobilized at the edge of an area of retention, probably attaining steady state, non-migrating conditions within approximately 90 days of the final release. Within the area of retention, LNAPL thicknesses in monitoring wells continued to fluctuate with changing groundwater levels, and LNAPL could be removed as a separate phase; but LNAPL on the margins of the area of retention remained fixed as a residual (API/NGWA 2004). Eventually, with LNAPL removal and because of natural water infiltration, the LNAPL

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became residualized throughout the entire area of retention. By the time the pilot test began, all of the LNAPL had been removed and any remainder was R-NAPL.

Product Levels
Sixteen (16) monitoring wells gauged LNAPL thickness, but of these only eight had measurable separate phase LNAPL. Product thickness in these wells ranged from a minimum thickness of 0.01 feet (0.3 cm) in MW-103, MW-302, MW- 306, and MW-307 to the maximum thickness of 7.21 feet (220 cm) in MW-203. Out of 322 product thickness measurements collected from March 1997 through January 2004, the median thickness was 0.62 feet (18.9 cm), the average thickness was 0.91 feet (27.7 cm), and seventy-five percent of the measurements were 1.3 feet (39.6 cm) or less.

Capillary Pressure Volume Estimate
Research published in 1990 by Farr et al. and Lenhard and Parker 1990 found that LNAPL in porous media resides not as a distinct layer saturating the pore spaces and floating on the water table, i.e., the pancake model; instead, LNAPL shares the pore spaces from the air-oil interface to below LNAPL-water interface with air, air and water, and water, until at some depth water alone occupies all the pores. Despite thickness, LNAPL occupies only a small fraction of the pores and the level of saturation level remains very low (Farr et al. 1990, Lenhard and Parker 1990). Even in wells where LNAPL thickness measures several feet, the LNAPL saturation remains very low. Field studies by Huntley et al. 1994 on wells containing up to 5 feet (1.5 meters) of product showed that LNAPL occupied from less than 1 to 50% of the pore space, but for most of the profile LNAPL occupied only 1 to 5% of the pores (Huntley, et al. 1994). In 212 LNAPL analyses at BP sites, "83% of all samples had LNAPL saturations less than 10%. In fine grained soils, maximum saturations were typically 2 – 5%; in coarse soils, maximum saturations are 10 – 56%," (API/NGWA Joint Meeting, 2004).

Large LNAPL thicknesses in wells often translate into small volumes of recoverable LNAPL and the thickness in wells often results in gross exaggerations of recoverable LNAPL. The degree of exaggeration depends on the NAPL properties and the specific soil characteristics. Research by Farr et al. 1990 indicates that "large NAPL thicknesses in wells can be associated with very small NAPL volumes in the porous medium," and field experience on a large number of sites corroborates this phenomenon.

Site-Specific Volume Estimation
The next step was to estimate the site recoverable LNAPL volume using the capillary pressure method. The original estimate developed using the conventional or pancake model, upon which the product only recovery system and VEFR were based, was 2,725 gallons (10.3 m^3).

   Fluid and Soil Properties
Table 1 presents the fluid and soil properties used to estimate LNAPL volume by the capillary pressure method. These are predominately literature values and consequently lend a degree of uncertainly to the model results. The van Genuchten α parameter was adjusted to calibrate the model to field conditions. These values resulted in a volume estimate that was reasonably close to the actual LNAPL volume recovered.

Table 1 - LNAPL & Soil Properties

Parameter	Units	Value	Source/Comment
LNAPL			
Density	g/cm^3	0.9	LNAPL testing
Air-water surface tension	dyne/cm	65.6	Literature value 65.6 (Source 1)
Air-oil surface tension	dyne/cm	32	Literature value (Source 2)
Oil-water surface tension	dyne/cm	42	Literature value (Source 2)
Air-oil Scaling Factor, β_{ao}	ratio	2.05	Scaled value
LNAPL-water Scaling Factor, β_{ow}	ratio	1.56	Scaled using air-water/oil-water surface tension
Soil – Silty Sand (Boring Logs)			
Conductivity	cm/sec	4×10^{-3} - 7×10^{-4}	24-hr Pumping test, December 2002
Irreducible water saturation	ratio	0.25	Est. from Mercer and Cohen, Table 3
Porosity	ratio	0.40	Silty sand estimate
van Genuchten α	cm^{-1}	33.53	Huntley & Beckett, 2002. The final value was obtained after calibrating with actual recovery
van Genuchten N	unitless	1.6	Huntley & Beckett, 2002

Source: 1) Adamski, et al., *LNAPL in Fine-Grained Soils: Conceptualization of Saturation, Distribution, Recovery, and Their Modeling,* Groundwater Monitoring & Remediation 25 no.1/Winter 2005.

