PRESSURE PULSE TECHNOLOGY (PPT): A REVOLUTIONARY FLUID FLOW TECHNOLOGY FOR POROUS MEDIA

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ABSTRACT

Pressure Pulse Technology (PPT) uses a process of periodic (eg. 15 pulses per minute) hydraulic excitations (via pressure pulses of water) to introduce hydraulic strain energy into the saturated formation. This energy, effective in geologic materials exhibiting elastic properties, (including unconsolidated sediments; sedimentary rocks), dislodges blocked matter, opens perforations, increases pressure, re-establishes connectivity to reservoir pressures and generally enhances or restores the formation’s permeability and a well’s capacity to produce fluids.

This paper reports the results of a field testing program whereby PPT was applied as an add on technology to enhance the effectiveness and operations of an existing pump and treat free product recovery system to enhance the recovery of di-octyl phthalate (DOP), a light non-aqueous phase liquid (LNAPL) residing in a shallow fractured dolostone water table aquifer. PPT effects included increased LNAPL thickness and recovery rates in excess of 500% vs non-pulsing conditions.

RÉSUMÉ

La technologie d'impulsion de pression (PPT) emploie un processus (par exemple 15 impulsions par minute) des excitations hydrauliques périodiques (par l'intermédiaire des impulsions de pression de l'eau) pour présenter l'énergie de tension hydraulique dans la formation saturée. Cette énergie, pertinente en matériaux géologiques présentant les propriétés élastiques, (y compris unconsolidated des dépôts; la roche sédimentaire), déloge la matière bloquée, ouvre des perforations, augmente la pression, rétablit la connectivité aux pressions de réservoir et généralement met en valeur ou restaure la perméabilité àformation’s et une capacité de well’s de produire des fluides.

Cet article enregistre les résultats d'un programme de test sur le terrain par lequel PPT ait été appliqué comme ajouter sur la technologie pour mettre en valeur l'efficacité et les fonctionnements d'une pompe existante et pour traiter le système libre de reprise de produit pour mettre en valeur la reprise du phtalate dioctylique (DOP), un liquide non aqueux léger de phase (LNAPL) résidant dans une couche aquifère rompue peu profonde de table de l'eau de dolostone. PPT effectue des cadences accrues incluses d'épaisseur et de reprise de LNAPL au-dessus de 500% contre des conditions non-non-pulsing.

1. INTRODUCTION

Source zone free product removal continues to be one of the primary limiting factors to a successful groundwater restoration program. Conventional pump and treat schemes, although initially successful at recovering free product upon their commissioning, essentially become groundwater containment schemes over time. Further, the progression in the environmental industry from active to passive groundwater restoration programs, including natural attenuation and monitoring, or enhanced insitu degradation of contaminants through the subsurface introduction of nutrients or other agents under non-pumping conditions, remain primarily effective for dissolved phase contaminants. The challenges in recovering free phase product, which give rise to long term dissolved phase restoration programs, are due to a number of physical conditions, including the free product’s specific gravity (or density), viscosity, and interfacial tensional forces.

In order to reduce the free product’s viscosity and tensional forces and thus aid in its recovery, surfactants, solvents or other such compounds have been introduced to the subsurface through a process termed “flooding” (Holm and Csaszar 1962). Flooding is a well documented secondary or tertiary oil recovery scheme employed in the petroleum industry whereby a fluid is pumped into the ground through a well to assist in the subsurface flow of liquids and thus to enhance the recovery of heavy oils from oil producing formations (Gatlin and Slobod 1960; Larson et al. 1982). Flooding effects are limited however, due to the development of viscous fingering and permeability channeling, which arise either due to permeability heterogeneities, or the physical interaction of fluids of varying viscosities (Davidson et al. 1999). In order to overcome the viscous fingering effects due to flooding, traditional flooding approaches have been enhanced, or augmented by applying the PPT (Spanos et al. 1999).

