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IMPROVED FILTER-PACK DESIGN FOR HYDROCARBON RECOVERY WELLS IN UNCONSOLIDATED AQUIFERS

by

Thomas R. Barrett

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IMPROVED FILTER-PACK DESIGN FOR HYDROCARBON RECOVERY WELLS IN UNCONSOLIDATED AQUIFERS

Thomas R. Barrett, M.S.

Western Michigan University, 1993

Laboratory sand tank experiments and two field studies were conducted to determine filter-pack designs that would increase the hydrocarbon flow rate into hydrocarbon recovery wells. Previous laboratory experiments have shown that using filter-packs of Teflon chips or sands treated with a water repellent spray will increase the rate of hydrocarbon recovery into wells in laboratory bail down test experiments.

The results of the laboratory investigations suggest that using a hydrophobic filter-pack with a median grain-size of 2.5-3.5 greater than that of the aquifer will provide the greatest rate of hydrocarbon recovery.

In two field studies, wells constructed with a hydrophobic filter-pack were installed immediately adjacent to wells constructed with a standard filter-pack. The results of the field studies indicate that hydrophobic filter-packs help draw product into wells, and thus facilitate hydrocarbon monitoring and recovery.

ACKNOWLEDGEMENTS

I appreciate the support of the faculty from the Geology Department of Western Michigan University. Special thanks are owed to my committee members, Dr. Grace and Dr. Kehew. I especially recognize the technical and financial support imparted to me from my advisor, Dr. Duane R. Hampton. This project is largely a continuation of research begun by Dr. Hampton. Without his support, and the cooperation of local consulting firms, this project would not have been possible.

I owe further gratitude to my family who have been behind me all the way. I am in deepest gratitude to my wife, Denise, for her patience, partnership and moral support throughout much of my college career.

Thomas R. Barrett

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INTRODUCTION

Statement of the Problem

Growing environmental awareness over the past decade has revealed that pollution of the subsurface is present and much more extensive than previously thought. Increased urbanization and the luxuries of modern civilization have created a need for large quantities of hazardous substances to be stored in close proximity to both ground-water resources and population centers. Petroleum is among the list of the more common hazardous substances. Petroleum, in several forms, is kept in underground storage tanks at gas stations and industries at a wide variety of locations. When leaks develop in these tanks, or more often the lines to these tanks, detection can be very difficult. Although recent legislation in some states requires removal of a great number of leaky underground storage tanks, spills into the subsurface continue to occur. As a result of petroleum spills ground-water resources are often lost and public health and safety may become at risk.

According to Farmer (1983), spilled petroleum, often gasoline, posses an environmental threat under any or all of four conditions:

1. The liquid petroleum (free product) flows above the water table causing migration from the spill location to adjacent areas through the subsurface.

2. Liquid product exists but is immobile, trapped in the pores at residual saturation both above and below the water table. This occurs where the degree of saturation is insufficient for mobility and where water-table fluctuations have severed the free product flow paths and the product becomes trapped in the pores by the surrounding water.

3. Volatilization of the product releases combustible vapors into the unsaturated zone, damaging vegetation and causing vapor accumulation in basements.

4. Some of the product dissolves in water, contaminating the ground-water with compounds such as benzene, toluene and xylene. These dissolved compounds flow with the ground-water in the saturated zone.

Rapid removal of the free product will reduce the extent of contamination in all the conditions mentioned above. Early detection of a leak or spill is probably the most important factor in minimizing the volume of free product released. After identifying a release, appropriate steps should be taken to cut off the source such as evacuation of the storage vessel or terminating the flow for a pipeline. Upon delineation of the extent of free product contamination, appropriate wells need to be installed for monitoring and removal of the free product.

Purpose of the Study

Wells constructed for the purpose of monitoring and removal of any type of fluid are typically built with a packing of a coarser, more uniform sand between the aquifer material and the well screen. The water well industry and the petroleum industry commonly use filter (gravel) packs in unconsolidated materials. The main reasons are: (a) stabilizing the borehole, (b) preventing the passage of formation fines, (c) increasing the effective diameter of the well, (d) reducing energy loss by allowing converging flowlines to flow through larger pores, (e) and increasing well yield by allowing for the use of a larger screen size (Ahrens, 1957; Hampton, Smith and Shank, 1991; Mader, 1979).

Previous laboratory experiments have shown that some filter pack materials may facilitate hydrocarbon flow into recovery wells, thus increasing the rate of hydrocarbon recovery from the wells (Hampton, et al. 1991). This paper presents the results of additional laboratory experiments to test for increased hydrocarbon production from wells with synthetic filter pack materials. This report also describes the application of the new technology to two field hydrocarbon spill sites.

CHAPTER II

FILTER-PACK SELECTION FOR HYDROCARBON RECOVERY WELLS

Introduction

The tendency for one fluid to be attracted to a surface in preference to another is unique between any two substances. The relationship between the contact angle of a drop of a test fluid on a solid surface immersed in a reference fluid and that test fluid's contact angle determines wettability (Domenico and Schwartz, 1990). The contact angle is defined as the angle of a tangent line drawn from a point where all three substances are in contact. A preferred wetting fluid will have a contact angle less than 90° (the fluid wets the solid) and a non-wetting fluid will have a contact angle of between 90° and 180° (Demond and Roberts, 1987). Measurements of wettability where hydrocarbon is the test liquid, water is the reference liquid and various solid substances are being tested are complicated by factors such as contamination of the solid surface, roughness of the surface, and immobility of the fluid on the surface due to adsorbed films of vapor (Dullien, 1979). The contact angle of the fluid also varies depending upon whether the fluid is advancing (imbibition) or retreating (drainage). Retreating fluids through a capillary have a contact angle greater than that of a fluid advancing through a capillary (Dullien, 1979), a phenomenon known as contact angle hysteresis.

Further difficulty arises in determining the wettability of filter-pack materials because they are not planar surfaces and direct measurements of contact angle are not possible. When dealing with porous media, measurements of capillary pressure are useful, indirect indicators of wettability (Dullien, 1979). In the case of two immiscible liquids, capillary pressure (P_c) is defined as the pressure difference between the wetting phase and the non-wetting phase. For penetration of the non-wetting phase to occur, it must reach a pressure greater than atmospheric pressure according to the equation:

$$P_c=(2\sigma/r)\cos(\theta\pm\phi) \qquad (1)$$

where, σ= surface tension

r= radius of the capillary

θ= contact angle

ϕ= half angle of the cone

Conventional methods of measuring capillary pressure using a porous cup tensiometer cannot normally be used when two immiscible fluids occur together as a tensiometer only measures the capillary pressure (relative to air) of the liquid wetting the porous cup. It is possible to measure the capillary pressure of each phase using two adjacent tensiometers, one with a water-wet ceramic cup and one with an oil-wet Teflon cup. Although this method is direct, it is difficult to place the tensiometers at exactly the same level and calibration of the tensiometers may not be possible. Furthermore, the method is based on the assumption of homogeneity.

When a hydrophobic filter pack is used, hydrocarbons maintain continuity through the porous filter pack and are permitted to drain to very low residual saturations (Dullien, 1979). The extent and rate of imbibition have been used by Bobeck et al., (1958) to predict wettability. Gatenby and Marsden (1957), and Melrose (1965) have attempted to correlate contact angles with imbibition rate. As imbibition depends upon viscosity of the fluids and the variables indicated in equation 1, a direct relationship between contact angle and imbibition is not present. For polymineralic sands, estimates of contact angles are not possible because each mineral will have a unique contact angle with each fluid (Dullien, 1979).

Hampton and Heuvelhorst (1990) used a simple technique to measure wettability of a porous substance. Their technique involves placement of a clear plastic tube vertically along the inside edge of a 1 liter glass jar which is filled with the porous media to be tested. The jars were tapped 100 times to establish equal packing. Water was poured down the tube until the jar was half-full and the cap was screwed on. After 24 hours the capillary rise was recorded. According to the following formula;

$$\text{Cos}\ \theta = hr\rho g/2\sigma \qquad (2)$$

where θ is the contact angle, h is the capillary rise, r is the average capillary pore radius, ρ is the fluid density, g is the gravitational constant and σ represents the surface tension of the fluid. This is the same as equation (1) when $\theta = 0$. The surface tensions of fluids are listed in chemistry reference books and the average capillary pore radius can be determined if the porous media is tested using ethanol as the fluid. It is assumed that ethanol wets all surfaces evenly, so the contact angle would be zero (Hampton and Heuvelhorst, 1990). After the average capillary radius is calculated using ethanol, the contact angle for water or hydrocarbon can be calculated.

The above method used by Hampton and Huevelhorst (1990) was applied to potentially hydrophobic materials. Using equation 2 to determine the contact angle of hydrocarbon with a substance, equation 1 can be solved or estimated. As the Cos of (0°) is 1 and the Cos of (90°) is 0, it is clear that lower contact angles for hydrocarbon indicate higher capillary pressures acting on hydrocarbon. Conversely, a high contact angle for water on a hydrophobic material causes a decrease in capillary pressure for water. This relationship dictates materials that may be superior filter-packs for hydrocarbon recovery wells. Preferred materials would be hydrophobic (oilophilic) in order to increase the capillary pressure of hydrocarbon relative to water.

Grain-Size Distribution

The ratio of the filter-pack grain-size to the aquifer grain-size has been studied probably more than any other aspect of filter-pack design. The specific purpose of a filter-pack determines the design criteria of the packing. The water well industry uses filter-packs for preventing sand production, to improve well efficiency, and to improve yield in underreamed boreholes (Ahrens, 1957). The petroleum industry also uses filter-packs for the purposes of increasing well yield, well efficiency, and preventing sand production as well as stabilizing the borehole.

The water well design criteria for production wells has changed through time. Ahrens (1957) suggested that for most applications a uniformly graded pack is recommended where the grain diameter of the 50% passing on a grain-size distribution curve is 5 to 10 times that of the aquifer's grain diameter at the 50% passing. More recently, the most widely accepted industry standard is that suggested by Driscoll (1986). This procedure requires a filter-pack 4 to 6 times the diameter of the 70% retained fraction of the aquifer sample. For comparison, the petroleum industry uses a filter-pack 5 to 6 times the median grain-size of the aquifer (Mader, 1979). Larger filter-packs (6-11 times larger) cause a reduction in permeability due to intrusion of aquifer fines into the filter-pack (Mader, 1979). Mader (1979) further reports that ratios greater than 11 cause sand production and ratios below 5 reduce overall production and efficiency.

None of the above methods address the unique conditions which occur when two fluid phases are present. Hydrocarbon recovery wells differ from water wells and hopefully from petroleum production wells in that more than one type of fluid will be entering the well. It would seem that using a coarser filter-pack would encourage free product flow into the well as the filter-pack is usually a quartz sand which is hydrophilic.

Mansur and Fause (1984) observed that free product would not enter a well with a very coarse-grained filter-pack. This occurrence may be explained possibly because the filter-pack is lithologically different from the aquifer. It is well documented that changes in lithology inhibit the flow of hydrocarbons through the subsurface. A new filter-pack design was suggested by Sullivan, Zinner and Hughes (1988) where the 70% retained grain-size of the aquifer is multiplied by 2.5 to 3.5 to give the 70% retained size of the filter pack. This encourages hydrocarbon passage by reducing the difference between the average grain diameter of the aquifer and the filter-pack. Sullivan et al. (1988) claim that the reduction in grain-size ratio between the aquifer and the filter-pack reduces the drop in capillary pressure across the filter-pack, thereby being less inhibitive than a coarser pack.

As it is generally accepted that the finer fraction of the sediments comprising an aquifer matrix control hydraulic properties, design of filter-packs should be based on the 70% retained size. A second purpose for basing design criteria on finer fractions is the elimination of the effect of right shifts in the grain-size distribution curve due to small fractions of coarse sediments. Samples collected in glacial terrains often yield pebbles, cobbles, boulders, or gravels in an otherwise sandy formation. A single pebble or cobble obtained in a sample gives a misleading grain-size distribution curve because it has the effect of indicating a formation is coarser than it is. This effect is caused by measuring the fractions retained in the sieve analysis by weight. It is possible that graphing the fractions retained by volume may be more representative. Figure 1 illustrates the effect of adding a 10 gram and a 20 gram pebble to a 100 gram field sample. The occurrence of the 20 gram pebble causes the curve of the cumulative percent retained to be 0.07 mm larger at 50% retained than the curve without a pebble. The difference between the two curves at 70% retained is about 0.03 mm. Designing a filter-pack based on the criteria of Sullivan et al., (1988) (2.5-3.5 times aquifer 70% retained) yields the filter-pack grain-size ranges of 0.7375 mm to 1.0375 mm for the sample with the 20 gram pebble added and 0.6375 mm to 0.8925 mm for the sample without a pebble added. The ranges are fairly similar with a great deal of overlap. For comparison, designing the filter pack based on 4 to 6 times the 50% retained yields values of 1.52 mm to 2.28 mm for the sample with the 20 g pebble and 1.22 mm to 1.83 mm for the sample without the pebble. The extent of the overlap between the two ranges is much less, indicating that (a) the difference between the aquifer 50% retained is greater than at 70% retained and (b) the 4 to 6 multiplier increases the difference between the design filter-pack grain-size for the sample with the pebble. It is clear that the design filter-pack range is affected by the change in the aquifer grain-size distribution curves due to the pebble.