    2) *Characteristics of Pipe-Type Cable Fluids and Development of Risk-Based Cleanup Goals, Interim Report,* Electric Power Research Institute (EPRI), March 19, 2002.

Product Thickness

Eight LNAPL volume estimates were prepared using separate phase thickness levels representative of different test conditions: an historic high water table and low water table base case, and before and after the water flood (hydraulic displacement) tests and before and after the Primawave pilot tests. The eight estimates, selected from data obtained after the full compliment of monitoring wells were installed, are summarized in Table 2. The six wells in Table 2 were all within the area of retention and the only wells with measurable LNAPL during the pilot test period.

Table 2 - Monitoring Well LNAPL Thickness (ft)

Condition	Date	Note	MW-201	MW-403	MW-202	MW-203	MW-103A	MW-301	Total
1	April 3, 2001	High Vol. Est.	3.28	--	0.56	5.08	--	--	8.92
2	Oct. 26, 2001	Low Vol. Est.	1.24	--	0.45	0.55	0.03	0.33	2.57
3	Jan. 14, 2004	Pre Water flood	--	0.14	0.2	--	0.22	0.01	0.56
4	Jan. 19, 2004	Post Water flood	--	0.15	0.74	--	0.25	0.01	1.15
5	Jan. 22, 2004	Pre-Primawave	--	0.25	0.91	--	0.42**	--	1.58
6	Jan 26, 2004	Post -Primawave	--	0.61	1.28	--	0.42	--	2.31
7	March 8, 2004	Pre-Primawave	0.01	--	1.10	--	0.49	--	1.60
8	March 19, 2004	Post-Primawave	0.05	0.53	2.49*	0.07	0.43	--	3.57

* 1.06 feet of LNAPL in well on 3/19/04 plus 1.43 feet of product bailed from MW-202 on 3/9/04

** The logbook value recorded was a spurious datum, so this value (lower) was interpolated from a plot of the product thickness levels for MW-103A.

Area of Retention

The area of retention is the soil volume within which LNAPL occupies the pores and exceeds the residual saturation such that it can potentially flow. Beyond the boundary, the zero line, LNAPL is at or below residual levels and is unable to flow or is absent. Within the area of retention, NAPL can become residualized by recovery and/or in combination with natural water infiltration

and ensuing snap-off and by-pass mechanisms. For the purpose of this paper, the zero product thickness line on Figure 1 defines the area of retention.

The absence of product in monitoring wells over an historic period provided the basis for the zero line position. This also contributes to why the estimate of recoverable volume using the capillary pressure method is greater than the actual recovered volume.

Results

Capillary pressure LNAPL volume estimates were calculated using OILVOL©, an oil volume estimator employing the methodology of Farr et al. 1990 and Lenhard and Parker 1990. OILVOL© calculates the free product volume using the equations by van Genuchten 1980.

The area of retention is divided into equally spaced rectangular grids. OILVOL© then uses krigging of the LNAPL thickness at different well locations to calculate product thicknesses at each grid node. Using the three-phase relation between fluid saturation and pressure, OILVOL© computes the vertical saturation of water and LNAPL. This is summed over the area of retention to yield an estimate of recoverable LNAPL. Table 3 presents the computation results for the eight conditions of interest. The analysis demonstrates large differences between the recoverable volume estimates using the conventional approach and the capillary saturation method.

