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Factors Governing the Rate of Appearance of Fuels in Monitoring Wells

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FACTORS GOVERNING THE RATE OF APPEARANCE OF FUELS IN MONITORING WELLS

by

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Delays in the appearance of free product (e.g. fuels) in groundwater monitoring wells often cause costly delays in site evaluation. Little is known about how monitoring well design and installation affect this rate of appearance. This study examined the effects of well screen open area, filter pack grain size and wettability, and well development methods on the rate of appearance and subsequent thickness of free product in wells.

Laboratory and field results indicate that free product appears faster in hydrophilic filter packs than in hydrophobic filter packs. Hydrophobic filter packs with a finer grain size than the "industry standard", seem to be more productive, and have a faster rate of appearance than coarser filter packs.

Results from a field experiment indicate that increased open area in well screens increases the rate of appearance and productivity of a monitoring well. Field investigations also indicate, in areas of free product contamination, the surge block development method may be counterproductive due to clogging of the near well zone by bacterial growth and fine material. Overpumping a well for development proved fastest in rate of product appearance, while bailing proved most productive.

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INTRODUCTION

Statement of the Problem

Fuels, lubricants and solvents are everywhere in our industrialized world. Unfortunately, these fluids often leak or spill, contaminating soil and groundwater. The environmental consulting industry is often called upon to delineate the extent and severity of the contamination problem as well as offer solutions for remediation of the problem.

When consultants are called upon to evaluate a contaminated site, monitoring wells are often installed to help gain a better understanding of the subsurface environment. Monitoring wells play a special role at hydrocarbon contaminated sites. The appearance of 0.125 in. (or more) of free product (separate-phase hydrocarbon) floating on top of the water in a well triggers a set of regulatory requirements. The Michigan Department of Environmental Quality (MDEQ) must be notified within 24 hours of the first appearance of free product at a site. A series of reports and mandated actions follows.

A typical problem faced by environmental consultants is how to respond to a hydrocarbon-contaminated site. By regulation, monitoring wells are installed to detect the presence of contaminants and determine the direction of groundwater flow. During well installation, the drill cuttings brought to the surface are usually a good indication of the level of contamination. Often the soil changes from tan to dark gray in color with a hydrocarbon odor as the drill hole deepens, suggesting a layer of contamination. After the well screen is installed, the consultant anxiously awaits the appearance of free product in a well before leaving the site to return to the office, which often is far away. Free product may appear in minutes, hours, days, weeks, or even months later. This poses a delay in site evaluation, which in turn can complicate remedial efforts in aquifers with contaminated groundwater. Understanding what factors of well design and development encourage the appearance of free product will hasten site evaluation.

There are various authors that recognize the problem of delayed appearance of product within a monitoring well. Abdul et al. (1989) observed that product could accumulate outside a well before capillary pressures are overcome, at which point product enters the well. Mansur and Fouse (1984) monitored three hydrocarbon recovery wells in a pumping test for their rate of fuel recovery at a free product contaminated site. The results indicate that product did not enter some wells whose filter packs were too coarse. In a more detailed study, Johnson et al. (1989) constructed a large-scale model of the movement of gasoline hydrocarbons. They showed that product could be trapped outside a monitoring well for relatively long periods of time. This was true even in a pea gravel, where capillary forces that could prevent product appearance in a monitoring well are relatively small.

Hampton and Huevelhorst (1990) address the benefits of using hydrophobic materials for filter packs. Their findings indicate that hydrophobic gravel packs outperformed hydrophilic gravel packs in terms of productivity. Hampton et al.

(1995) conducted two field investigations intended to compare gravel pack performance. The first experiment compared two product monitoring wells three feet apart whose only difference was the gravel pack materials used. Product appeared about one month quicker in the well with a hydrophobic gravel pack than in the adjacent well with the industry standard hydrophilic pack. Eventually the thicknesses in the two wells were the same. Product disappeared from both wells at the same time when the water table rose. The second experiment compared prepacked filter packs, both hydrophilic and hydrophobic with standard sand packs, hydrophobic packs of Teflon and sand, and natural pack wells. The results indicate that prepacked screens with hydrophobic filter packs produced product most quickly. However, thicker hydrophobic filter packs with equal volumes of Teflon and sand proved most productive.