As the pebble does not play a significant role in

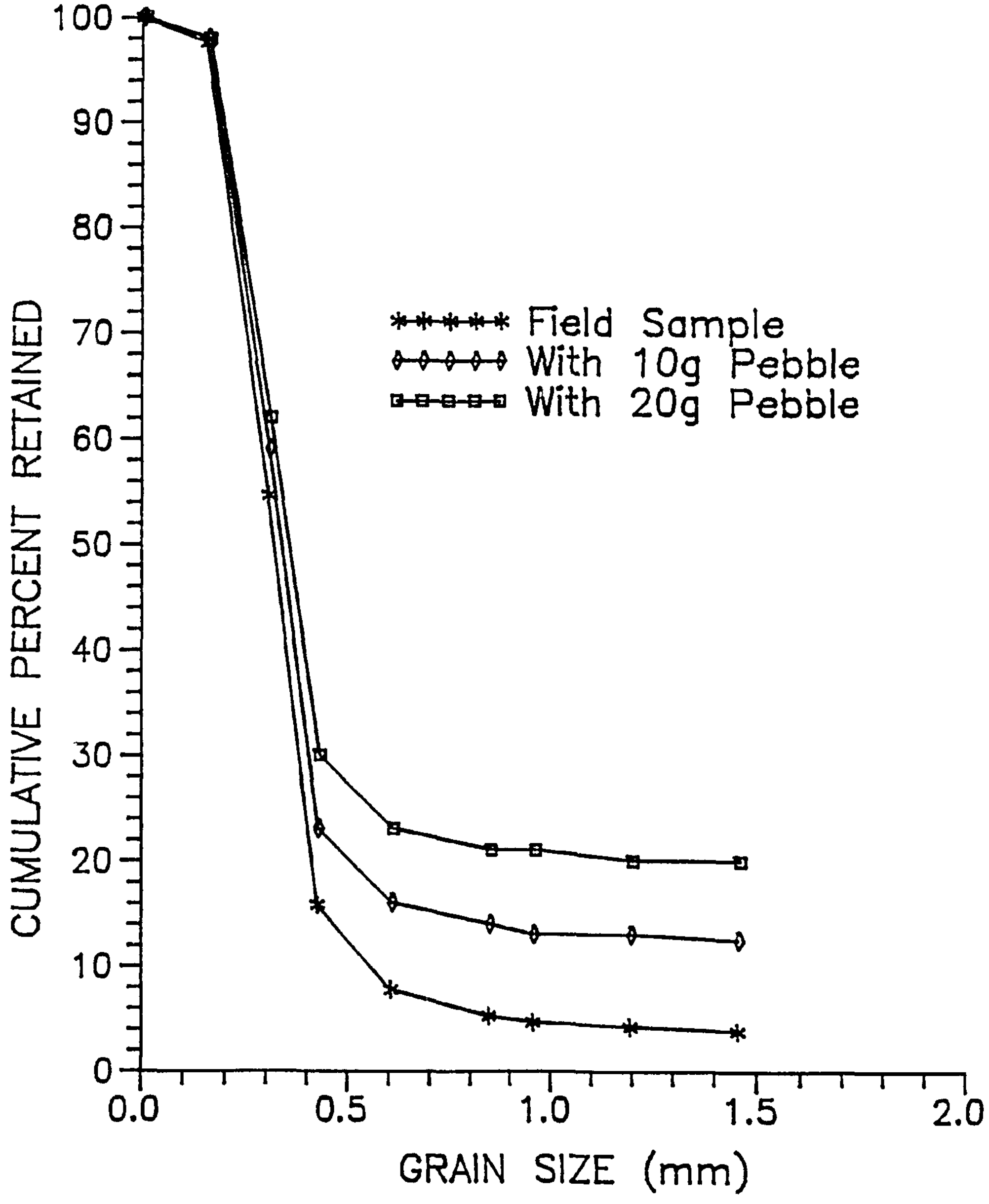

Figure 1. Grain Size Analysis of a Field Sample Without Any Pebbles Compared to the Same Sample With a 10 g and 20 g Pebble.

determining the hydraulic properties, and it will not invade the screen, it may seem plausible to produce a grain-size curve based on the material with the pebble removed. This, however, would not represent the aquifer. As the design criteria using the 70% retained size is least affected by the presence of the pebble, it would be the most appropriate method for determining filter-pack design. The value of the multiplier that is most appropriate remains to be tested in more laboratory experiments although sand tank experiments performed by Hampton and Heuvelhorst (1990) found that 3.5 times the aquifer 70% size worked best.

Grain Material

Hampton and Heuvelhorst (1990) noted that certain substances, when used as filter packs in sand tank experiments, facilitated the rate of hydrocarbon recovery into wells after pumping of the wells (bailer tests). These bailer tests were conducted on a variety of filter packs. Their results indicated that pretreatment of the filter pack sands with water repellent sprays caused hydrocarbon (kerosene) to move into the wells more rapidly than the same untreated filter sand during bailer tests. The disadvantage to using the treated sands was the traces of ethylbenzene and xylene detected in leach test experiments

(Hampton et al., 1991). The presence of the leachate prohibits the use of treated sands in the field environment.

The results of more laboratory sand tank experiments (bailer tests) indicated that PTFE (Teflon) chips, when used as a filter-pack, can significantly increase the rate of hydrocarbon recovery into wells (Hampton et al., 1991). Teflon outperformed both the untreated and the treated sands. Teflon is nonreactive and produces no leachate.

The hydrophobic (oilophilic) nature of the treated sands and the Teflon causes the filter-pack to be much more permeable to hydrocarbon than ordinary sand. This was predicted by equations 1 and 2 that describe how capillary pressure increases as the contact angle of a fluid on a substance decreases. Liquid hydrocarbons have a much smaller contact angle with Teflon than with untreated sands. Water has a much higher contact angle with treated sands and Teflon than with untreated sands. The contrast between the contact angles of water and hydrocarbon on a material describes the wettability difference. If a material is oil wet and has some oil saturation, it will tend to be more permeable to oil than when it is water wet with the same oil saturation. For a hydrocarbon recovery well, it is most desirable to use a hydrophobic material such as Teflon as a filter-pack since Teflon chips will draw product into the well by capillarity and Teflon increases the permeability of a filter-pack to hydrocarbon.

Grain Shape

Rounded quartz sand is the industry standard for filter-packing wells in the water well industry. Quartz sands (preferably at least 95%) are preferred because of their chemical inertness. The only disadvantage of using well-rounded sand is that rounded grains may permit more aquifer fines to reach the well screen or enter the well. However, using a filter-pack 3.5 times the 70% retained size of the aquifer should prevent passage of fines through the filter-pack. Angular sands may chip during placement which can reduce filter-pack permeability and provide a source of fines for screen plugging. Well-rounded sands are preferred over angular sands for most observation and recovery wells.

CHAPTER III

LABORATORY EXPERIMENTS

Laboratory Experiment 1

Methods and Materials

The sand tank experiment apparatus consists of a 40 gallon (135 liter) glass aquarium which was 90 cm long by 50 cm high by 30 cm wide. The aquarium was fitted symmetrically with four, 5.08 cm diameter, 10 slot well screens which had been cut in half lengthwise from top to bottom. The screens were placed vertically against the sides of the tank and cemented with bentonite. Two wells were positioned equidistant from the edges on each of the two long sides of the aquarium. Four filter packs could be tested in one sand tank experiment. The aquarium was packed with bentonite in the bottom and all the corners to protect the caulked edges from reactions with the hydrocarbons.

Since chemically treated sands and Teflon chips performed well in previous laboratory experiments, it was decided to test sands treated with a new Teflon product. The product is marketed under the name of Soil Shield, a liquid form of Teflon that is applied to fabrics to protect against staining. The liquid Teflon could also be applied to a sand to be used as a filter-pack for a hydrocarbon recovery well.

The four filter-packs to be tested were (1) Teflon chips, (2) an angular chert treated with the spray-on Teflon, (3) a well rounded quartz sand, and (4) the same quartz sand treated with the Teflon spray. The objectives were to (a) determine if grain shape affected the performance of treated sands, (b) compare the Teflon-treated quartz sand with the same untreated sand, and (c) compare these results with the performance of the Teflon chips.

The first requirement was to locate a well rounded quartz sand and an angular chert sand that had similar grain-size distributions to that of the Teflon chips. It was especially important that the 70% retained size of each of the filter-packs be about the same grain-size since the design is based on that size. The filter sands chosen were Milan Supply's #4SB (a well rounded quartz sand) and Humble Sand's #7 (a crushed angular chert). Once the filter-packs to be used were determined, an aquifer sand was selected that had a 70% retained 3.7 times finer than the filter-packs. Figure 2 is a grain-size distribution curve of the filter packs and the aquifer sand for experiment 1. The aquifer sand is a uniform quartz sand.

Several 4 gallon buckets of both the rounded quartz sand and the angular chert sand were treated with the

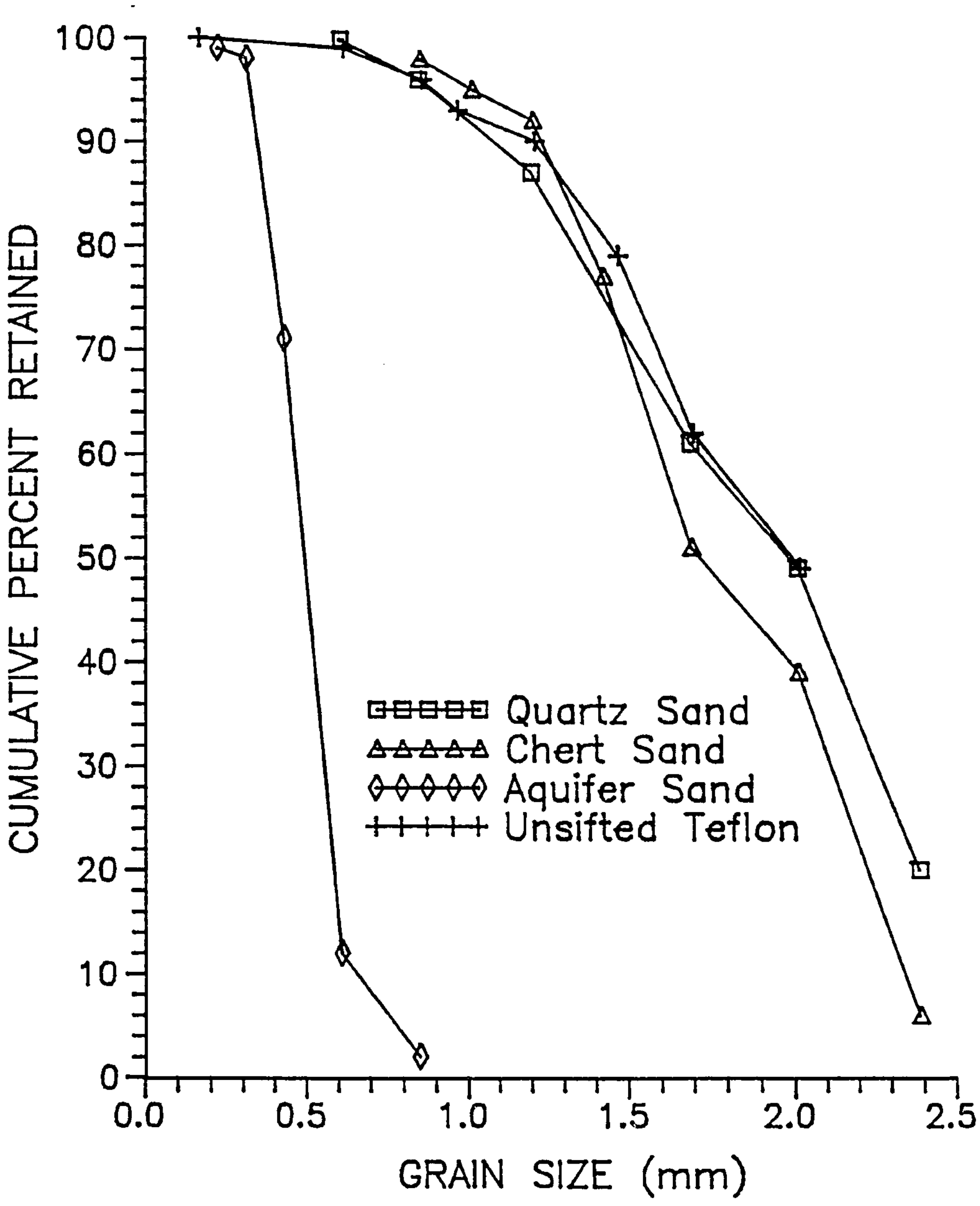

Figure 2. Grain-Size Distribution of Filter-Packs and Aquifer Sand for Tank 1.

Teflon spray. Treatment consisted of spreading the sands out on plastic and cardboard to a thickness of a few grains. The spray was then applied by a hand held, pressurized, spray bottle. The Teflon was applied evenly as a fine spray about 6 inches from the sand. Approximately 10 minutes was alotted for drying time before the sands were stirred with a rake, sand was added and more Teflon was applied. The process was repeated until the sands appeared to be thoroughly treated. Four gallons of each sand were treated. A ratio of 1 gallon of Teflon spray to 6 gallons of sand was used. The sands were allowed to dry for 2 days at 30-35°F. Samples of both the treated chert and the treated sand were immediately placed in an oven set at 70°C and baked for 24 hours. These samples were collected for batch (leach) testing.

The tank was prepared by cementing the open side of the screens to the glass sides of the aquarium using a bentonite paste. Each of the four wells was then fitted with a 4 inch half-circular sheath that fit around the well screen leaving a 1 inch annular space between the screen and the sheath. The annular space was filled with approximately 2 inches of the appropriate filter-pack through a narrow tremmie pipe. Next, the aquifer sand was distributed throughout the tank in relatively flat layers via a 3/4 inch diameter tremmie tube. The level of the aquifer sand was kept below that of the filter-pack materials to avoid infiltration of the aquifer sand into the filter-packs. The procedure was repeated until the tank was nearly completely filled. This required about 181 kg of Milan Supply's FS-25 sand for the aquifer. The tank was then filled about 2/3 full of tap water using a hose. Most of the water was added by injection down the wells for development, but some water was added through a centrally located horizontal trough located on the surface of the aquifer sand. The trough was a short section of 5.08 cm diameter stainless screen which had been cut in half lengthwise. The addition of water through the top of the tank caused the sand above the saturated zone to become wetted, simulating natural conditions . After the water levels in the wells stabilized, the capillary rise (or suppression) of water in the filter-packs was measured. The untreated quartz sand had a capillary rise of about 6.0 cm above the water level in the well. The Teflon chips suppressed water entry to a depth of 5.8 cm below the water level in the well. The treated chert sand and the treated quartz sand had capillary suppressions of 3.0 cm and 2.75 cm respectively.

The last step in the tank preparation was the addition of 4.5 liters of blue dyed kerosene. The kerosene was added slowly through the trough at the top of the tank.

The level of kerosene in the wells took several days to stabilize. Stabilization occurs when the system has equilibrated, and was determined when the fluid levels in all the wells were approximately the same. The elevation of the product/air interface and the elevation of the product/water interface were both recorded. Elevations were measured from the bottom of the tank. The difference between the two elevations gives the product thickness, which was also recorded for each well. When product thicknesses in the wells were equal, the tank was prepared to begin bail down tests. For the purposes of these sand tank experiments, a bail down test consists of pumping out a predetermined volume of product and systematically measuring the fluid levels and recording the times as product returns to the wells. For these experiments, as in past experiments, the product recovery was measured for 2 hours.

A series of bailer tests were conducted and repeated 3 times. In each set of bailer tests, the wells were tested in a different order so the sequence the wells were tested in did not repeat and could not be a factor in data interpretation. In each test approximately 0.5 liter of fluid was removed, consisting of 0.4 liter of product and 0.1 liter of water. A waiting period of at least 48 hours was required between any 2 successive bail down tests to allow the tank to return to equilibrium conditions before conducting another bail down test. In order to restore the fluid levels to the conditions present before a bailer test, frequently product (about 0.5 liter) had to be added. It is uncertain whether the loss of product due to a bailer test was due to evaporation of product from the tank or if product was introduced and trapped into previously water wet pores. Four sets of bail down tests were conducted in this experiment, with the order of testing varied in each set of tests.

Results

The results of the first bail down test are illustrated in Figure 3. The initial product thicknesses were approximately 25 cm but varied by 2.5 cm over the course of the tests. After 120 minutes of recovery, the untreated sand clearly outperformed the other filter packs with a product thickness of 12.5 cm. The treated sand had the second greatest product thickness with just over 8.1 cm. The Teflon chips had the least product thickness with 7.1 cm.