Pressure Pulse Technology (PPT) uses a process of periodic (eg. 15 pulses per minute) hydraulic excitations (via pressure pulses of water) to introduce hydraulic strain energy into the saturated formation. This energy, effective in geologic materials exhibiting elastic properties, (including unconsolidated sediments; sedimentary rocks), dislodges blocked matter, opens perforations, increases pressure, re-establishes connectivity to reservoir pressures and generally enhances or restores the formation's permeability and a well's capacity to produce fluids.

In 2000, the same Pressure Pulse Technology was employed at an operating industrial facility located in Cambridge, Ontario, Canada to assist in the recovery of a light non-aqueous phase liquid (LNAPL) and to ultimately enhance the effectiveness of the current free product pump and treat scheme which has been operating since 1995.

In the following sections, the performance of PPT in enhancing free product recovery will be discussed.

2. PRESSURE PULSE TECHNOLOGY

2.1 Background

About 15 years ago, Tim Spanos at the University of Alberta finished the initial development of a rigorous theory of porous media mechanics. Previous simplifications and assumptions were examined, found wanting, and corrected, resulting in a theory that is more thermodynamically sound than either Darcy theory for non-dynamic flow, or Biot-Gassmann theory for wave propagation. As stated, The phenomena of PPT and the benefits arising from its applications do not fall within the "conventional" view of porous media mechanics. What is being done during systematic PPT is not radical, but currently accepted porous mechanics models cannot correctly account for such dynamic effects (Spanos et al. 1999).

Scientists and engineers working in fluid flow have been taught that the quasi-static Darcy flow paradigm ($q \propto \partial p/\partial \ell$) (see Figure 1), where gradient is a macroscopically defined quantity ($\partial p/\partial \ell = (p_1-p_2)/\ell$), is a sufficient theory for porous media flow over a wide range of conditions. Perhaps some inability to correctly predict flow rates or dispersion behavior in clays, shales or fractured media is admitted, but otherwise Darcy theory is accepted uncritically.

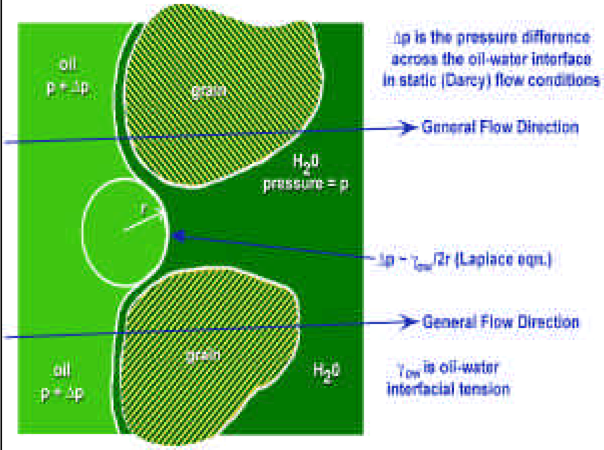


Figure 1. Static Darcy Flow Conditions

Similarly, geophysicists working with porous media wave mechanics have been taught that Biot-Gassmann theory is sufficient to describe porous media wave propagation, given a wavelength much greater than the particle size. Neither of these "fundamental" theories is complete, although each may be sufficient for practical purposes under certain restrictive conditions.

2.2 Current Flow and Wave Paradigms

Darcy theory is a quasi-static theory, and contains no inertial terms. Thus, when liquid or solid phase accelerations are important with respect to the system flow velocity, one may expect effects that cannot be quantitatively explained. This does not invalidate the Darcy paradigm within the restrictive conditions for which it was stipulated (no inertial effects). However, it does mean that Darcy theory is incapable of predicting or quantifying the effects that we will report in this article. This is an important point: because Darcy-based flow theories cannot explain our results, it proves that a more complete theory is required.