All of the above suggest that the design and installation procedures of monitoring wells may have an impact on the rate of appearance of free product in these wells. Most of the design criteria for monitoring wells are borrowed from the water well industry. Very little has been published on the design criteria for water table monitoring wells that encounter LNAPL (Light Non-aqueous Phase Liquid) hydrocarbons. Driscoll (1989) suggests that monitoring well design depends on three basic criteria. First, what is the purpose of the well? For example, is it to be used for delineation of the water table elevation, or is it to be used for recovering contaminants? Second, the hydrogeologic environment in which the well is to be installed will affect the design criteria for the monitoring well. Third, the chemical nature of the contaminants will determine what types of well materials are acceptable to be used in assuring the efficiency and longevity of a monitoring well.

Screen Selection

Encouraging product to enter a monitoring well is limited to whether or not the design aspects are alterable and what development method is used. The well screen material and construction are design criteria subject to the consultant's judgment. The well screen is the intake portion of the well which serves as a filtering device to prevent sediments from entering the well while still allowing water and product to enter the well. The screen also serves as a structural support in unconsolidated aquifer materials (Driscoll, 1989).

Driscoll (1989) suggests the following criteria for monitoring well screen selection. First, the material used in the well and well screen should be inert relative to the environment that it will encounter. Second, open area should be maximized to facilitate rapid sample recovery. Third, slot sizes should be small enough to retain the filter pack or natural formation but open enough to permit well development. Fourth, slot openings should be non-plugging in design. The slot openings, slot design, open area, and screen diameter should permit effective development. Specific sizing information seems to be left up to the consultant's judgment and experience. Presumably, one can use the criteria given for the design of a water well. Driscoll (1989) suggests that the slot size in the well screen should be determined by using the finest portion of the aquifer material with a sixty percent passing and forty percent retained grain size analysis. Driscoll (1989) recommends that a more conservative approach of using a screen in which fifty per cent of the aquifer material is retained by the well screen be used when: the aquifer is corrosive in nature, reliability of the sample is in doubt, the aquifer is thin and overlain by a fine-grained loose material, development time is short, or the formation is well sorted.

Filter Pack Selection

Filter pack selection in water wells is addressed by Driscoll (1989). The primary purpose of a filter pack is to make the zone immediately around the well screen more permeable. This increases the effective hydraulic diameter of the well, while also helping to filter out fines from filling in the well, which could render it inefficient (Driscoll, 1989).

Wilson (1995) gives guidelines on sizing the filter pack for monitoring wells. He recommends using the USEPA's guidelines of using a grain size of three to five times the fifty percent retained portion of the average grain size of the finest portion of the formation. A grain size analysis of the filter pack should yield a curve that is smooth and gradual with a uniformity coefficient of 2.5 or less. Wilson also recommends using the ASTM D 5092 standard for filter pack selection. He suggests a filter pack that is four to six times the thirty percent finer grain size in formations that are fine and uniform and six to ten times the thirty percent finer grain size of the formation if the formation has silt-sized particles and has a highly non-uniform grain size. Hampton et al. (1995) found that monitoring wells are more productive in aquifers with hydrocarbon free product, when a hydrophobic filter pack with a median grain size of 2.5-3.5 times that of the formation material was used.

Well Development

When a monitoring well is installed it is often necessary to use some sort of well development technique. Well development is performed for a variety of reasons: (a) to repair damage caused to the formation by the drilling method used; (b) to alter the physical characteristics of the aquifer, such that water moves freely to a well; (c) to selectively remove foreign materials and fines introduced by the drilling process; and (d) to restore the natural hydraulic conductivity and water quality of the formation being sampled (Wilson, 1995; Driscoll, 1989).

Surge Block as a Development Method

There are a variety of methods used for well development. Surging is one of the most widely accepted methods. A surge block that is slightly smaller than the diameter of the well is lowered into the well. This surge block works much like a piston; it is raised and lowered in the well with increasing vigor forcing water back and forth through the screen (Wilson, 1995; Driscoll, 1989).

Bailing as a Development Method

Bailing is a cost-effective alternative to a surge block as a development method. Bailing allows for removal of the fine particles from the well but also forces some water back and forth through the well screen. A bailer is attached to a cord and lowered to various depths within the well screen; it is agitated up and down within the well where the bottom sump on the bailer collects water and fine material to be removed from the well (Wilson, 1995).

Overpumping as a Development Method

Finally, overpumping is often utilized as a well development technique. Water is drawn though the well screen at a rate that is higher than the ability of the formation to produce water. A variation of this method involves allowing the column of water removed from the well to fall back into the formation causing a surging action. This method allows for removal of the fine materials from the well while causing the desired disruption of the near borehole formation (Driscoll, 1989).