The second set of bailer tests was conducted with greater uniformity than the first set. The results for the second set of bail down tests differed from the first set (Figure 4). This time the initial product thicknesses were

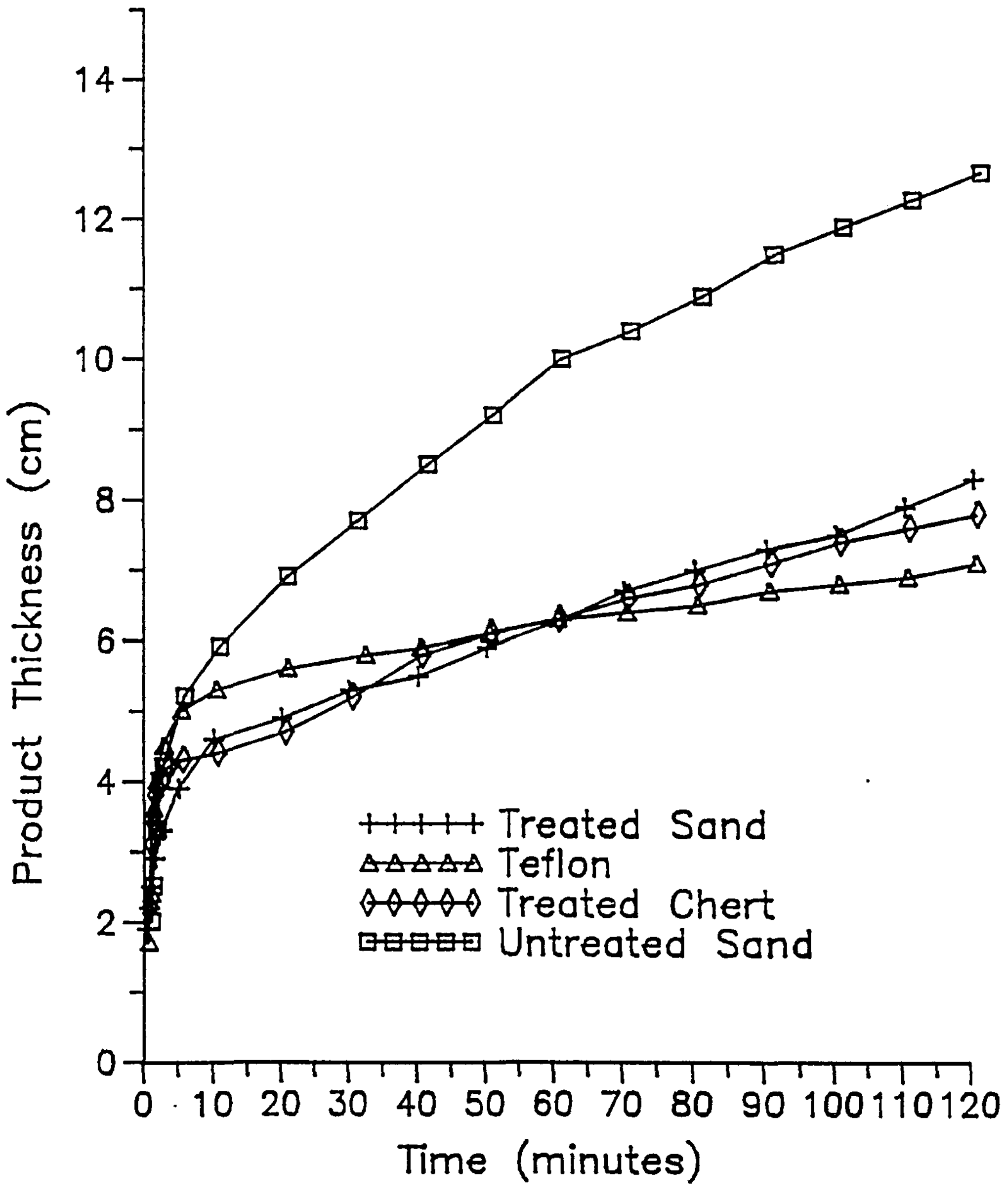

Figure 3. Results of Bail Down Test Set 1 on Tank 1.

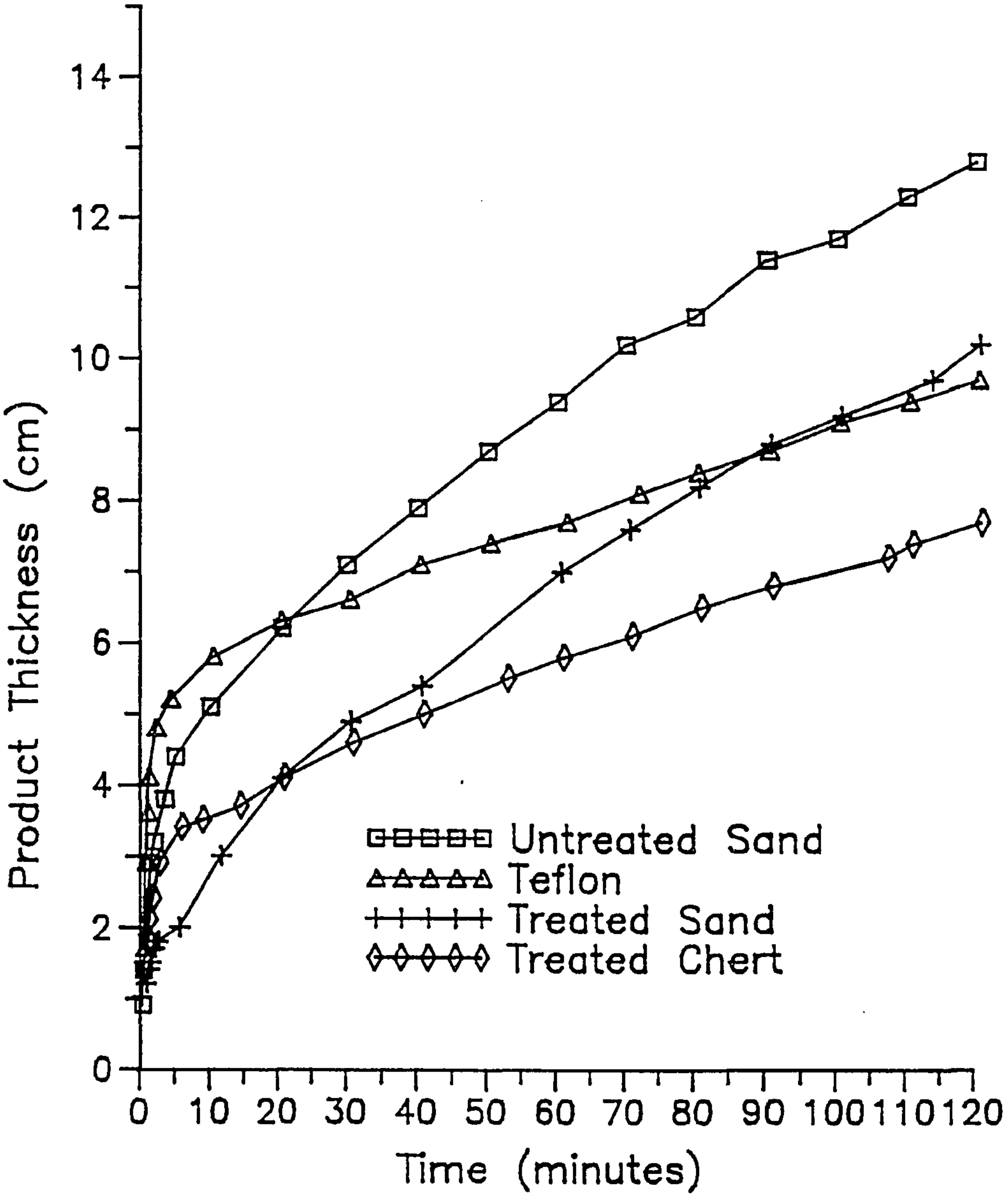

Figure 4. Results of Bail Down Test Set 2 on Tank 1.

maintained at 20.5 cm (± 1.0 cm). The untreated sand still outperformed the other filter-packs; however, the treated chert performed the worst with a product thickness of 7.5 cm after 120 minutes. The treated sand and the Teflon performed nearly the same with about 9.7 cm of product thickness after 120 minutes.

Product was added to the tank (900 ml) between sets two and three. The third set of bailer tests yielded a completely different set of data (Figure 5). Initial product thicknesses were kept at 20.0 cm (± 1.0 cm). The performance of all the filter-packs were nearly equal. Note that all the filter-packs recovered nearly 13 cm more product than in the previous 2 test sets. This may indicate that the filter-packs were now saturated with product and the product was free to pass through the filter-packs rather than becoming trapped in the pore spaces of the filter-pack.

Figure 6 shows the results from the fourth set of bailer tests. The bailer tests were run with high initial product thicknesses (25 cm). The results appear similar to those from the third set. The differences in performance are small. The average product thicknesses in the wells after 2 hours is, again, nearly 13 cm greater than in the first two sets of bail down tests.

The data from this experiment do not show enough

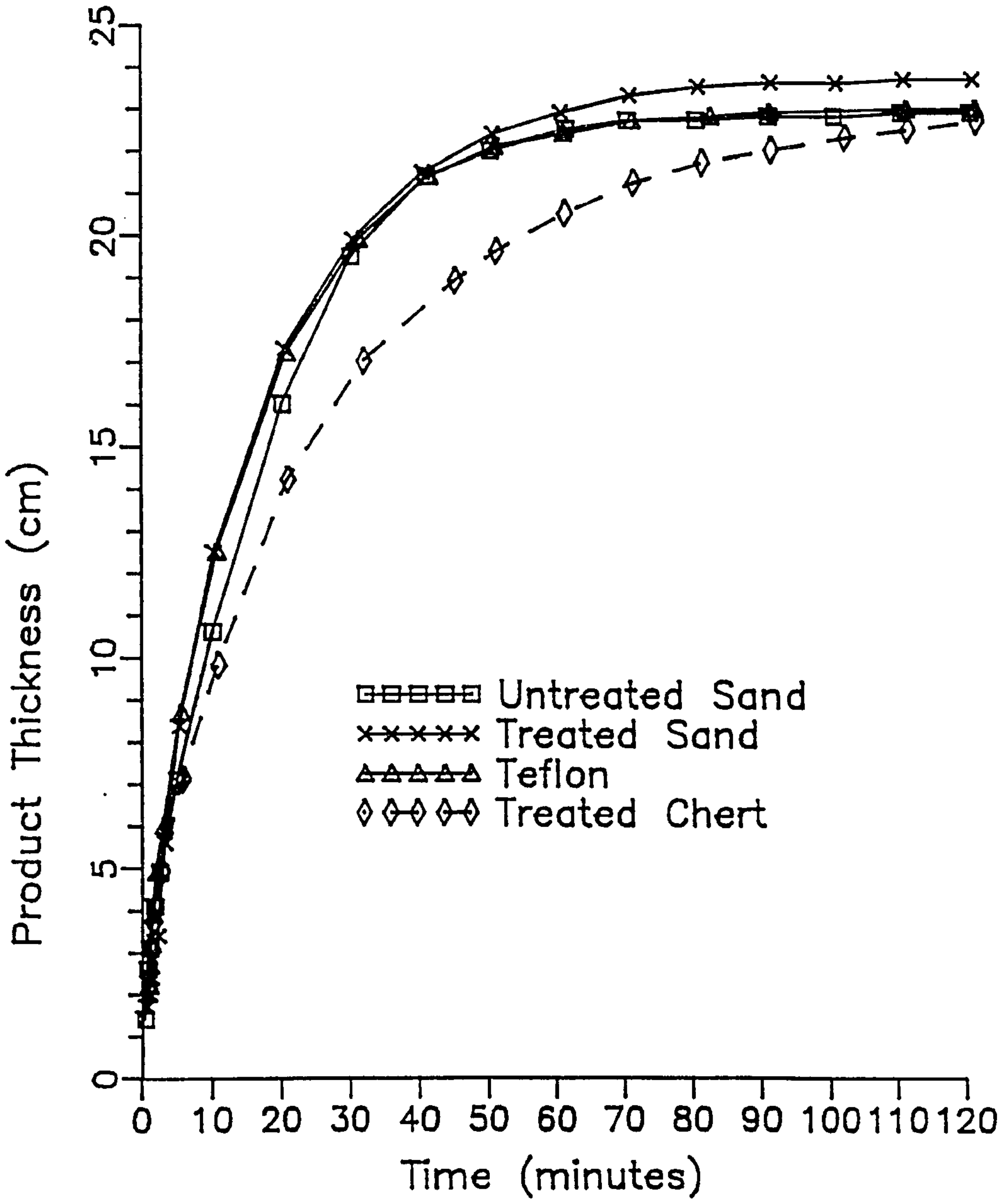

Figure 5. Results of Bail Down Test Set 3 on Tank 1.