The Biot-Gassmann theory of wave propagation in porous media is to wave mechanics what Darcy theory is to flow mechanics. Biot-Gassmann theory is based on a set of assumptions that have recently been shown to be inadequate. The two most important flaws are the following:

- Porosity is assumed a constant scalar quantity; and,
- The energy in a porous medium can be described by a single-valued function.

It has recently been demonstrated that porosity plays a fundamental thermodynamic role in porous media and must be treated as a thermodynamic state variable. As an example, in attempts to develop physically consistent models of sand production, porosity plays a role similar to that of temperature in metals (Geilikman et al. 1993). In sand production, the formation goes from a porosity of 29-32% to a condition of complete liquefaction at porosities >50%, under the influence of gravitational forces and seepage forces. The liquefaction phase transition is akin to temperature-induced melting of metals.

In the Biot-Gassmann development of wave propagation models for porous media, it was assumed that, for a representative elementary volume, a single functional could express the energy state. This leads to a conundrum that can be demonstrated by a simple example. If a single energy functional is sufficient, there can be only one value and direction of maximum gradient, and if the energy is solely a function of pressure, this means that there can only be one flow direction. However, for decades people have conducted flow experiments where two continuous immiscible fluid phases (e.g. oil and gas) are induced to flow in opposite directions or at 90º. This implies that a single energy functional is insufficient. Indeed, recent work has shown that if N continuous phases exist, N energy functionals (linked together by the laws of physics and properly scaled) are required (de la Cruz and Spanos, 1989). For example, in a sand-oil-water system, it is theoretically possible that the three phases can be moving relative to one another in three different directions.

Clearly, Darcy theory does not include inertial effects; for example, it is known to be inapplicable at flows involving turbulence (Barenblatt et al., 1992), where internal energy dissipation from inertial effects are important. During the large amplitude excitation applied to the cells in our experiments, inertial effects, sudden acceleration and deceleration of the pore fluid, dominate the flow regime. To overcome this limitation of Darcy flow theory, it is insufficient to introduce empirical factors: a new flow theory including inertial effects must be formulated at the correct scale from fundamental physical principles.

2.3 Development of a New Theory

A new model of wave propagation in porous media was developed to overcome limitations associated with the restrictive assumptions in the Biot-Gassmann theory. The de la Cruz and Spanos model (1989, 1993) utilizes volume averaging in conjunction with physical arguments to construct a set of macroscopic continuum equations that more completely describes wave propagation in a fluid-filled porous medium. This model includes porosity as a dynamic variable that plays a fundamental role in both the thermomechanics and thermodynamics of the porous medium. Also, the model includes explicit thermomechanical coupling; that is, first-order heat generation from compression and expansion of the phases due to external heating and cooling or due to pressure changes. Incidentally, this latter aspect also accounts for well-known wave attenuation behavior in a natural way, without empirical attenuation relationships for which parameters must be evaluated for each specific case.

Imposing the microscopic boundary conditions of no slip, continuity of stress, conservation of momentum transfer and continuity of heat flux to the following equations develops this theory:

- Equations of motion for a fluid;
- Equation of motion for an elastic solid;
- Continuity equation for a fluid;
- Continuity equation for a solid;
- The solid heat equation; and,
- The fluid heat equation.

It is assumed that the porous medium is composed of pores of random size and orientation, but macroscopically homogeneous and isotropic, enabling the use of volume averaging principles for specific parameters. As a preliminary solution, assuming a plane-wave, new dispersion relations for S and P waves have been constructed. This resulted in four P waves and two S waves, whose phase velocities and attenuation are frequency dependent.

The resulting model consists of coupled, first order macroscopic equations which describe wave propagation in porous media saturated with a single viscous compressible fluid. These equations have been derived and published elsewhere (de la Cruz et al., 1989, 1993), and will not be repeated here. The basic characteristics of the model include inertial mass coupling between the phases, porosity as a variable, energy dissipation because of phase compression, and rigorous incorporation of the dilatational behavior of all phases.