PRELIMINARY EXPERIMENT

Methodology

A laboratory experiment was conducted in order to gain a better understanding of filter pack selection as it relates to the rate of appearance of free product. A 90 cm long, 30 cm wide, and 63 cm tall glass tank was filled with two different sands. For the sake of cost and convenience these sands were deposited in two layers. The bottom layer was a relatively coarse sand approximately 20 cm thick. This layer was overlain by a finer sand (#52 Milan) approximately 40-45cm thick which was considered to be the formation material of interest.

Since it was not possible to drill into the tank and then fill in the borehole annulus with the filter pack material, another method of filter pack installation was required. Before the formation material was poured into the tank, three pieces of five-inch diameter chimney pipe were placed in the tank with two-inch diameter well screens inside of the chimney pipes. The tank was filled with the coarser sand on the bottom and the # 52 Milan sand on top. After the formation material was in place, the filter pack material was poured between the chimney pipe and the well screen. For the sake of cost and availability of material, all three filter packs were filled from the bottom of the tank with a 32 cm. thickness of the 10/20 untreated filter pack. From this point to the top of the tank, each pipe was filled with a different filter pack. After all of the filter packs and the formation material were in place, the chimney pipes were removed in order to allow the formation and filter pack to be in hydraulic connection.

Three types of filter packs were tested. One filter pack was used as a control that represented the typical "industry standard" of using a filter pack that is approximately three to five times the 70 percent retained portion of the formation material. Another filter pack was tested using the same sand as the control but it was treated with a silicone spray, made by Camp Dry®, in order to make the sand hydrophobic. The third filter pack tested was a finer sand which was approximately 2.5 times the grain size of the 70 percent retained portion of the formation material. This filter pack was a resin-coated sand that was treated by the vendor of the sand to make it hydrophobic. A grain size analysis was performed on the two formation materials and the three filter packs in order to analyze the grain sizes. These grain-size analyses are shown in Appendix A.

After the formation and filter packs were completed, water was added through the wells and allowed to equilibrate at approximately 38 cm above the bottom of the tank. A glass plate was lain across the top of the tank to be used as a datum for the product thickness measurements.

In order to simulate a spill, 3.6 L of blue-dyed kerosene was added in 200-ml increments in six different locations on the top of the tank. Because the kerosene was dyed blue it was possible to monitor the wells visually for the first appearance of kerosene in the wells. After the first appearance of kerosene in the well, an oil/water interface probe was used to measure the product thickness within each well at increasing time intervals.

Hampton et al. (1995) showed that a hydrophobic gravel pack that is 2-3 times as coarse as the formation materials' 70 % retained portion was more productive in encouraging product to enter a well than the traditional "industry standard" of using a hydrophilic filter pack that is 4-6 times the 70 % retained portion of the aquifer formation material. The rate of appearance of product in the monitoring well was expected to follow the same pattern, as did the productivity of the monitoring well. The initial hypothesis was that filter packs that were treated to be hydrophobic, and that had a grain size that was 2.5-3.5 times that of the formation material, would have a faster rate of appearance than would wells with a coarser filter pack.

Results From Laboratory Experiment

The results of the laboratory experiment are pictured in Figure 1. Table 1 shows the rate of appearance of kerosene in the respective monitoring well and Table 2 shows the productivity of each monitoring well at the end of the experiment.

As can be seen in Figure 1, the most productive well proved to be the resin-coated 20/40 sand. This well reached product thicknesses of over 29 cm. The next most productive well was the well with the treated 10/20 sand filter pack. This well reached thicknesses of over 23 cm. Finally, the least productive well was the untreated control well, intended to represent the industry standard. This well reached product thicknesses of only 14 cm.