Table 3 - Capillary Pressure LNAPL Volume Estimates

Condition	Date	Description	Recoverable LNAPL (gal)
1	April 1, 2001	High-volume pre-recovery estimate	233
2	Oct, 26, 2001	Low volume pre-recovery estimate	6.8
3	Jan. 14, 2004	Pre-Water flood estimate	0.06
4	Jan. 19, 2004	Post Water flood estimate	0.5
5	Jan, 22, 2004	Pre-Primawave Test Estimate	1.1
6	Jan. 26, 2004	Post Primawave Test Estimate	2.3
7	March 8, 2005	Pre- Primawave Test Estimate	1.6
8	March 19, 2005	Post Primawave Test Estimate	11.4

Estimates based on the conventional approach greatly exaggerated the expected recoverable volume. Conversely, in this instance, the capillary pressure method yielded a high volume base case estimate (when the groundwater table was near its historical low) of 233 gallons (0.88 m^3) and a low volume base case estimate (when the groundwater table was near its historical high) of 6.8 gallons (0.03 m^3). Actual recovery after 4.5 years was approximately 90 gallons (0.34 m^3).

The high volume base case estimate of 233 gallons (0.88 m^3) is closest to what was recoverable over time. This estimate demonstrates that while there was a total LNAPL thickness of approximately 9 feet (2.7 meters) over the site at one time, and one well having over 5 feet (1.5 meters) of product (at the same time), the actual recoverable volume is very low in this soil with dielectric fluid.

Primawave Process

Primawave is an *in situ* injection process that harnesses highly accelerated fluid pressure pulses to mobilize contaminants and move fluids, contaminants, or treatment amendments through saturated porous or elastic media (soil and rock). The process creates subsurface pressure waves of high amplitude and low frequency akin to those moving through the earth following an
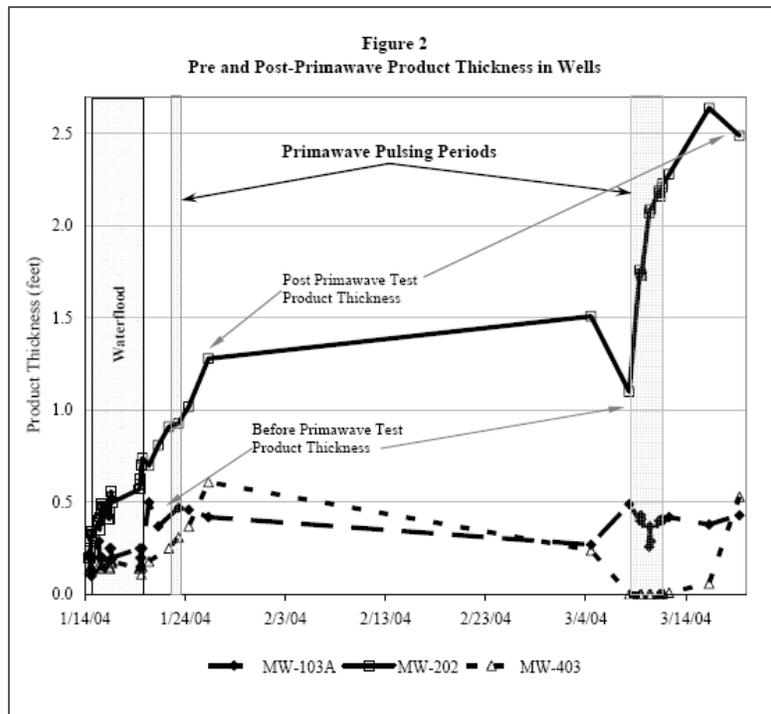
earthquake. The pressure pulses are unique because they open pores, increase pore interconnectivity, and combined with a purpose designed injection scheme, optimize the mobility of residual and separate phase product as they travel through the media. The pressure pulses are also capable of dispensing and dispersing fluids, thereby improving approaches such as *in situ* chemical oxidation. The capacity of Primawave to increase pore size, pore interconnectivity, and disperse fluids means that we may have to re-think widely accepted remedial approaches.

Capillary Pressure Analysis Following Primawave Pilot Test

Primawave was piloted for the purpose of investigating whether it could mobilize LNAPL more quickly and whether it could mobilize R-NAPL. A quasi-static water flood test (hydraulic displacement) preceded the Primawave pilot. During the water flood, water was injected into the formation to evaluate if LNAPL could be mobilized by this means and to provide a basis of comparison for the Primawave test. Testing began in January 2004 after installation of a specially designed Primawave injection well (IW-1, Figure 1).