One important aspect of the new wave propagation theory is that it predicts the existence of a non-seismic porosity-pressure diffusional wave that is symbiotically coupled to a quasi-static porosity diffusion process (Geilikman et al., 1993), and travels at velocities on the order of 5-150 m/s in porous media. This wave is not predicted by Biot-Gassmann theory. The role of the porosity diffusion wave in the mechanics of pressure pulsing in the laboratory and the field is paramount: it is the porosity-pressure diffusion wave that leads to the flow enhancement, as shown in Figure 2.

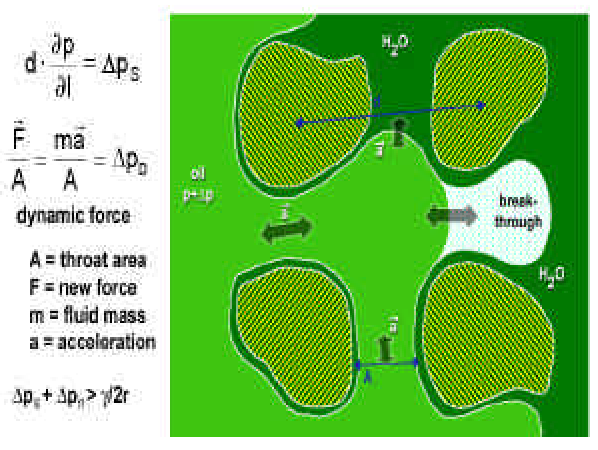


Figure 2. Flow Enhanced Dynamic Force

The porosity diffusion wave disperses geometrically just as any other wave, therefore, as it propagates from the source, its magnitude drops. However, in many cases, particularly those involving irreversible deformations such as compaction (overburden downward movement), energy can be systematically extracted from the gravitational stress field. This is an important aspect: suitable high-amplitude pressure pulsing can trigger dilation and liquefaction; this process is dominated by the overburden stresses and yield (shearing) processes arising from gravitational and flow forces that also feed energy into the porosity diffusion wave propagation process. Indeed, if the wave can continue to extract energy from the surroundings, it can propagate with far less attenuation than expected from geometrical spreading.

The existence and characteristics of the porosity diffusion wave has been demonstrated, measured in the laboratory (velocity ~ 8.0 m/s in a 36% porosity oil saturated sand pack at <0.5 MPa confining stress), and is considered to be critical to the flow enhancement phenomena we observe. The porosity diffusion wave also appears to be important in earthquake mechanics as a mechanism for the triggering of more remote earthquakes in critically stressed regions through an increase in pore pressure arising from a large perturbation (Geilikman et al., 1993).

3. PPT FIELD APPLICATION

3.1 Site Geology and Hydrogeology

As shown on Figure 3, site geology includes from ground surface to approximately two metres below grade; granular fill, from 2-15 metres grade fractured and weathered dolostone; from 15-25 metres below grade a zone of low permeability dolostone which acts as an aquitard between the upper fractured and weathered dolostone bedrock, and an underlying fractured dolostone bedrock unit which extends from approximately 25 to 100 metres below grade. Historic hydrogeologic studies characterized the upper dolostone bedrock to have an average horizontal hydraulic conductivity of 2.5 x 10^{-5} m/s and a porosity ranging from 5 – 10 %. Shallow unconfined groundwater flow is in an easterly direction beneath the site at a depth of approximately 2.5 metres below grade.