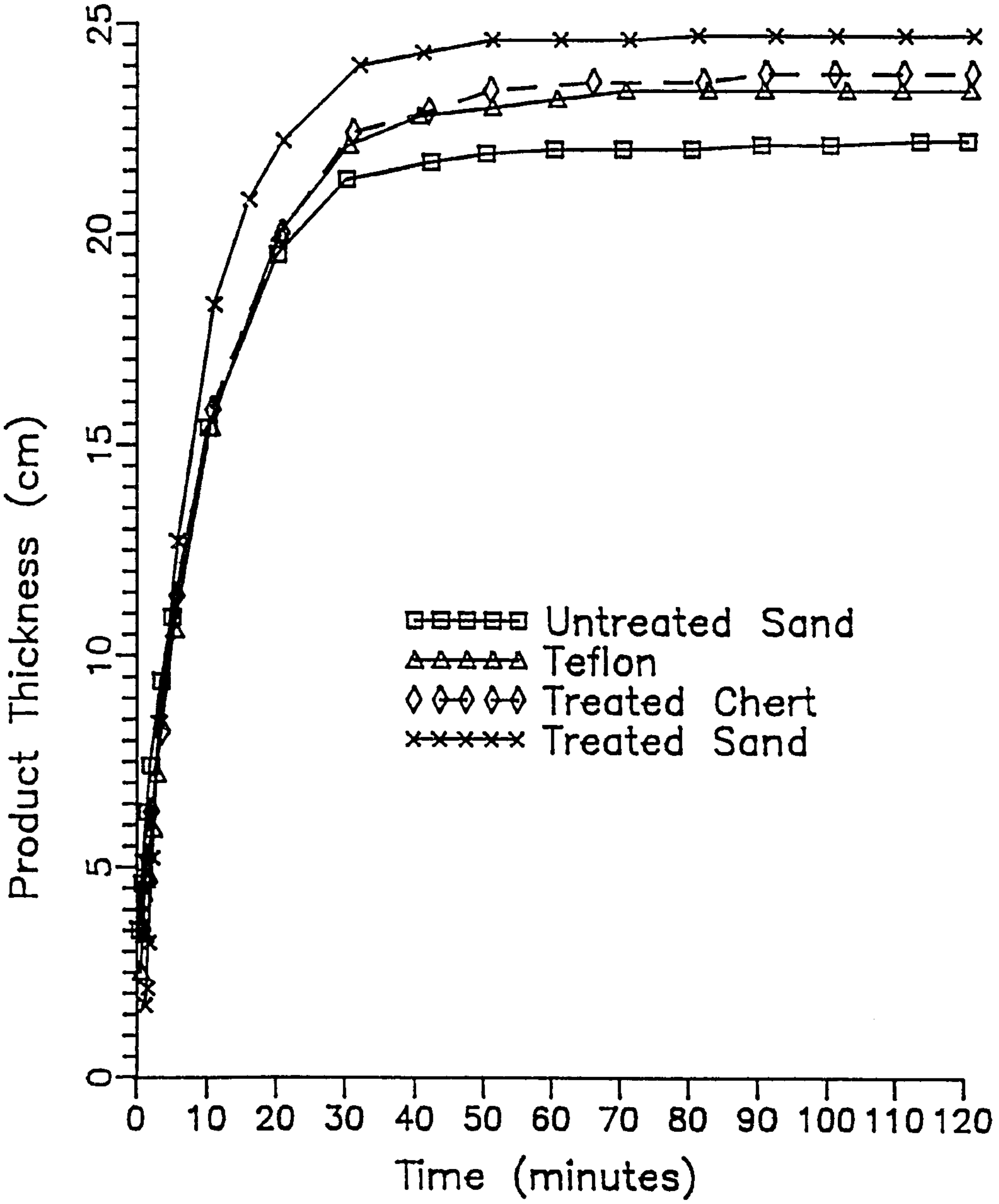

Figure 6. Results of Bail Down Test Set 4 on Tank 1.

consistency to obtain any direct conclusions. Previous laboratory investigations conducted under similar conditions using the same apparatus (but with different sand types) have provided much clearer data for interpretation. The inconsistencies suggest that properties, other than the filter pack material, are controlling the product recovery rates. As the procedure for constructing the tank was identical to procedures used in previous experiments, it is unlikely that the method of setting up the experiment caused the inconsistencies.

One possible explanation for the inconsistencies is the aquifer sand. The aquifer sand (Milan Supply #FS-25) had not been used in previous experiments. Although the measured grain-size distribution curves appeared to be similar to those used in previous experiments (Red Flint #35-45), FS-25 was measured to be some finer (Figure 7). The ratio of the filter sands to the aquifer sand was approximately 3.7. This ratio is outside the range of 2.5 to 3.5 suggested by Sullivan et al. (1988). It is possible that the gross change in lithology (grain-size) inhibited the flow of product from the aquifer into the filter-packs. An important trend in the results of the test was the decrease in the performance of the untreated sand with respect to the other filter-packs. The results from the first data set (Figure 3) had the greatest difference in

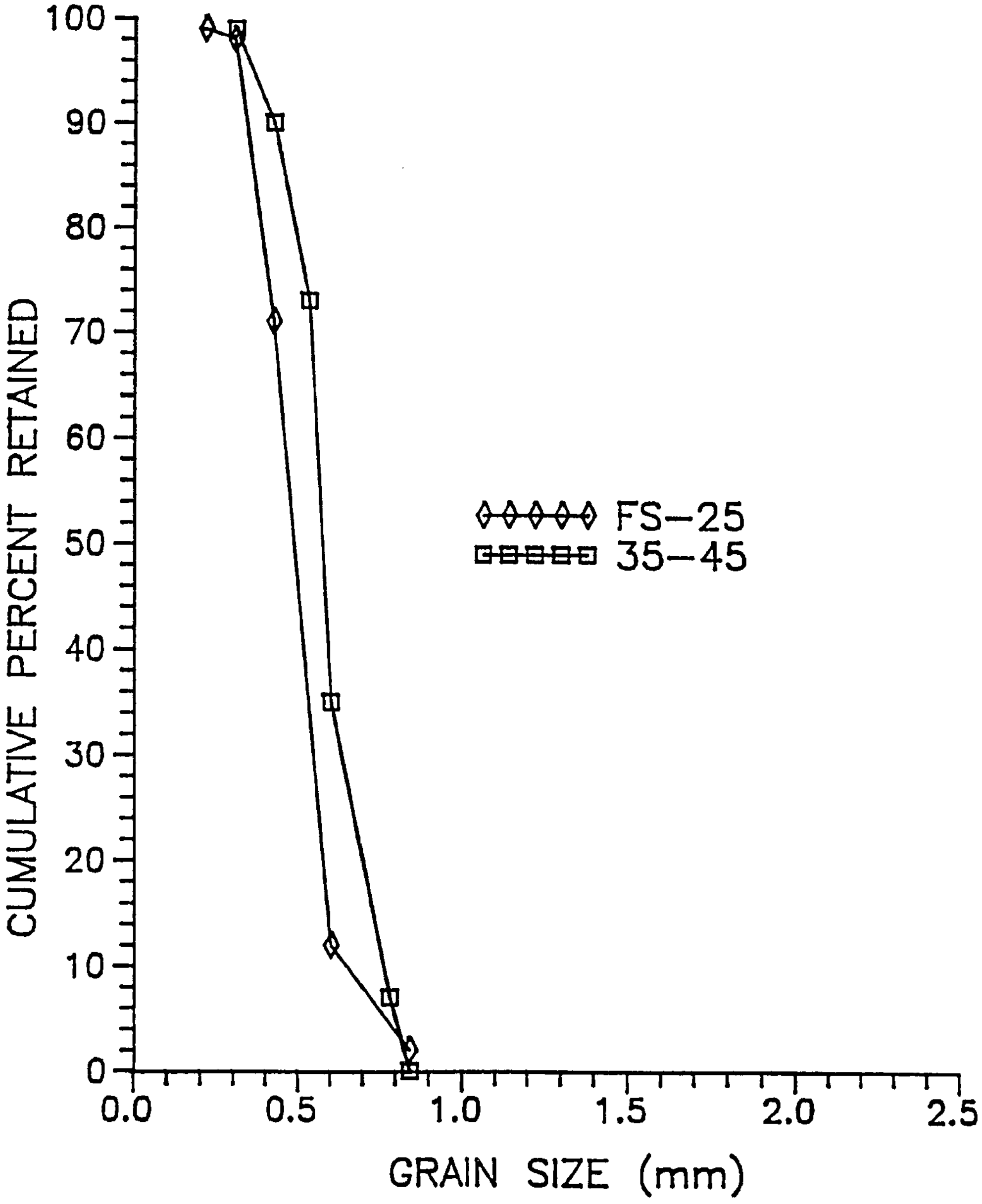

Figure 7. Comparison of Aquifer Grain-Size Distribution Curves.

performance between the untreated filter-pack and the other filter-packs. The gap was closing by the second data set (Figure 4) and the difference was non-existent by the third data set (Figure 5). The untreated sand performed the worst by the fourth trial (Figure 6). As the pore spaces of the hydrophobic filter-packs (all but the untreated sand) were not saturated with product initially it is likely that their performance was poor during the first several tests because product was entering the pores of the filter-pack rather than entering the well. This is supported by the difficulty in removing product from the hydrophobic filter-packs in the first 2 sets of bailer tests. The untreated sand easily provided more product. This trend was reversed by the third set of bailer tests.

The increased performance of all the filter-packs in the last 2 data sets may be explained by the addition of more product between test sets 2 and 3.

In order to maintain identical fluid levels between individual tests, product was added to the tank in uneven intervals (mid-set) during the first test set. The drop in levels between some of the trials was thought to be due to volatilization. Volatilization had not occurred at that rate in previous laboratory experiments.

Laboratory Experiment 2

Methods and Materials

Although Experiment 1 did not yield data which could be conclusively interpreted, previous laboratory experiments indicated that filter-packs constructed of Teflon chips allowed for more rapid recovery of product into wells during bailer tests (Hampton et al., 1991). The lack of available granulated Teflon and high cost of using Teflon chips warrant the effort to minimize the quantity of the material used.

The objective of Laboratory Experiment 2 was to (a) determine if a Teflon chip/sand mixture will perform well as a filter-pack, and (b) evaluate the performance of 3 filter-packs consisting of 3 different ratios of a Teflon/sand mixture relative to a filter-pack of 100% Teflon chips. Any differences in performance would be attributed to the ratio of the Teflon/sand mixture.

The ratios of the Teflon/sand mixtures were measured by volume because the materials have different densities. The density (particle) of Teflon was experimentally determined to be about 2.05 g/cc and the density of the sand is approximately 2.65 g/cc. Ratios of 75%, 50% and 25% Teflon were used as well as a 100% Teflon chip filter pack. The 75% by volume Teflon mix was 67% Teflon by weight. The 50% Teflon mix was 42% by weight and the 25% Teflon mix was 20% Teflon by weight.

The sands to be used in this experiment were Red Flint's #35-45 for the aquifer sand and Milan Supply's #4SB. Grain-size distribution plots of these sands are indicated with the 100% Teflon curve in Figure 8. Grain-size distribution curves of Teflon chip/sand mixtures cannot be directly produced from sieve size analysis which are based on the cumulative weight percent retained. Normally, material density is uniform and the cumulative weight percent retained is equal to the cumulative volumetric percent retained. As the particle densities of the Teflon and sand are not equal, the volumetric percent retained does not equal the cumulative weight percent retained. Because the volumetric proportions of each material may change during the sifting process, a cumulative weight percent retained grain-size curve is not meaningful. It is possible to construct a curve for a 50-50 volumetric mixture that is the average of the other two curves. As the grain-size distribution curves of the Teflon and the sand are in close agreement at the 70% retained size, it is not necessary to hybridize the distribution curves for the various Teflon chip/sand mixtures.

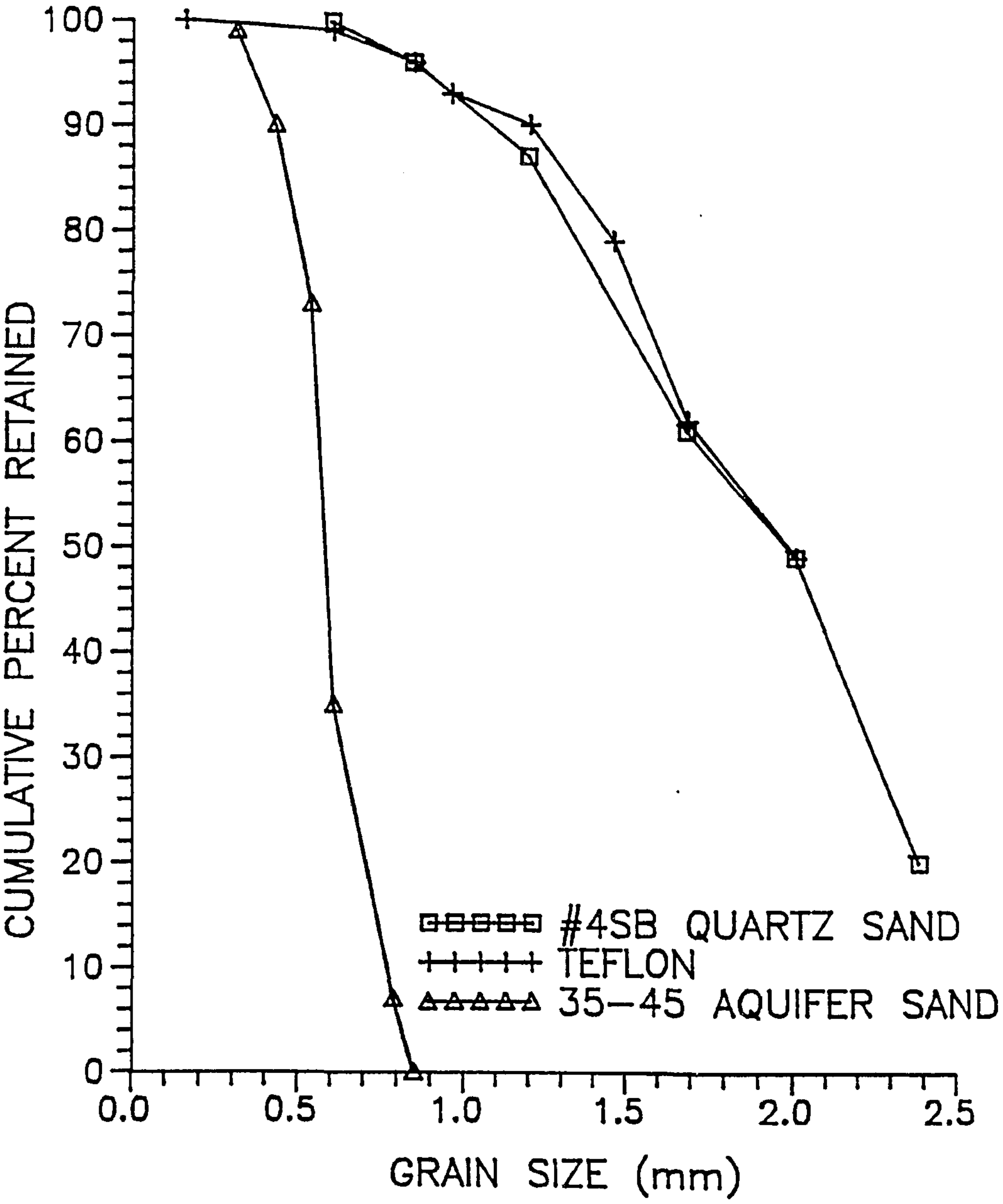

Figure 8. Grain-Size Distribution of Filter-Packs and Aquifer Sand for Tank 2.

The grain diameter of the 70% retained size of the aquifer sand is approximately 0.56 mm (Figure 8). The grain-sizes of the 70% retained for the filter-pack materials are 1.55 mm and 1.61 mm for the sand and Teflon chips respectively. The respective ratios of the filter-packs to the aquifer sand are 2.8 and 2.9. These ratios are within the range of 2.5 to 3.5 suggested by Sullivan et al. (1988). After mixing the filter packs in the volumetric ratios listed above, the tank was constructed using the same method as described in Experiment 1. Approximately 181.4 kg of Red Flint #35-45 aquifer sand was used.

The majority of the water was added through the 4 wells via a hose. To wet the sand, some of the water was added through the trough on top of the aquifer sand. After the wetting was completed and well levels had stabilized, 3.5 liters of dyed product (kerosene) was added through the top of the tank. When product thicknesses in the wells stabilized at approximately 18.0 cm, bail down testing began using a Geopump II peristaltic pump.