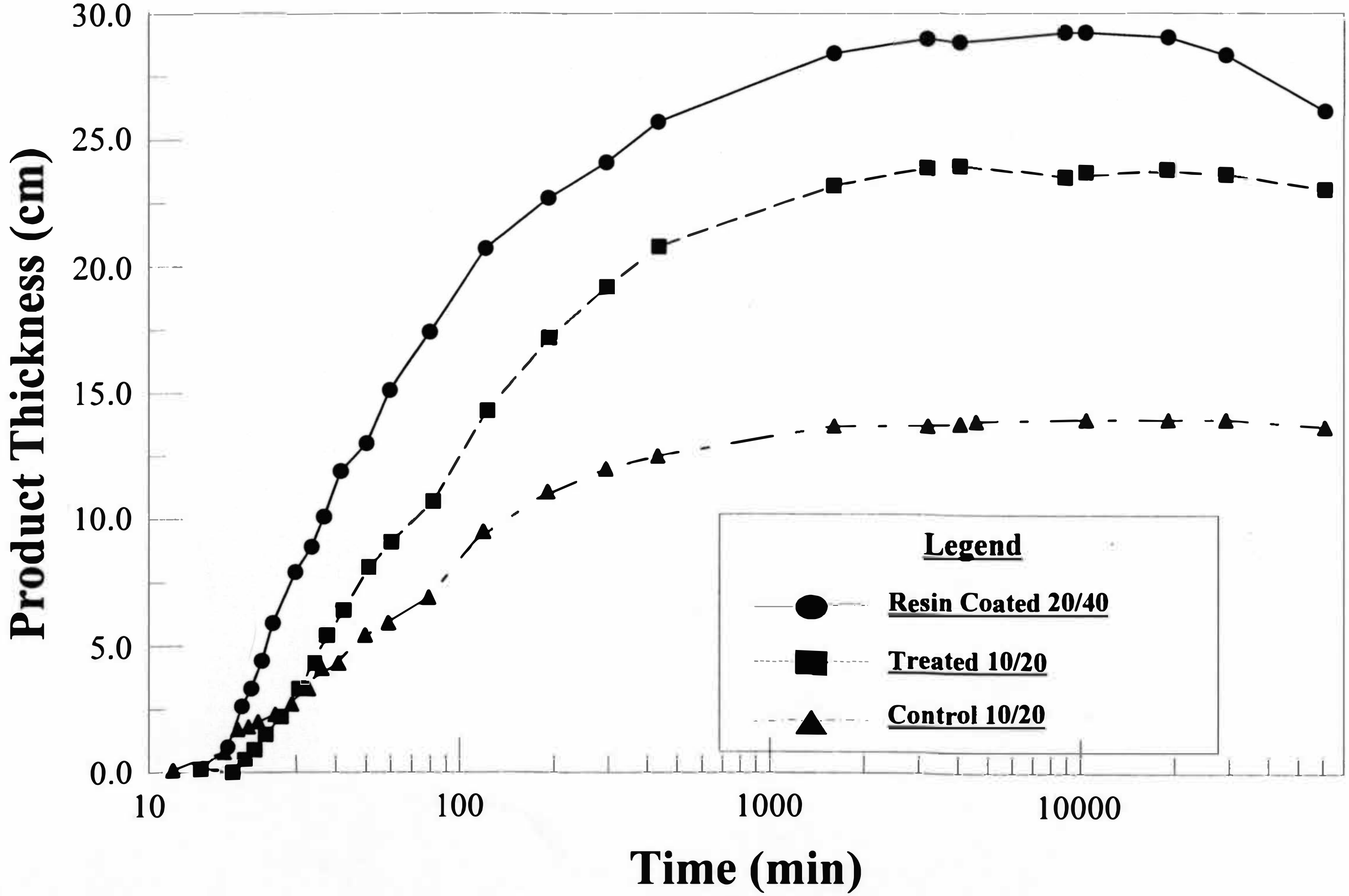


Figure 1. Appearance of Product in Laboratory Wells.

Table 1

Appearance of Kerosene in Laboratory Monitoring Wells

Type of Filter Pack	Time of Appearance, x
10/20 Sand Untreated Control	$0 \leq x \leq 12{:}00$ min.
20/40 Sand, Resin Coated, Finer grained	$0 \leq x \leq 14{:}45$ min
10/20 Sand, Treated with Camp Dry®	$18.70 \leq x \leq 20.53$ min.

Table 2

Productivity of Laboratory Monitoring Wells at End of Experiment

Type of Filter Pack	Amount of Kerosene in Well
20/40 Sand, Resin Coated, Finer Grained	26.2 cm.
10/20 Sand, Treated with Camp Dry®	23.1 cm.
10/20 Sand, Untreated Control	13.7 cm.

The rate of appearance of kerosene in these wells was as follows. The first well to have kerosene appear was the untreated control well. Kerosene appeared in this well between 0 and 12 minutes from the time of the simulated spill. Kerosene appeared next in the well with the finer-grained, resin-coated, 20/40 sand between 0 and 14.75 minutes from the time of the simulated spill. Kerosene appeared last in the well with coarser-grained, hydrophobic gravel pack of 10/20 sand. Kerosene appeared between 18.70 and 20.53 minutes after the time of the simulated spill.