3.2 Site Characterization

Site characterization activities at the site have identified a free phase zone and a dissolved phase zone of di-octyl phthalate (DOP) in the northeast corner of the site. The DOP has a density of 0.9861 g/cm^3 and viscosity of 150 cp. The free product LNAPL layer has a measured average thickness of 0.5 cm within the on-site plume, within the fractures in the bedrock located at a depth of approximately 2.5 metres below grade. The dissolved phase plume is shown cross-sectionally in Figure 3. Historic DOP free product recovery rates in the northeast corner of the site have ranged from 20-45 ml/week using a conventional pump and treat system augmented with manual free product recovery using a peristaltic pump. Pump and treat activities have included the continuous withdrawal of groundwater from three individual recovery wells which are steel cased, 0.1 m in diameter and continuously grouted from ground surface to a depth of 2.5 metres below grade. From 2.5 to approximately 8.5 metres depth, the well is completed as an open hole in the bedrock. The recovered LNAPL is shipped off-site for disposal at a licensed facility, while groundwater is treated through micronic and coalescing filters prior to polishing via activated carbon filters. Treated groundwater is either reused on-site as makeup water for industrial chilling purposes or discharged to the sanitary sewer.

Figure 3. Site Geology Map

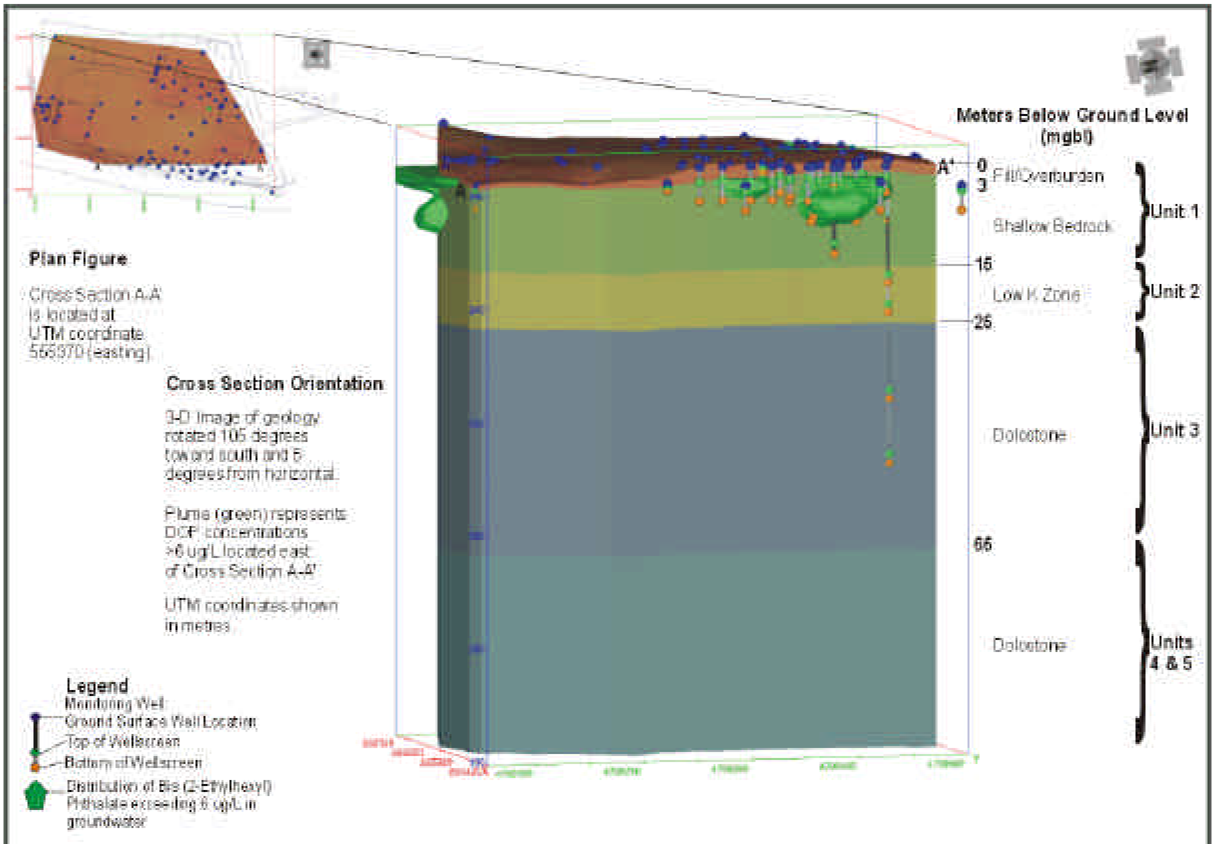


FIGURE 3: SITE GEOLOGY MAP

3.3 Study Objective and Methodology

The overall objective of augmenting the current pump and treat system with PPT was to document and measure the effect of pressure pulsing on a shallow unconfined bedrock aquifer and the resulting increased free product levels and recovery rates of DOP LNAPL from the previously documented impacted northeast corner of the site.