The first set of bail down tests started with the 75% Teflon well and progressed clockwise around the tank to the 50% Teflon well, the 100% Teflon well and lastly the 25% Teflon well. In each test, 360-425 ml of product were removed. The second set of tests began with the 100% Teflon well followed by the 75% Teflon well, the 50% Teflon well and the 25% Teflon well. The third set of tests began with the 25% Teflon well and progressed to the 50% Teflon well, the 75% Teflon well and finally the 100% Teflon well.

Results

The results of the first set of bail down tests are shown in Figure 9. The product recovery of the wells with filter-packs containing 50% or more Teflon was much greater than the recovery of the 25% Teflon well after 120 minutes. The recovery rates of the 50% and 75% wells were nearly equal during the 120 minute test. The rate of recovery into the 100% well was slow initially, but after the first 40 minutes the rate of recovery (slope of the line in the graph) increased relative to the other wells. This may be due to the time delay for the highly oilophilic 100% Teflon filter-pack to become saturated with product.

The 100% Teflon well outperformed the other wells in the second set of bail down tests (Figure 10). The 25% Teflon well performed the worst. The 75% Teflon well outperformed the 50% Teflon well. This set of bail down tests suggest that an increase in the amount of Teflon chips used in a filter-pack is accompanied by an increase in the product recovery rate of a well. As in Laboratory Experiment 1, the performance of all the wells increased by the second bail down test set.

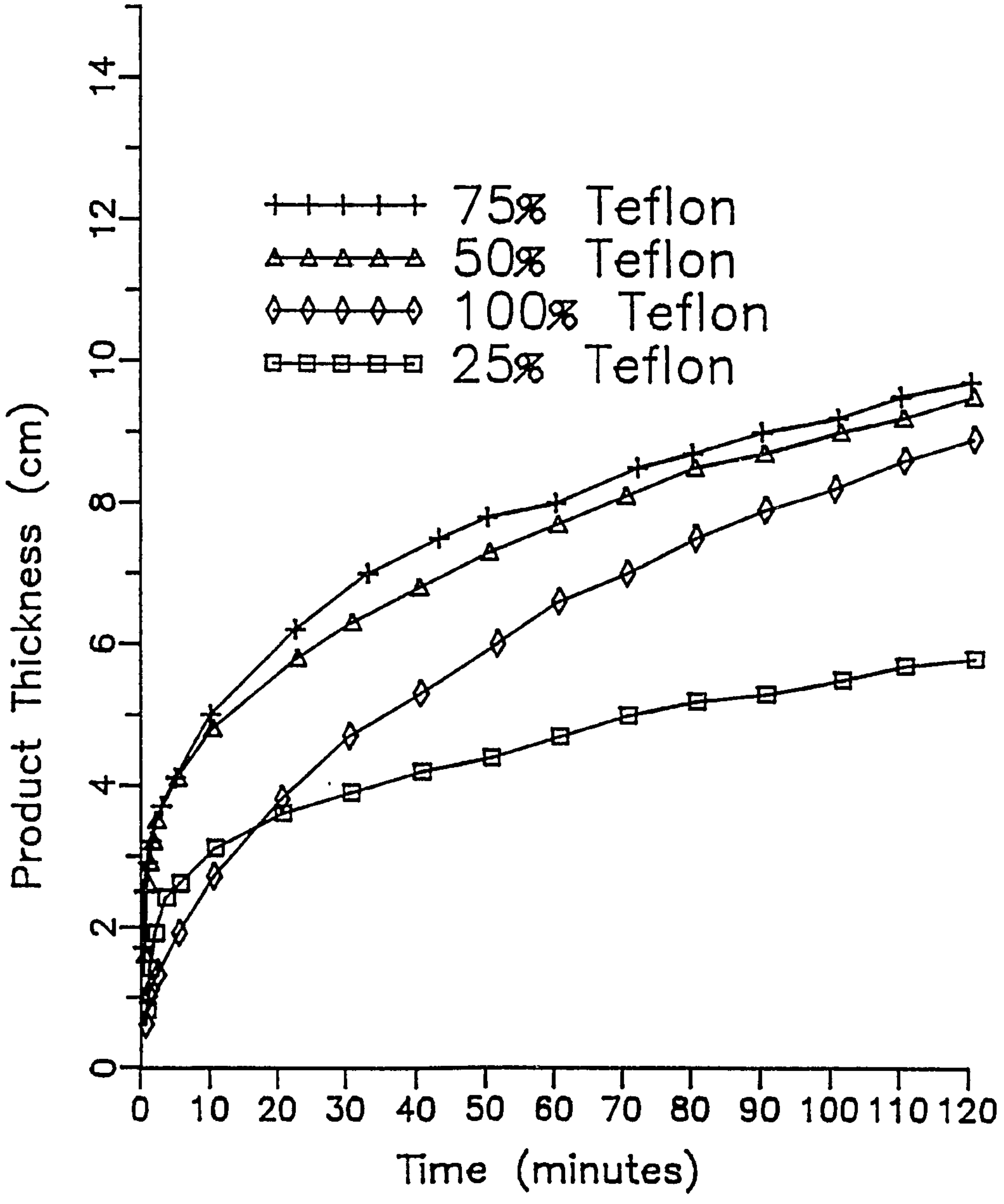

Figure 9. Results of Bail Down Test Set 1 on Tank 2.

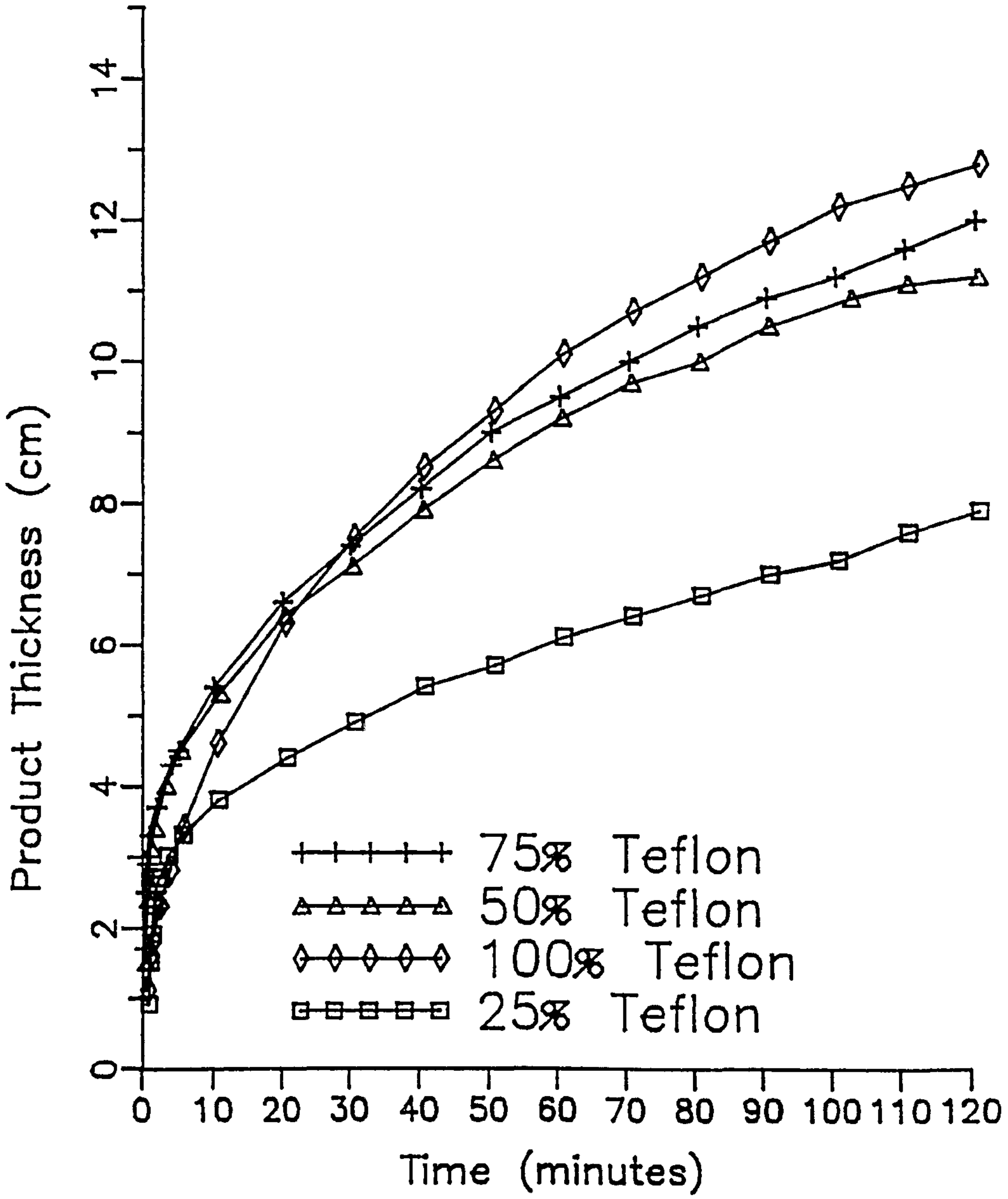

Figure 10. Results of Bail Down Test Set 2 on Tank 2.

The results of the third bail down test set are nearly identical to the second set (Figure 11). The performance of all the filter-packs roughly replicated the results of the previous test set.

The results of this experiment yield several important conclusions. The time delay for the more hydrophobic (oilophilic) filter-packs to reach a peak performance is probably a function of product saturation of the filter-packs. This is supported by the observation that the performance of the hydrophilic or least hydrophobic filter-packs increases the least in repeated tests. The performance of filter-packs with little affinity for product does not improve from the first set of bail down tests. Quite the opposite is true in the case of more hydrophobic filter packs. As previously noted, the data for Laboratory Experiment 2 strongly suggest that increasing the ratio of Teflon to sand in a filter-pack increases the product recovery capability of the filter-packs. Their performance increased after the first bail down test set. The data further imply that a filter-pack mixture with 50% Teflon will provide approximately 92% of the product recovery of a well filter-packed with 100% Teflon chips.

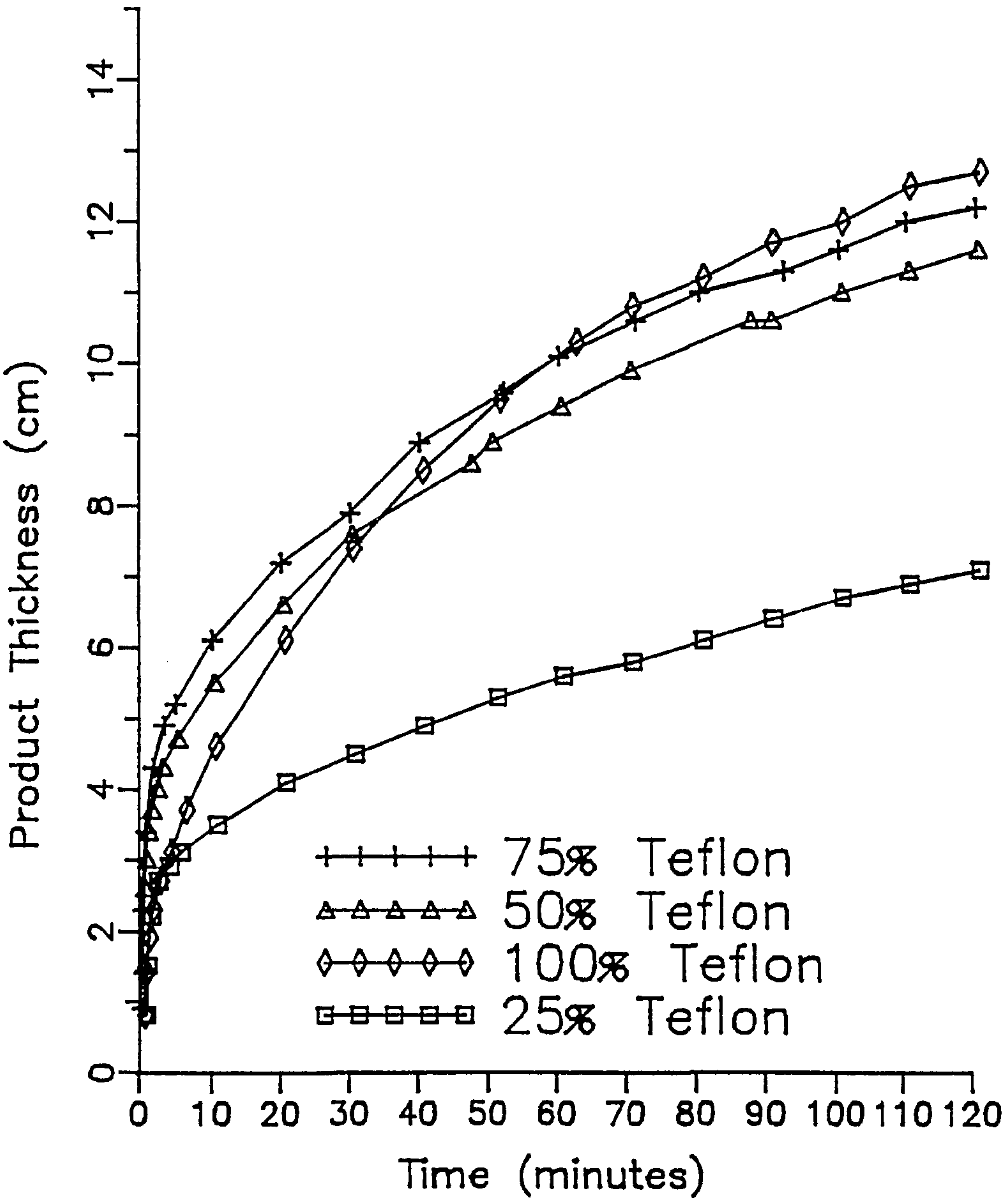

Figure 11. Results of Bail Down Test Set 3 on Tank 2.

CHAPTER IV

FIELD STUDIES

Field Study 1

Introduction

The proven success of Teflon chips as a filter-pack in laboratory experiments required field verification to determine if the new design was truly worthwhile. The less controlled field environment can introduce variables not present in the laboratory sand tank experiments.

Preferred characteristics for initial field testing include (a) a homogeneous aquifer sand, (b) isotropic conditions, (c) evenly distributed and ample product thickness, and (d) an aquifer grain-size distribution that can be matched (as previously discussed) with the available Teflon grindings.

Methods and Materials

With the cooperation of an environmental engineering firm, a site was located in a glacial outwash terrain. The site was contaminated from a 10 inch diameter 2000 psi petroleum pipeline rupture that occured approximately 3 years prior to this investigation. The valve that leaked into an unlined pit spilled an undetermined volume of product. This valve is located in the southeast corner of Figure 12. The flow of groundwater is toward the north by northwest. Free product occurs as a thin sheen in wells MW-9(A-C) about 160 ft. directly down gradient from the valve. Records indicate that these wells had product thicknesses of approximately 3 inches 1 year previous to this investigation. Several inches of product have intermittently occurred in both MW-3 wells which are immediately down gradient from the source about 20 ft. away. Presently, a dissolved plume has migrated to the north of the property line.