Conclusions From Laboratory Experiment

As mentioned previously, Hampton et al. (1995) found that filter packs that were treated to be hydrophobic had better long-term productivities than did wells that had filter packs that were hydrophilic. He also found that hydrophobic filter packs that are 2.5-3.5 times as coarse as the formation material were more productive than wells designed with the "industry standard" of using a filter pack 4-6 times as coarse as the formation material. The results of this experiment are consistent with his findings. Figure 1 clearly shows that the long term productivity of a monitoring well is benefited by using a filter pack which has a grain size that is 2-3 times the formation materials' 70% retained portion, and is hydrophobic in nature. This was represented by the resin-coated 20/40 sand in this laboratory experiment. The next best option is using a hydrophobically treated filter pack, with a grain size that is consistent with the industry standard of 4-6 times the formation material 70% retained portion. In this laboratory experiment this was represented by the treated 10/20 sand. Finally, the least desirable option is the industry standard of using hydrophilic sand that is 4-6 times the 70% retained portion of the formation material. In this experiment this was represented by the control 10/20 untreated sand.

The rate of appearance of kerosene in the laboratory monitoring wells was not consistent with the initial hypothesis. One would expect that the most productive well would also have the fastest rate of appearance. This was not the case in this experiment. The hydrophilic well that had a grain size 4-6 times that of the formation material had a faster rate of appearance than both of the hydrophobic wells. A possible explanation is because the materials in the hydrophobic/oleophilic wells are oil wet, these materials tend to hold the kerosene in the filter pack until the filter pack is saturated with respect to kerosene. Once this saturation is reached, breakthrough of product into the monitoring well occurs, but not without delaying the rate of appearance of kerosene within the monitoring well.

Finally, it is also possible that the stratification within the tank contributed to the delay in the appearance of product in one well but not in the other. When the formation material was placed in the tank some layering of the uniform aquifer material was evident. It is possible that these layers served as high conductivity pathways for the kerosene. If this were the case, it would be plausible that the stratification of the tank controlled the rate of appearance of kerosene in the monitoring wells.

FIELD EXPERIMENT

Site Overview

A field experiment was performed to determine how the design and development of monitoring wells affected the rate of appearance of free product. A site in Carson City, Michigan, was chosen for the site location (Figure 2). The site is located at 801 North Williams street, Carson City, MI. The site served as an oil refinery from 1935 until the early 1990's, at which time it was shut down and became a bulk fueling station. Free product hydrocarbons are encountered in contact with groundwater presumably resulting from the historical operations of the oil refinery (SEG, 1994).

In 1945 the Michigan Department of Conservation conducted an investigation due to a oily sheen observed on the surface of Fish Creek and oil seeps coming from the banks of Fish Creek west of the Cemetary (DELL, 1993). In 1968, the Department of Conservation conducted another investigation on the site which involved installing 22 monitoring wells. Subsequent to the investigation, two french drain style recovery systems were installed in an attempt to prevent further migration of free product towards Fish Creek. One of the drain systems has been shut down while the other (on the west side of the cemetery) is still in operation. Further monitoring and site delineation has been conducted by two environmental consulting firms (DELL, 1993, SEG, 1994)