In order to accomplish this, water and free product levels were measured prior to, during, and post pressure pulsing activities in 15 wells (recovery and/or monitoring) in the area of the PPT activities. During and after pressure pulsing activities, level monitoring and free product pumping events were maintained to document changes in production rates from existing product recovery wells. Monitoring of free product in all monitoring wells was also completed to determine if free product levels became measurable in wells where it had not previously been documented.

3.4 PPT Instrumentation and Operation

The PPT application at the site was affected by installing one tooling assembly in one of the on-site 0.10 metre ID, 8.5 metre depth, steel cased recovery wells (see Figure 4). Prior to pulsing activities, the static water level (water table) was measured at 2.5 metres below grade. Prior to, during and subsequent to the pulsing activities, water levels and LNAPL thicknesses were measured in 15 separate monitoring wells, up to 100 metres from the pulsing well.

From June 5, 2000 to August 25, 2000, pressure pulsing was applied at the site in one well (identified as “Pulsing Well” in Figure 2), at a depth of 2.5 metres below grade; at a frequency of 15 pulses per minute and a continuous water injection rate of 27 L/min. Electricity to operate the pulsing unit was obtained on-site. The delivery of the pressure pulses of water was through the patented pressure pulsing device, whereby water was instantaneously injected into the well bore through the open bottom of the PPT tool. Compressed air was obtained from the facility on-site to activate the pulsing device at a pressure of 80 psi; and water used for pulsing was initially obtained from the on-site municipal system, and later switched over to utilize the groundwater being pumped from the three on-site recovery wells. During the pulsing period, the pulsing injection rate of 27 L/min was balanced by a combined removal rate of 27 L/min from the three recovery wells (RW2, RW4 and OWC).