The glacial deposits are a reasonably uniform, medium sand with little change in grain-size with depth. The samples collected for grain-size analysis were taken from the side of an 8.25 inch OD hollow stem auger after the auger had made several revolutions at 20 ft. of depth. Two samples were collected from the sides of the auger, each at approximately the same depth but in adjacent boreholes. A surface sample was also analyzed for comparison. The grain-size analyses for the auger samples gave identical grain-size distribution curves (Figure 13). The surface sample was slightly finer than the auger samples. The grain-size distribution of the available Teflon chips was too coarse to be used as a filter-pack for this aquifer

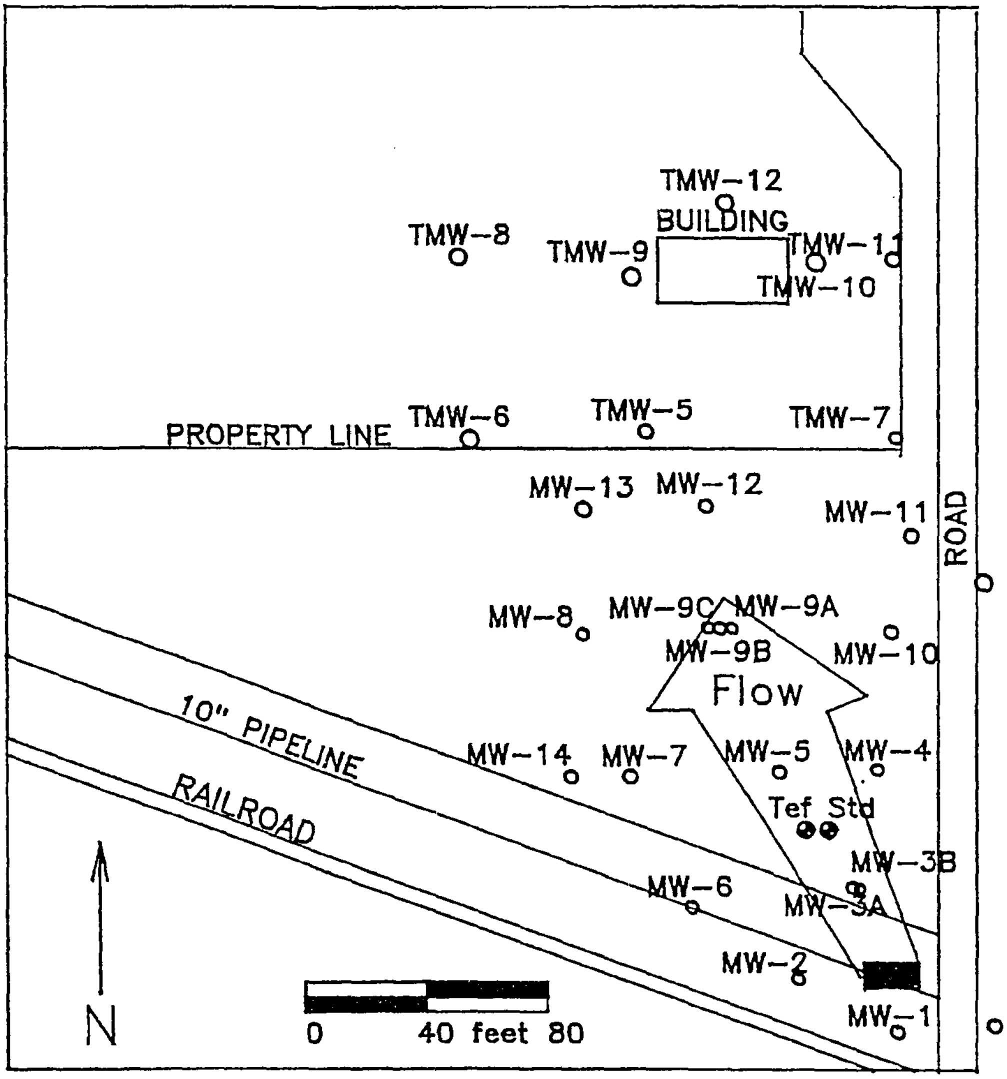

Figure 12. Map of Site 1.

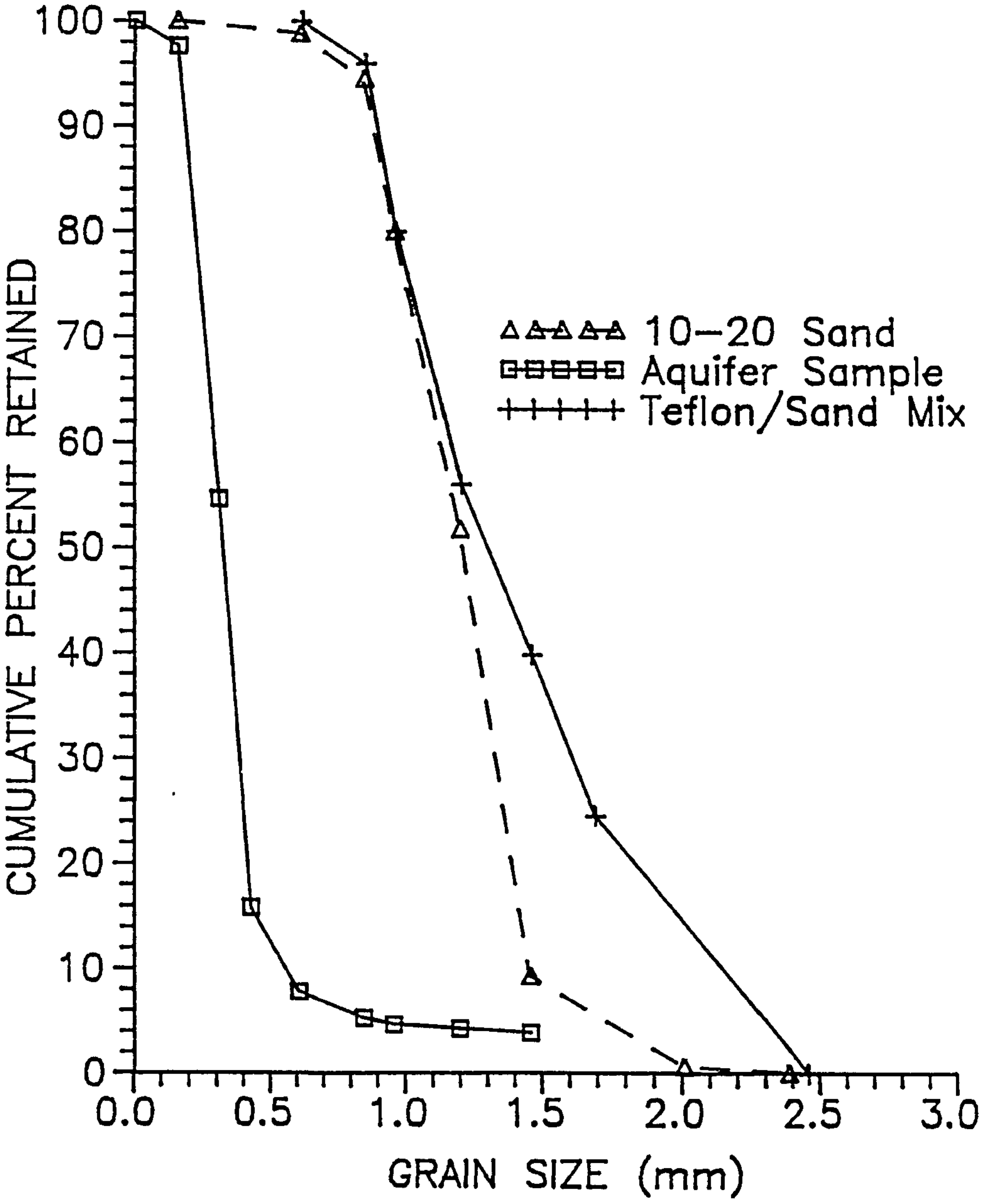

Figure 13. Grain-Size Distribution Curve of Filter-Packs and Aquifer Sand for Site 1.

without some alteration. The available Teflon chips were mixed with an equal volume of a 50/50 combination of two finer Colorado Silica sands (#10-20 and #16-40). In order to produce an appropriate sand for mixing with the Teflon chips, the coarse fraction passing a #14 sieve of the #10-20 sand was mixed with the fine fraction retained on a #20 sieve of the #16-40 sand. The resulting grain-size distribution curve is the average of the materials that were mixed. The calculated Teflon/sand mixture (average of Teflon curve and composite sand curve) is shown with the standard pack in Figure 13. This curve could not be measured directly due to the different densities of the two constituents as explained in Chapter III.

Depth to the top of the unconfined aquifer was between 3.6 and 4.0 m (12-13 ft) throughout the site. Wells MW-3A, MW-4, MW-5 and MW-9A all had skimmers which were removing free product. Free product recovery has continued for at least 2 years.

In order to test the performance of a Teflon filter-pack, another well with a standard filter-pack would have to be placed immediately adjacent to the Teflon packed well. The placement of the wells also needed to be in a location thought to have free product. Locations inside or adjacent to the arrow indicating flow in Figure 12 are well suited for recovery well placement.

The best location for the wells was determined to be between MW-5 and MW-3A. During April of 1992, the Aquifer Dipstick, a new tool used to measure free-product thickness (Hampton et al., 1990) was used at several spots on the site. Although the indicator strip did not yield unambiguous evidence of the presence of free-product, the well were placed in the most likely location for free-product. The well with the standard filter pack was drilled with a 20.9 cm OD (15.9 cm ID) hollow stem auger. The well was augered to a depth of 6.1 m (20 ft). A 3 m (10 ft) long, 5.08 cm diameter, #10 stainless steel screen was lowered down the hole and threaded to a 3 m long 5.08 cm PVC riser. About 113 kg of the standard filter pack sand commonly used by the contractor was placed from the bottom of the borehole to a depth of about 2.3 m (8 ft) (Figure 14).

The well with the Teflon/sand mixture was placed 61 cm west of the standard filter-packed well. The well was drilled to the same depth using the same equipment on the same date (April 6, 1992). As the Teflon chips were in limited supply, the driller emplaced the Teflon/sand filter pack from a depth of 1.5 ft below the water table to 2.5 ft above the water table (± 0.75 ft). The approximate design details are illustrated in Figure 14.

The wells were developed by the contractor at a later date. The contractor recorded fluid levels occasionally.

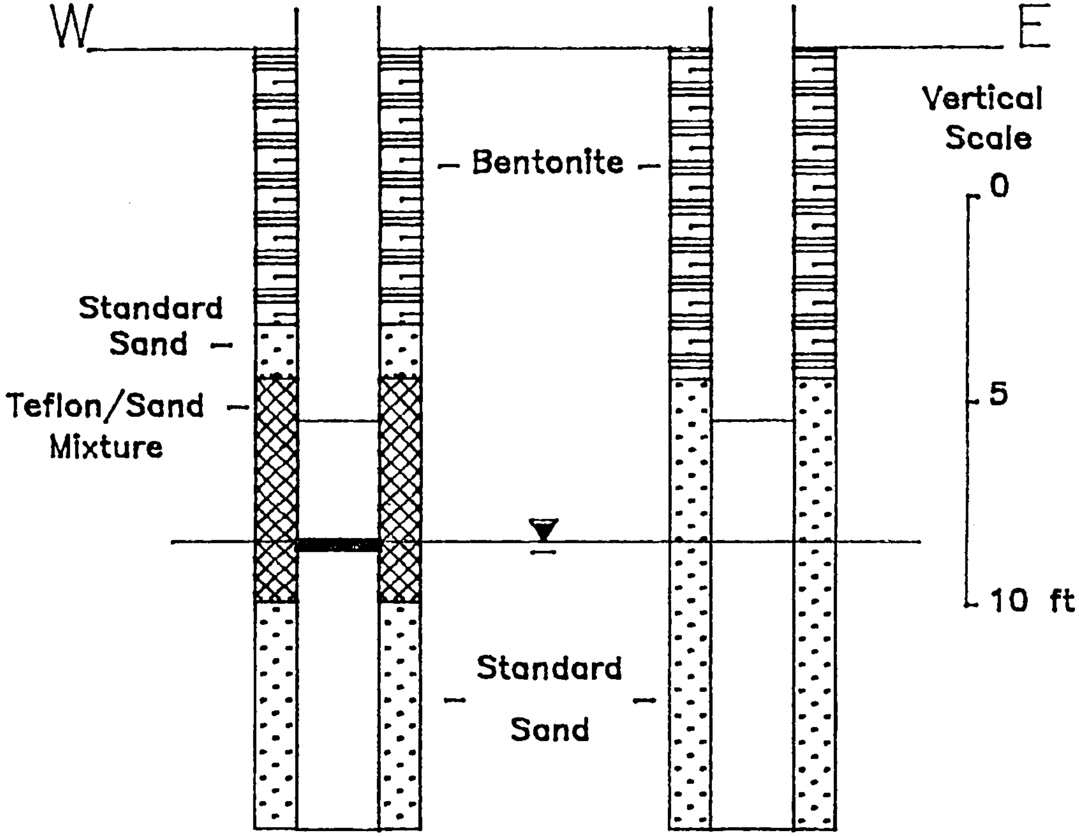

Figure 14. Well Constructions for Site 1.

Results

Less than three weeks after installation of the wells, free product was measured to be 7.6 cm in the Teflon/sand filter-packed well while no product was detected in the standard filter-packed well. A skimmer pump was placed in the Teflon/sand packed well and product was recovered for 3 weeks until the well quit producing product. The product thickness in the well diminished below detection and the pump was removed from the well. During September of 1992, The Teflon/sand and standard packed wells were measured to have 20.3 and 2.54 cm of product, respectively. By October of 1992 (6 months after installation of the wells), free product was measured to be 19 inches in the Teflon/sand packed well and 3 inches in the standard packed well. As the previous laboratory experiments had shown, the filter-pack design does not affect the product thickness in a well after equilibrium conditions have been met. The presence of product in the Teflon packed well does not necessarily indicate that this design will be capable of greater recovery rates than the standard design. One possible explanation for these results is that a localized heterogeneity in the aquifer may have allowed for product to occur in the Teflon/sand packed well and not the standard packed well. Another possible explanation suggested by Abdul, Kia and Gibson (1989) is that liquid hydrocarbon must attain a critical entry pressure before it can enter the larger pores of the filter-pack and the well. For a standard filter-pack, the pore space is occupied by water which the hydrocarbon must displace before entering the well (imbibition). If the hydrocarbon never attains the critical entry pressure, product may not enter the filter-pack and the well. Johnson, McCarthy, Perrott and Hinman (1989) performed a sand tank experiment that had glass wells placed adjacent to observation wells with slotted screens. Through the use of a small video camera, the authors noted that product had not entered in some of the wells, although the product was 2 cm thick in the adjacent sand. Using a hydrophobic filter-pack circumvents this difficulty by drawing the product into the pore space by capillarity. Wei (1991) demonstrated that the entry pressure required for hydrocarbon to imbibe into a matrix of water wetted glass beads became zero when the beads were treated with a hydrophobic material. Some of his experiments further demonstrated that the entry pressure became negative, causing spontaneous imbibition.