Originally, a 5-day Primawave pilot test was to follow the water flood. The pilot test began in January 2004 but extremely cold temperatures froze the water lines and the pilot test was abandoned after two days. The total amount of pulsing time was approximately six hours and 270 gallons (1.0 m^3) of water were injected. Pulsing was intermittent because of the difficulties imposed by the weather. A second pilot test attempt began in March 2004. The total pulsing time was approximately 21 hours (intermittently) over four days with 515 gallons (1.9 m^3) of water injected. Shortly into the test it became apparent that the injection well (IW-1) was not installed properly and that pressure was short circuiting to the surface through the well annulus and not fully reaching the water-bearing unit. This development severely compromised the test, which was eventually abandoned after a failed attempt to repair the well and a failed attempt at pulsing in a conventional monitoring well. However, the test still had a measurable impact on mobilizing R-NAPL.

Product increases beyond trace amounts (i.e., >0.05 feet [1.5 cm]) appeared in seven wells during the March Primawave test as opposed to four wells during the January Primawave test. Figure 2 shows the LNAPL thickness levels in three wells where measurable product appeared during the water flood and Primawave tests. The LNAPL thickness measurements selected to evaluate Primawave after the test were the LNAPL thickness measurements made on a single date and time that yielded maximum cumulative LNAPL thickness in all wells.

Figure 2
Pre and Post-Primawave Product Thickness in Wells

Source: Wavefront Energy and Environmental Technologies, Inc., Northeastern US Report, April 2004

Primawave continued to pressurize the system for a period following the test and some time may elapse before maximum product levels stabilize (Wavefront April 2004). On this basis and on the maximum product thickness in Figure 2, separate phase thickness levels were selected for comparison and volume estimation using the capillary pressure method.
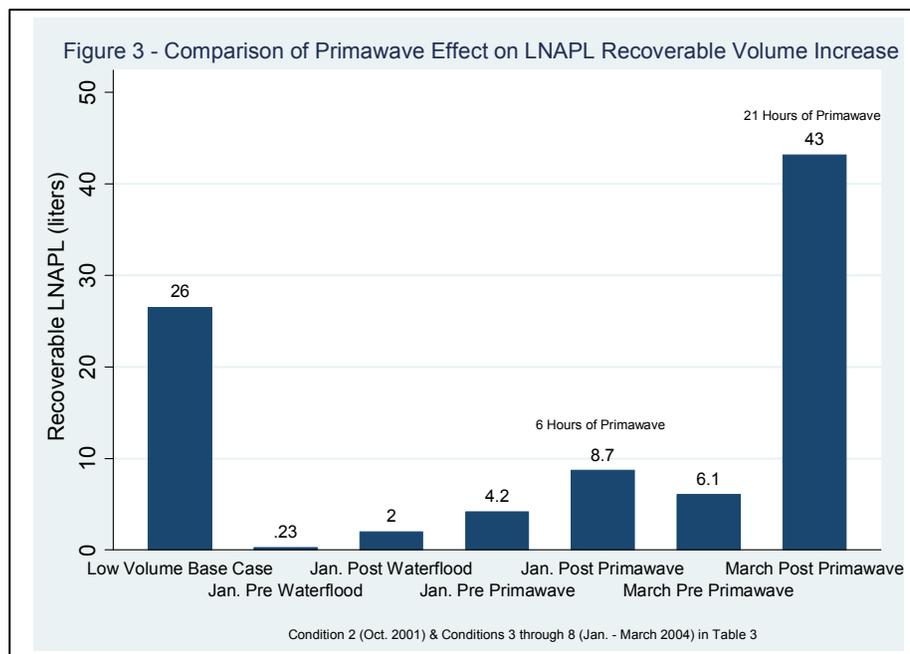
Product thickness changes were observed shortly after the Primawave test began. During the March Primawave test, on March 9, after pressure pulsing for five hours, the LNAPL level in MW-202 increased sharply and approximately 1 quart (0.95 liter) of LNAPL had to be bailed to relieve head pressure that prevented more LNAPL from entering the well. One quart of liquid equates to 1.43 feet (43.6 cm) in a 2-inch (5.1 cm)-diameter well and this height was added to the cumulative well thickness to account for the volume removed. MW-202 is 26 feet (7.9 meters) from the Primawave injection well (IW-1 in Figure 1).