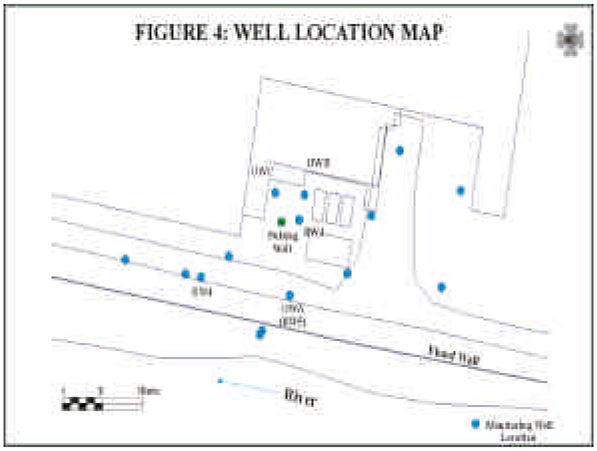


Figure 4. Well Location Map

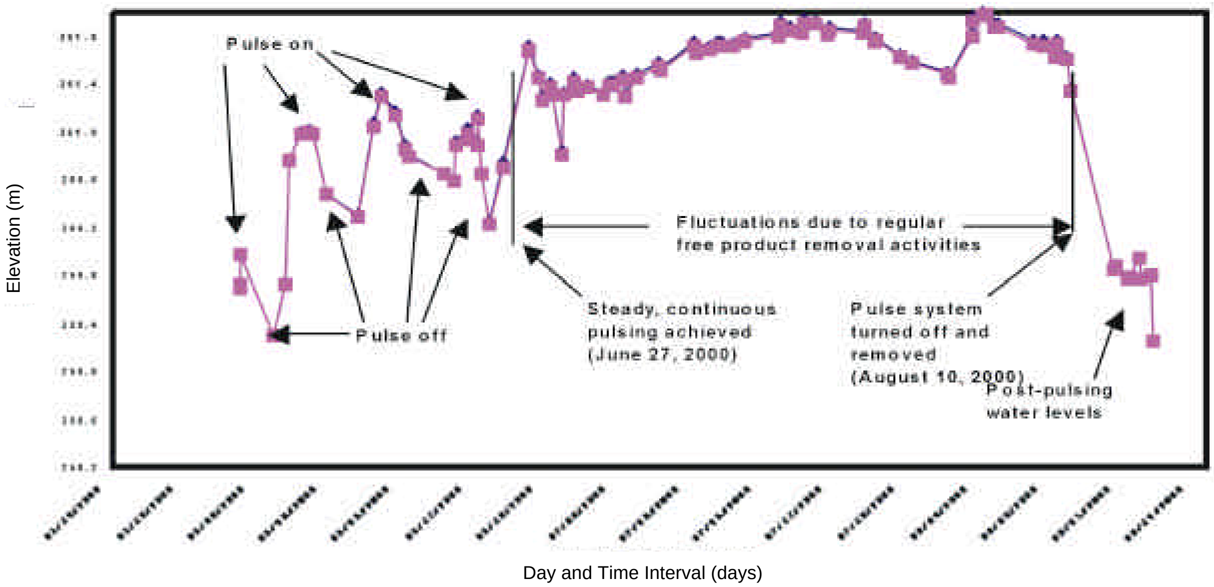
4. RESULTS AND DISCUSSION

As noted above, one pulsing well was activated during the field testing period at a constant rate of 27 L/min. In order to maintain a water injection/withdrawal balance, groundwater extraction was occurred at the three recovery well locations at 9 L/min each.

4.1 PPT Effects on Water Levels

The hydrograph presented as Figure 5 presents the changes in water levels at the OWC location during the testing period. It is noted that the same water level trends were measured at the other monitoring locations, however, the effects of the pulsing are subdued with distance from the pulsing well.

Figure 5. Water Levels at OWC.



The effects of pressure pulsing are clearly evident within initiation of pulsing. The increased water levels are as a direct result of the pulsing activities, and the trend evident through the first several weeks of pulsing coincide with the on/off cycling of the pulsing tool. From June 27/00 to the end of the pulsing period on August 10/00, the water levels remained relatively stable at OWC and the other monitoring locations, while the pulsing tool was operated on a continual injection basis of 15 pulses/min and a total injection rate of 27 L/min. As shown on Figure 5, water levels were increased, and maintained at the OWC location, approximately 10 metres upgradient of the pulsing well, by as much as 1.5 metres from non-pulsing levels.