Field Study 2

Introduction

Although the results of the first field study support the predicted advantage of using a hydrophobic filter-pack to draw product into a well, the standard filter-packed well never accumulated enough product to initiate product recovery for comparison with the other design. A second site was chosen to compare various filter-pack designs. In addition to comparing Teflon filter-packs with standard filter-packs, an alternative design was also tested. Prepacked screens were donated by Johnson Filtration Systems Inc. and Diversified Well Products Inc. Each company provided two 1.5 m lengths of 10 cm I.D. prepacked screens with a standard sand-pack and two 1.5 m lengths of 10 cm I.D. prepacked screens with a mix of the standard sand and Teflon chips. The screens provided by Diversified Well Products were mill-slotted PVC and the screens donated by Johnson Filtration Systems were wire-wrapped PVC. Wire-wrapped screens have a greater percentage of open area compared to mill-slotted screens. It is expected that the increased open area of the screen provides a better "window" into the aquifer, allowing fluids to pass through its mesh more readily than other screen constructions.

Methods and Materials

A site was located where a refinery had leaked an undetermined volume of product into an unconsolidated sand aquifer for at least 20 years. The precise source of the product has not yet been determined.

On July 28, 1992, two 5.08 cm PVC wells were installed next to an existing well (OW-25). The wells were hand augered to a depth of about 4.4 m (14.5 ft). The wells were placed at 60 cm increments in a line directly east of well OW-25 and labeled OW-25A and OW-25B respectively. Each well had a 1.5 m long mill slotted (10 slot) PVC screen. The purpose of these wells was to determine if the aquifer was homogeneous and whether fluid levels changed significantly over small distances in identical wells. An ideal location for the study would have laterally continuous, homogeneous deposits with nearly equal product thicknesses in each well. Grain-size analyses of samples taken roughly at 30 cm intervals with the hand auger indicated that the sediment sizes graded from a fine sand near the surface to a medium sand with some gravel at the screened interval. There was virtually no difference in sediment sizes between the two wells indicating that the sandy soils at the site were reasonably homogeneous.

The field site was designed to test various monitoring/recovery well designs. The wells were to be drilled about 47.5 m east of the hand augered wells. This site was adjacent to a previously installed 5.08 cm well (MW-17) that had been pumping free product for one year until August 27, 1992, when drilling began. In August, 1991, this well had 148 cm of free product. A map of the site is shown in Figure 15.

Split spoon samples were collected every 76.2 cm during drilling of the first well (CR-1A). As samples generally corresponded with a well log of MW-17, none of the other wells were sampled for sieve analyses. A graph of the grain-size distribution curves of the aquifer sands located at the screened interval and curves of the filter-pack materials are provided in Figure 16. The screened interval of most of the wells is between approximately 2.7 and 5.9 m where a clay layer was encountered at the bottom. Note the distribution curves for the screened intervals indicate that the formation grades from a medium-fine sand at about 2.4 m of depth to a medium gravel at 4.9-5.4 m of depth. The filter packs are designed to prevent the passage of the finest layers encountered in the screened interval. The 70% retained size of the finest layer of the aquifer material (2.6-3.7 m) is about 0.35 mm. The available Teflon chips were much coarser than the aquifer median grain-size required so the Teflon chips were sifted using a #10 screen. The chips that passed were used for

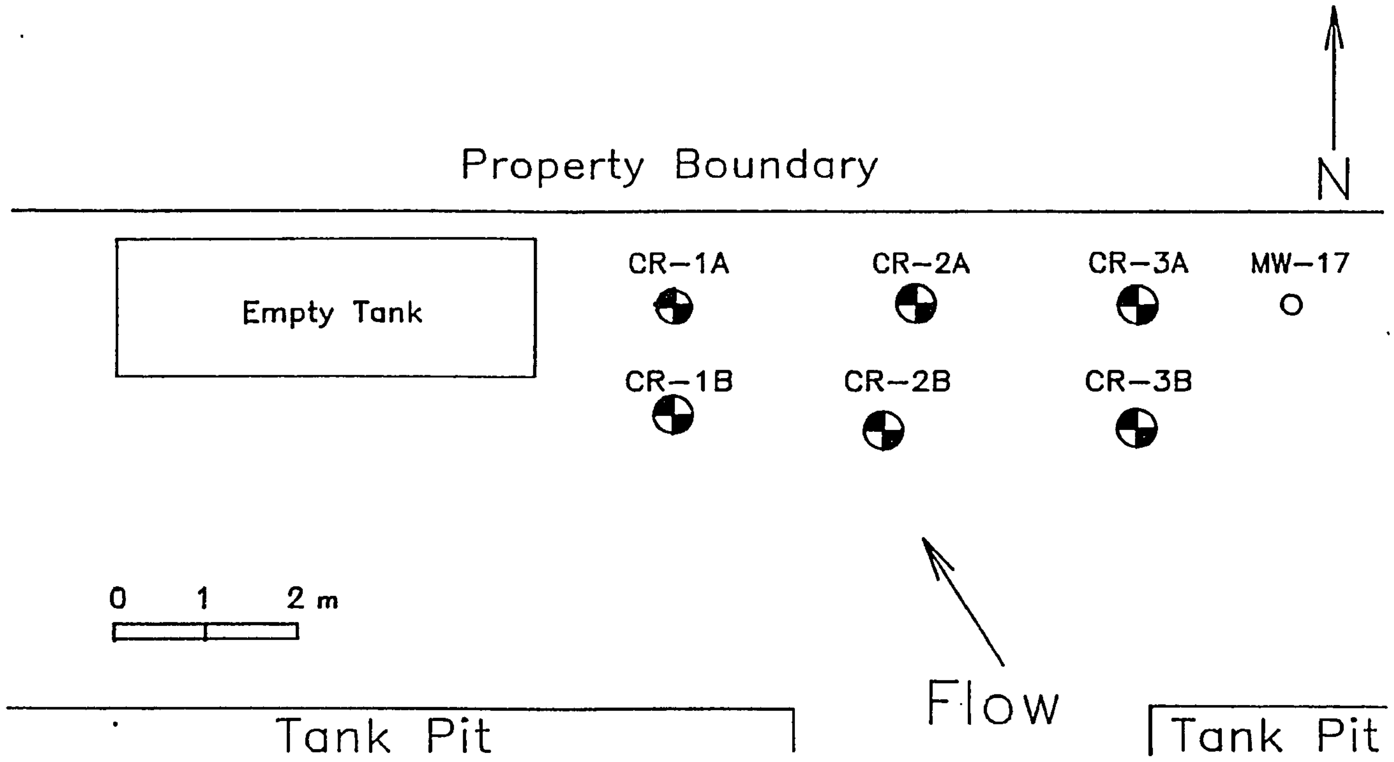

Figure 15. Map of Site 2.

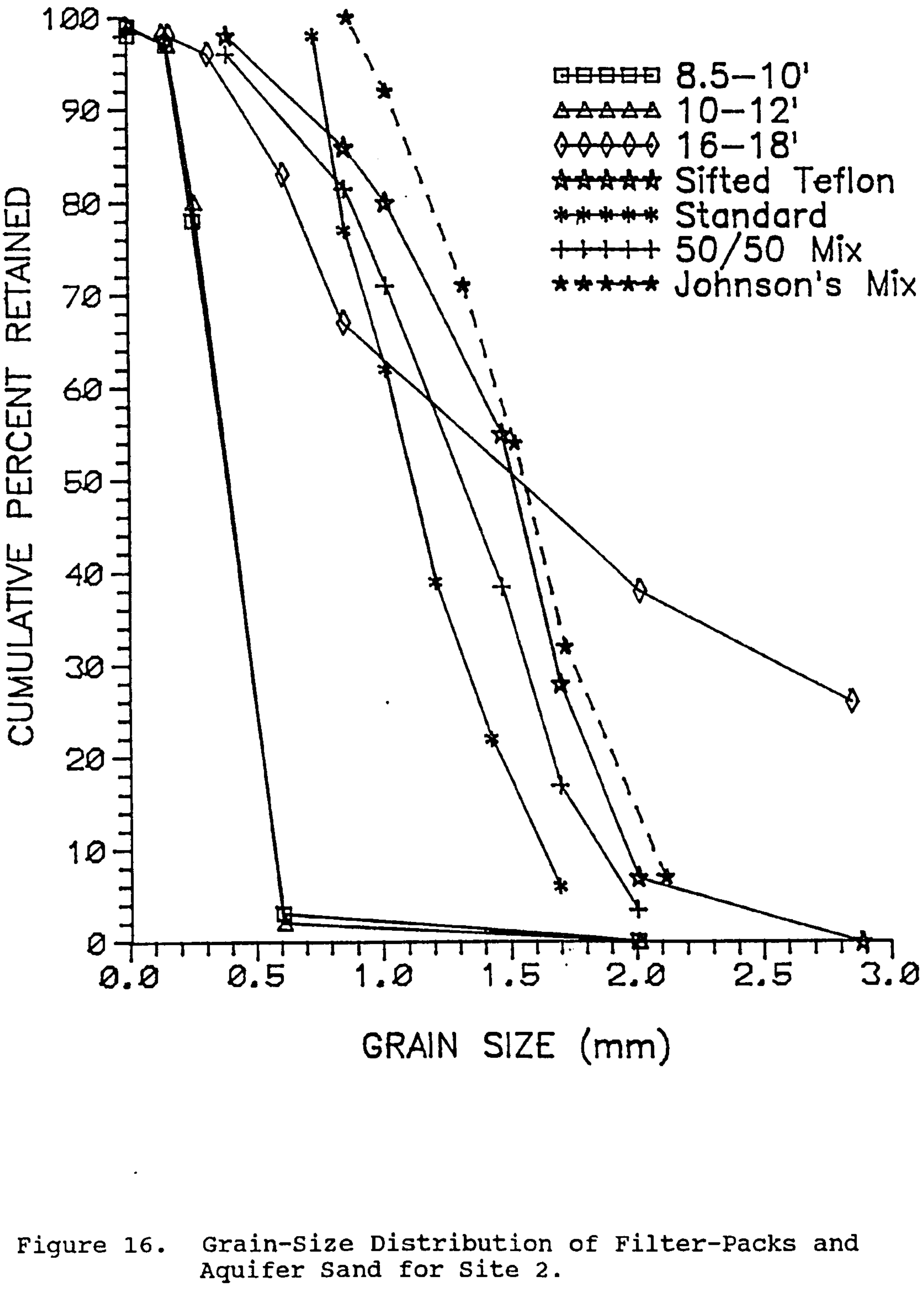

Figure 16. Grain-Size Distribution of Filter-Packs and Aquifer Sand for Site 2.

this study, and the retained fraction was kept for later use. The 70% retained size of the sifted Teflon chips and the standard filter pack (70-80) sand are 1.25 and 0.85 mm respectively. This yields a filter-pack/aquifer grain-size ratio of 3.5 for Teflon and 2.4 for the standard quartz filter-pack. A 50/50 mixture (by volume) was made of the Teflon chips and the 70-80 sand. The 70% retained size of the mixture is approximately 1.0 mm which yields a filter-pack/aquifer grain size ratio of 2.8. These values are within Sullivan et al.'s (1988) guideline for filter-pack grain-size distribution for separate phase recovery wells.

The grain-size distribution curves for the prepacked screens are also shown in Figure 16. The standard sand used by Diversified Well Products gives nearly the same distribution curve as the standard pack shown. The Teflon chips were sifted using a # 12 screen which, when mixed in a 50% volumetric ratio with the sand, yields a composite curve similar to the 50/50 mix shown. Johnson Filtration Systems' standard sand was significantly coarser than the the other sands shown. Johnson's Teflon was screened using a #40 (0.42 mm) sieve. The fraction passing was not used for the screen construction. The composite of the 50% Teflon mix (by volume) is shown in Figure 16. Note that the 70% retained size is 1.3 mm, or 3.7 times the aquifer 70% retained grain-size. Although this figure is slightly outside the recommended limit of 3.5, the sands coarsen with depth. At the depth to free product (about 13.3 ft or 4 m), the formation sands coarsen to about 0.6 mm. This size gives a filter-pack/aquifer grain-size ratio of about 2.2, just below the suggested ratio.

The well designs are shown in Figures 17 and 18. The six new wells installed are all labelled with a CR prefix. Because four of the eight prepack screens were damaged in transport from the manufacturers, the well designs were altered from the original plan. Originally, each entire screened interval would consist of one well design. In order to salvage the study, the well designs were hybridized to place at least one 5 ft section of each screen type in the product/water interface zone. The top of fluid is located at approximately 406 cm (13.33 ft) below grade. Each of these wells is constructed with 10 cm diameter PVC. The diameter of the outer screens of the prepack screens is 14.22 cm. The preexisting well, MW-17, is constructed of 5.08 cm diameter PVC.

All of the wells were drilled by a hollow stem auger. The installation of the wells required two days. Each well was developed with a surge block upon completion.

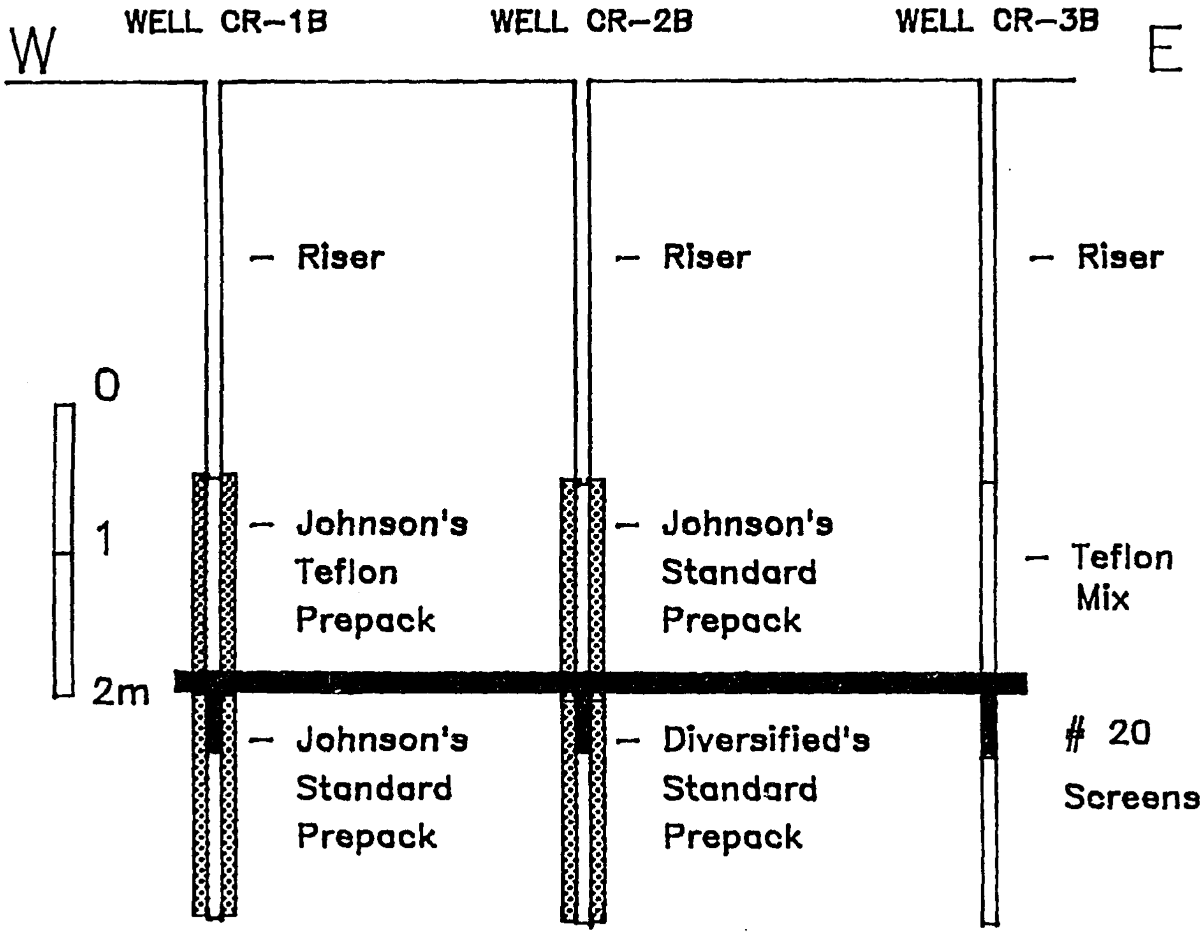

Figure 17. Well Construction of Row B Site 2.