This situation is not unique. At a Midwestern United States site where the Primawave well was not compromised, product levels increased in one monitoring well positioned more than 100 feet (30.5 meters) from the Primawave injection well such that the well had to be bailed six times, and bailing was required in two other wells. This occurred despite rising water levels (Wavefront July 2004). At the same Midwestern site "product thickness increases occurred in 50% of the monitoring wells located within 100' from the pulse well," (Wavefront July 2004). Forty-three percent (43%) of the wells within 100' – 200' experienced product thickness increases in response to pulsing; and 15 percent (15%) of the wells within 200' – 300' experienced the same (Wavefront July 2004). At a site in dolostone in Canada, NAPL was heard cascading into a monitoring well 20 feet (6.1 meters) from the pulse well (Panter 2006).

Product thickness levels in MW-202 and MW-403 increased sharply following both Primawave trials. The effect is more pronounced during the March test, where MW-202 shows a very steep increase in LNAPL. Particularly interesting is MW-403, where LNAPL thickness rose sharply and quickly after both the January and March Primawave pilot tests, but particularly in the March test, where there was no measurable LNAPL in the well before the pilot test.

Capillary Pressure Estimates

The product thickness increases in monitoring wells following the water flood and Primawave pilot tests were converted to recoverable volumes using the capillary pressure approach. Figure 3 shows that all the volume estimates are well below the historical Low Volume Base Case for recoverable LNAPL except for one notable

Figure 3 - Comparison of Primawave Effect on LNAPL Recoverable Volume Increase

Condition 2 (Oct. 2001) & Conditions 3 through 8 (Jan. - March 2004) in Table 3

exception. The other volume estimates are all well below the base case, implying that all or most of the LNAPL appearing during the pilot test period was R-NAPL.

Since the LNAPL source terminated in 1985, 16 years before recovery began, followed by approximately 5 years of recovery, and since snap-off, by-pass and degradation mechanisms acted to immobilize the LNAPL for almost 20 years, the recoverable volume estimates beginning in January 2004 most likely represent mobilized residual as opposed to actual separate phase product.

The January pilot test increased LNAPL recoverable volume beyond the pre- and post-water flood tests and compared to the period before the pilot test. The results for the March pilot test are acute, showing that Primawave increased recoverable LNAPL well beyond the period before the pilot test and, most noteworthy, beyond the Low Volume Base Case. Even considering the uncertainty in the measurements, the January LNAPL volume increase is appreciable and indicates that residual LNAPL is being mobilized. During the March pilot test, the estimate of recoverable product increased more than 700 percent compared to the period immediately before the pilot test. Most of this increase must have come from residual LNAPL as opposed to separate phase LNAPL because the recoverable volume increased in both January and March pilot tests compared to the pre-Primawave LNAPL volume, and because the March Primawave test increased recoverable volume dramatically beyond the Low Volume Base Case, by 165 percent. The dramatic 1.43-foot (43.6 cm) product increase in MW-202 in just a few hours also strongly suggests movement of residual.

Recovery Rate Evaluation

The product only skimmer system removed 37 gallons (0.14 m^3) in 15 months when the LNAPL was more readily extractable. This equals 2.5 gallons/month (0.009 m^3 liters/month) of actual recovery. With an estimated total of 90 gallons (0.34 m^3) removed in 54 months, the actual net removal rate for the conventional approach was 1.7 gallons/month (7.6 x 10^{-3} m^3/month).