4.2 PPT Effects on Free Product Thickness

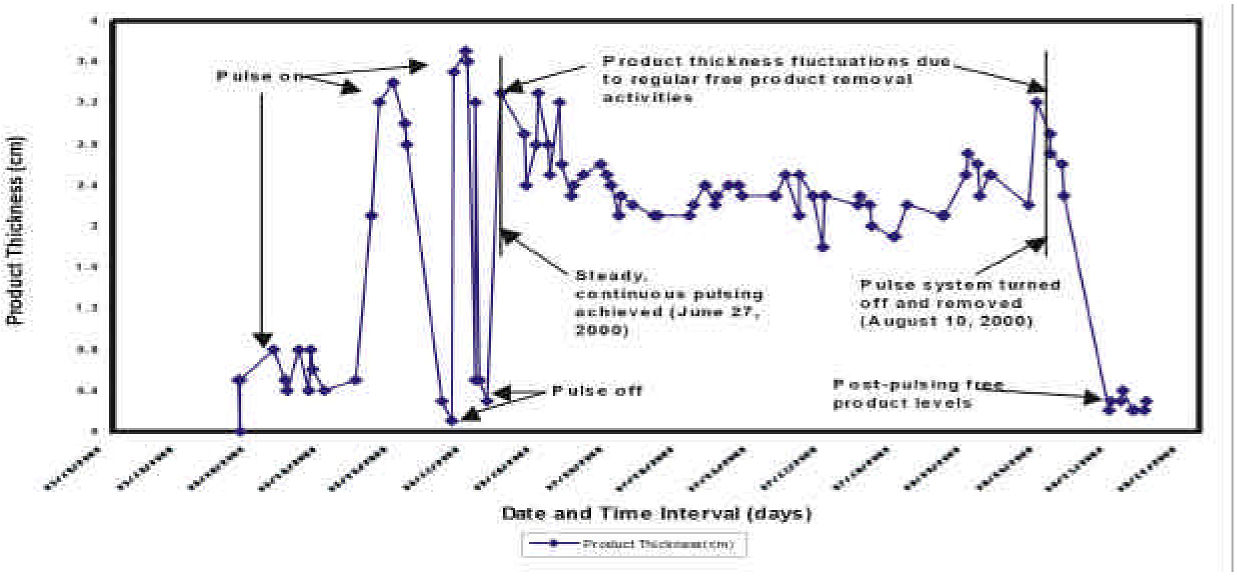
The hydrograph presented as Figure 6 presents the changes in free product thickness at the OWC location during the testing period. As shown, several days of pulsing had passed until the effects of pressure pulsing on the free product thickness were evident at this monitoring well located approximately 10 metres upgradient of the pulsing well (see Figure 4). However, after approximately one week of pulsing, the free product thickness measured in OWC increased from approximately 0.5 to 3.5 cm, an increase of 800%. From the period of June 16 to June 27 the pulsing tool was turned off and on several times to document the effect on free product thickness. Each time the pulsing was ceased, the free product thickness responded by dropping to pre-pulsing levels, and when pulsing was reinitiated, product thicknesses increased in the order of 800%.

During the period of June 27 to August 10/00, while continuous pulsing rates were maintained, regular free product pumping events were initiated. Under these conditions, a consistent thickness of approximately 2.5 cm was maintained, an increase of 500% from non pulsing thicknesses.

4.3 PPT Effects on Free Product Recovery Rates

As noted above, free product pumping events were initiated on June 27/00 and continued on a regular (daily to every two days) basis. In comparison, free product pumping events have occurred approximately once per month over the last several years, as it took approximately one month for free product levels to recharge to a comparable thickness to the month prior.

Figure 6. Free Product Levels at OWC.



Historical Non-Pulsing Calculations					
Total Days	Total Litres	Litres/ Day	Litres/ Mth.	Litres/ Yr.	Rate Increase
3072.00	114.10	0.037	1.13	13.56	-
Pulsing Calculations					
Total Days	Total Litres	Litres/ Day	Litres/ Mth.	Litres/ Yr.	Rate Increase (%)
52.00	9.50	0.18	5.56	66.68	492

Table 1. Free Product Recovery Rate Calculations

A summary of free product recovery rates are shown in Table 1, which compares historical recovery rates with those rates induced by pressure pulsing. As shown, free product recovery rates are increased by nearly 500% as a result of pressure pulsing.

5. CONCLUSIONS

In summary, PPT has had a direct impact at the site, including an increased water level in the vicinity of the pulsing well by as much as 1.5 metres, an increased LNAPL thickness increase of up to 800%, and increased LNAPL recovery rates up to 5 times faster (or 500% greater) than non-pressure pulsing rates. These increased free product thicknesses and recovery rates will result in a significantly shortened free product source zone removal program.

This reduction in time and mass of source zone removal through the application of PPT will significantly assist in the success of overall groundwater restoration schemes implemented, and the subsequent application of other schemes designed to restore groundwater with dissolved phase impacts.

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