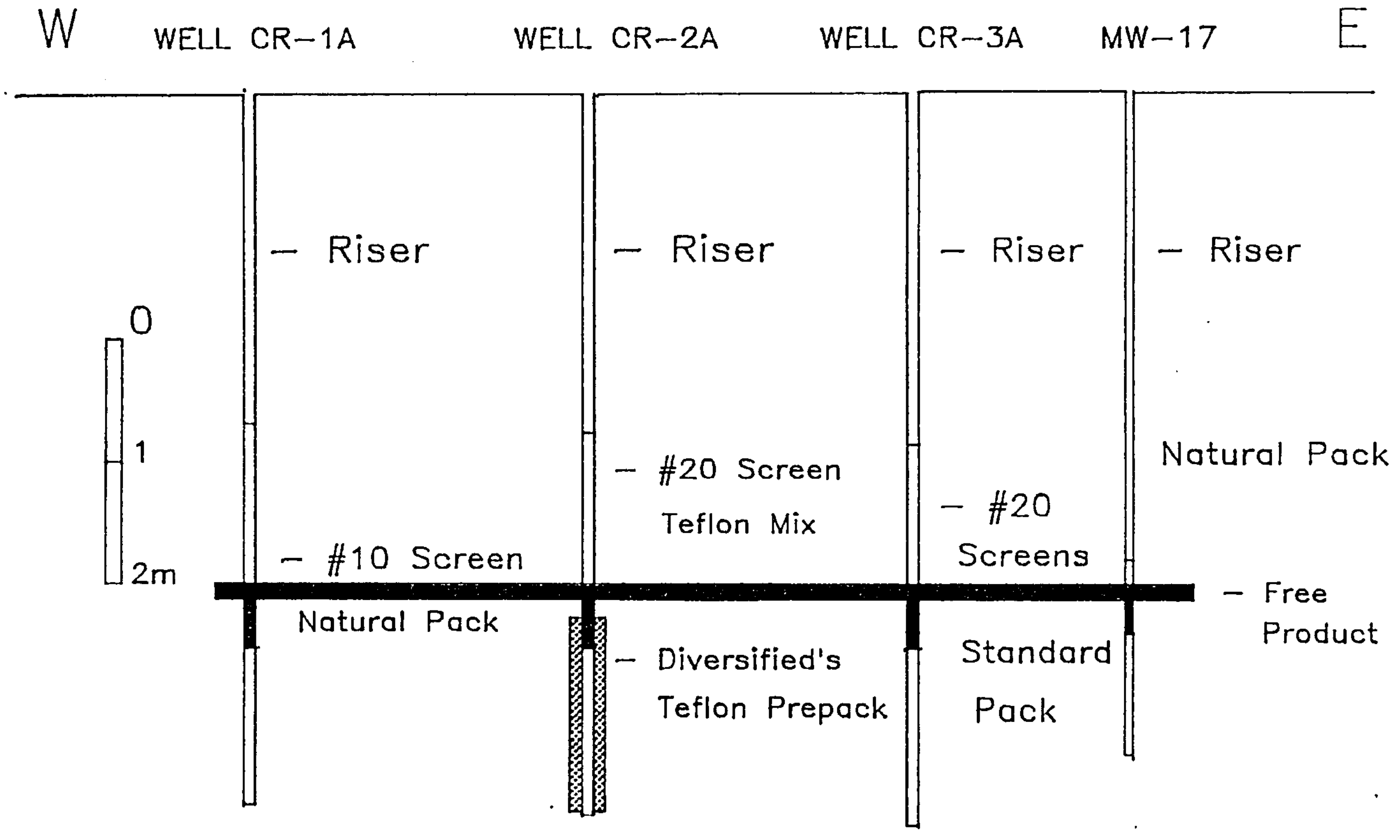

Figure 18. Well Construction of Row A Site 2.

Results

Figure 19 is a record of the product thicknesses (in cm) in all of the wells mentioned above. As the wells labelled with an OW prefix were installed before the wells with a CR, it is expected that they will reach equilibrium before the CR wells. Changes in product thicknesses depend upon precipitation events. Precipitation causes the water table to rise, which in turn decreases product thickness because product is trapped in residual saturation below the rising water table.

With a top of fluid depth of about 406 cm (13.3 ft) below grade, it is possible that product is not saturating the lower 1.5 m screen which spans from 411.5-563.9 cm (13.5-18.5 ft) below grade. This depends upon product thickness in the aquifer. One method for evaluating the product thickness in an aquifer based on product thickness in a well is to use the following approximation;

$$\text{Actual Thickness} = H(1-G_0)\div G_0 \qquad (3)$$

where G_0 is the specific gravity of the product and H is the product thickness in the well. Approximating the specific gravity as 0.8 (which agrees with laboratory measurements) and using the product thickness in well CR-2A on day 39, the product thickness in the aquifer could be as little as 5.5 cm. This indicates that the product thickness in the

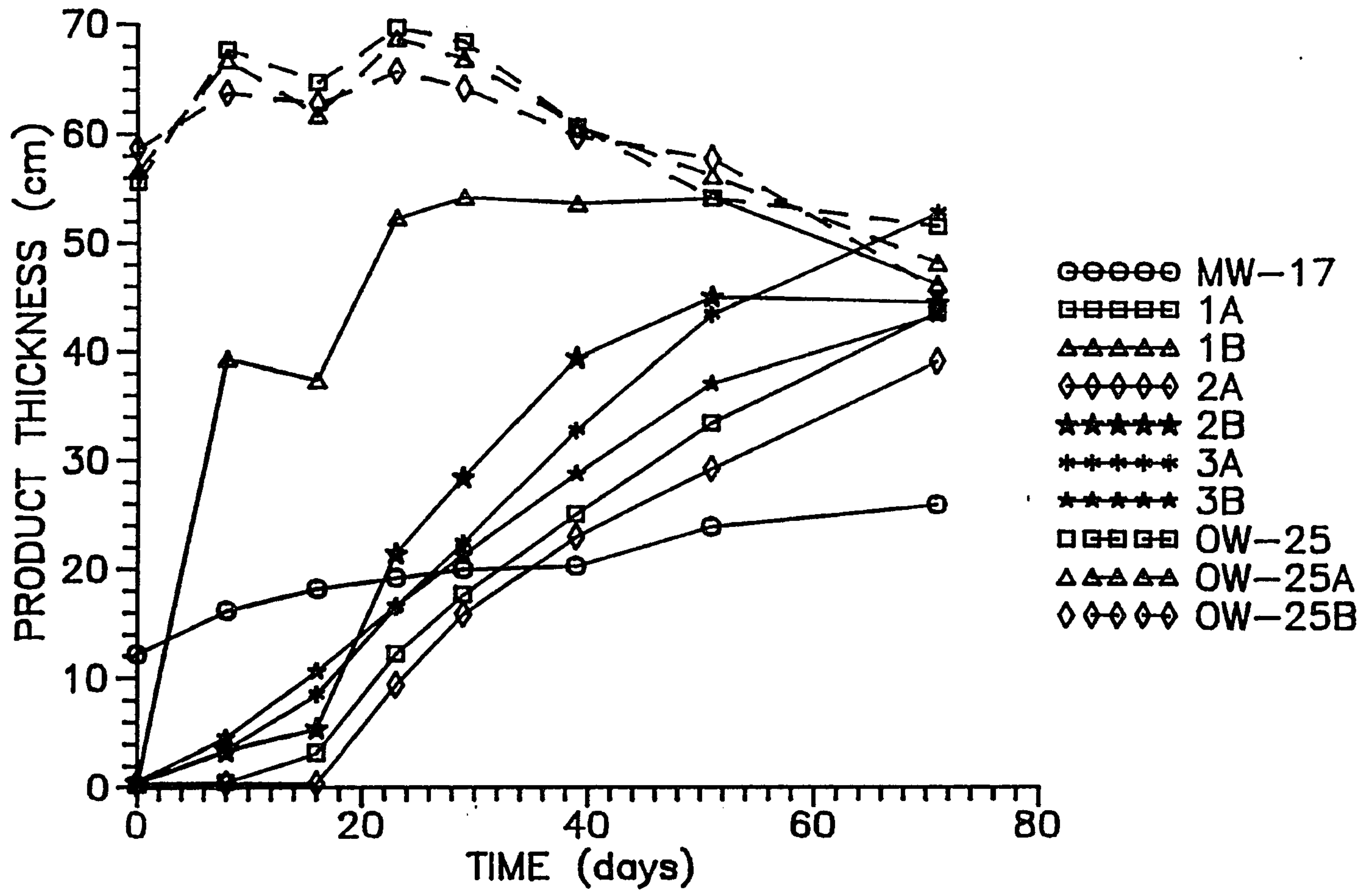

Figure 19. Product Thicknesses in Wells at Site 2.

aquifer may not have reached the lower, Teflon prepack screen. However, this well has not reached a state of equilibrium with the aquifer so the product thickness in the well cannot be used to compute aquifer product thickness. For the purpose of more accurately estimating actual product thickness, a well in equilibrium with the aquifer would be a better choice. The product thickness in well 1B (Johnson's Teflon Prepack) has stabilized and is probably in a state of equilibrium with the aquifer. Substituting the product thickness from well 1B on day 39 into equation 3 yields an actual product thickness of 12.75 cm (0.42 ft). Based on this calculation, the Teflon prepack screen provided by Diversified Well Products may be in contact with the product.

Bail-down testing of the wells was begun in November of 1992. Approximately 4 liters of product were removed for each test. The results from the first bail-down test indicate that the fluid levels in the tested well return to equilibrium after 1 week. After two hours of recovery the field tested wells have recovered less than 7 cm of product. Recovery is slow in comparison to laboratory sand tank experiments. Records of fluid levels for the past 120 days have indicated that product thicknesses may vary by up to 10 cm. Variations in product thickness in the wells may represent variations in product thickness in the aquifer.

Small scale heterogeneities in the aquifer may cause product thicknesses to vary. It is likely to be difficult to test the wells under similar conditions with fluid levels changing. Further bail-down testing is required.

At an unspecified date, product recovery is to begin at the new wells. The consulting firm operating the site will pump product from one well at a time and meter the volume of product produced. The average flow rate from a well can be easily determined by dividing the volume produced by the time interval that pumping persisted.

As the Teflon filter-packed wells have facilitated initial product flow into the wells, Teflon filter-packed wells will probably be capable of producing the most product in the field as they have in laboratory sand tank experiments. The prepack Teflon screens are expected to out-produce the standard prepack screens. The standard pack is expected to out-perform the natural pack as the coarser standard filter-pack will not have much of a water capillary fringe. The product should be able to drain freely by gravity into the well. Laboratory studies have confirmed that coarser hydrophilic filter packs outperform finer hydrophilic filter packs (Hampton and Heuvelhorst, 1990).

CHAPTER V

CONCLUSIONS

The use of hydrophobic filter-packs provides two distinct advantages over using conventional filter-packs. In locations where product thicknesses are not great the product may not acquire enough pressure (positive) to move laterally into the larger pores of a filter-pack or a well (gravity drainage). Hydrophilic (conventional) filter-packs do not exert a significant capillary (suction) pressure on the product and product may never enter the well. Hydrophobic filter-packs are wetted by the product and therefore exert a capillary (suction) pressure on the product drawing it to the well.

The other significant advantage of using hydrophobic materials as filter-packs is the increase in the rate of production from hydrocarbon recovery wells. Although the first laboratory experiment described in this paper did not yield results that favored the most hydrophobic material it is likely that grain-size or another variable affected the results.

The results of Laboratory Experiment 2 indicate that mixing the hydrophobic filter-pack with a conventional hydrophilic filter-pack provides most of the advantage of an exclusively hydrophobic filter-pack. There are several advantages to mixing filter-packs. The most practical advantage is that hydrophobic materials are expensive and standard filter-packs (sand) are inexpensive. Mixing the materials provides enhanced hydrocarbon production at a reduced cost relative to a 100% hydrophobic filter-pack. Use of a sand also ensures a more uniform placement of the hydrophobic material. As mentioned earlier, Teflon's density is about 2.05 gm/cc, just 1.05 gm/cc heavier than water, which can cause sorting during emplacement of the filter-pack in the saturated zone. Prepacked screens also avoid emplacement difficulties.

Another benefit of mixing the materials is the ability to shift the grain-size distribution. As the size of the hydrophobic material may not be readily changed, mixing it with an appropriate standard sand may shift the grain-size distribution curve to match the design criteria for a given application.

The guidelines for designing a filter-pack for a hydrocarbon recovery well begin with picking the filter-pack material. If Teflon chips are not available, other potentially hydrophobic materials can be readily tested using Hampton and Heuvelhorst's (1990) procedure for measuring contact angle. Contact angle is directly proportional to wettability and thus, hydrophobicity. The more hydrophobic the filter-pack, the greater the hydrocarbon recovery rate.

The results of this study indicate that a relatively small filter-pack/aquifer median grain-size ratio of 2.5-3.5 will increase the production from a well with a hydrophobic filter-pack such as Teflon. For hydrocarbon recovery wells with a standard filter-pack, a slightly larger ratio of 4-6 such as that suggested by Driscoll (1986) will perform the best.

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