In order to compare the conventional recovery rate to the recovery rate while using Primawave, the recoverable LNAPL estimates for the January and March pilot tests were converted to gallons/month. Using Primawave, the January pilot test LNAPL extraction rate was approximately 0.4 gallons/hour (0.0015 m^3/hour) and the March pilot test extraction rate was approximately 0.6 gallons/hour (0.0023 m^3/hour). Extended, these rates equate to approximately 300 gallons/month (1.1 m^3/month)

Figure 4 - LNAPL Recovery Rate Comparison

and 415 gallons/month (1.6 m^3/month), respectively. Figure 4 shows a comparison between the
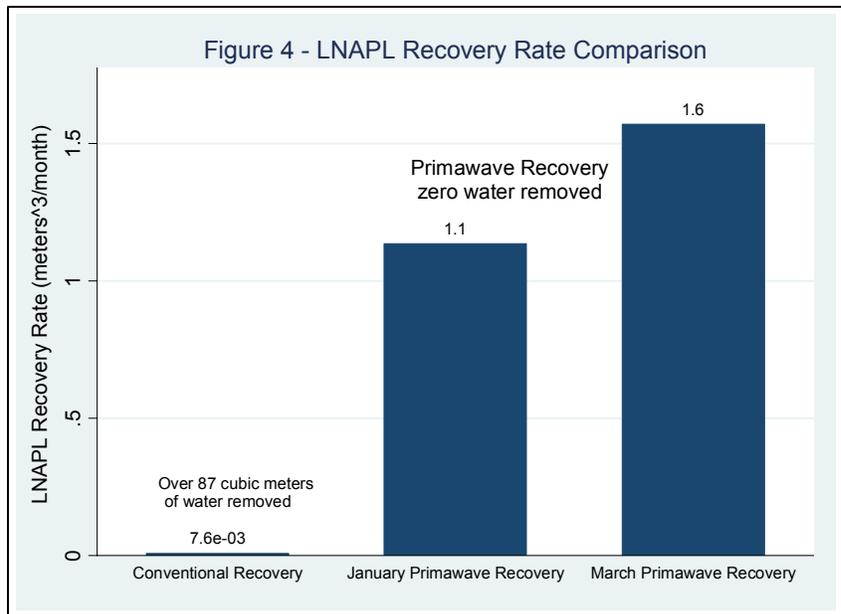
conventional and Primawave recovery rates. The increased recovery rates derive from a point in time when LNAPL was more difficult to remove because of the time since the releases ended and because product recovery had effectively reached diminishing returns by time the pilot tests were conducted.

Summary and Conclusions
Primawave appears to have mobilized residual in several wells and made it available for recovery by increasing LNAPL thickness in wells. This observation was repeated on two separate trials separated by approximately two months in silty sand soils. Despite the pilot test limitations imposed by cold weather and a compromised injection well, Primawave increased LNAPL thickness within a few hours of intermittent treatment and LNAPL levels continued to increase for some time following the end of the pilot tests.

The greatest LNAPL increase was in one well 26 feet (7.9 meters) from the injection well. The limit of Primawave influence was not determined, but it appeared to extend beyond this distance. Given that LNAPL levels increased in wells in a relatively short time frame, when free product had already been removed, indicates that Primawave enhanced LNAPL movement many times beyond what would be expected in a conventional setting. R-NAPL was mobilized in moderate to low permeability soils contaminated with a NAPL having a high NAPL-water interfacial tension. In more permeable media or with a NAPL with a lower interfacial tension, the recovery would likely be many times greater. Primawave appears to have increased LNAPL recovery rates by more than two orders of magnitude compared to conventional removal, even after conventional removal was terminated because of asymptotic recovery.

It is hypothesized that the following mechanisms account for mobilizing R-NAPL: (1) Pulsing generates extremely large instantaneous pressure differentials on either side of entrapped NAPL blobs, (2) pulsing simultaneously generates exponential increases in groundwater velocity that exert a driving force on the entrapped NAPL blobs, and (3) pulsing increases pore size and interconnectivity thereby reducing the capillary entrapping force. When pulsing is repeated every few seconds, the driving forces continue and NAPL blobs begin to move. As the blobs move, they contact one another and cohesive forces cause the blobs to coalesce forming continuous NAPL that is much more amenable to flow. Some wells exhibited decreases in LNAPL thickness in response to Primawave. In these instances it is believed that pulsing lowers the pore aspect ratio, thereby lowering the pore displacement pressure, causing the NAPL thickness to decrease. It is further hypothesized that the Primawave process lowers the capillary and bond number thresholds required to mobilize residual, but this is an area for further research.

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