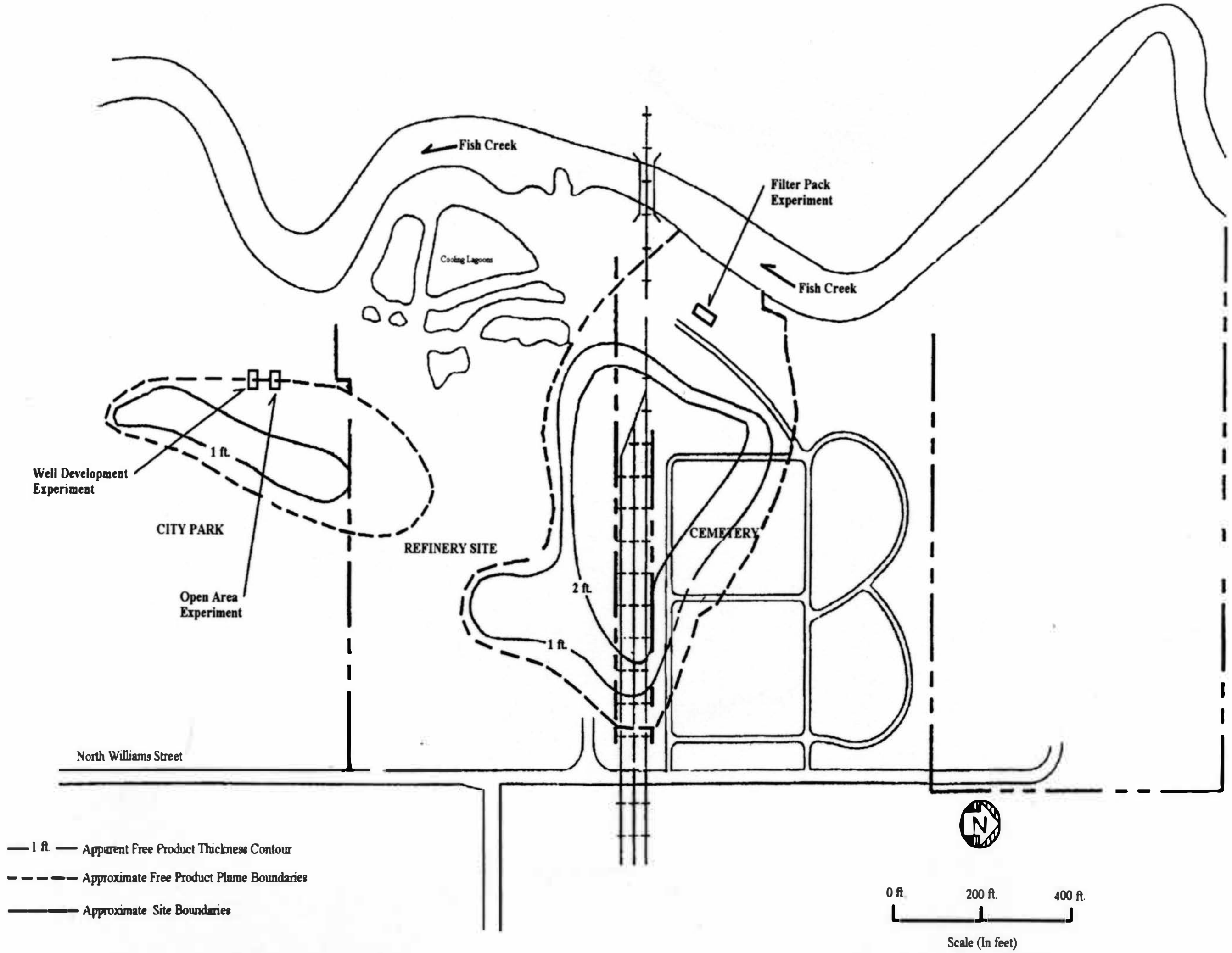


Figure 2. Site Map of Field Experiment.

As pictured in Figure 2, there are two plumes emanating from the oil refinery that eventually migrate offsite. A crude oil plume has been identified that extends north from the northern boundary of the refinery to the center of the cemetery and then west to Fish Creek. This plume reaches thicknesses of over two feet. A documented valve failure at the loading facilities located along the railroad tracks, as well as historical refinery operations, are believed to be the sources for the plume in this area.

A refined product plume up to one foot thick has also been identified which extends to the southwest from the refinery into a city park. The plume appears to be emanating from the vicinity of OW-15, possibly from a leak in storage tank #33, but other sources are possible (SEG, 1994).

The site is underlain by 15-20 feet of fine to coarse grained, well sorted sands which coarsen downward into a sandy gravel. This formation is underlain by up to10 feet of clay which is underlain by up to 6 feet of silt, which grades downward into 2-5 feet of sand and gravel. In the vicinity of the cooling lagoons and the southwestern corner of the city park, a peat formation is encountered that is approximately 2-4 feet thick. The upper saturated formation beneath the cemetery and refinery is approximately 4-6 feet thick in the cemetery and increases in thickness to approximately 15 feet on the refinery. Within the city park, the saturated formation decreases in thickness to approximately 6-8 feet. The underlying clay layer is approximately 10 feet thick in the cemetery and refinery and decreases in thickness to 1-5 feet in the city park. The underlying silt layer has a relatively constant thickness, but pinches out towards the city park. Grain size analyses of the aquifer formation material are shown in Appendices B and C (DELL, 1993, SEG, 1994).

Groundwater flows east to west towards Fish Creek. Less permeable soils and recharge of effluent water in cooling lagoons create a mounding effect at the center of the refinery's west side, which in turn diverts flow north and south of this area. The average hydraulic gradient is 0.005 ft/ft with a flow velocity of 5.5 ft/day (SEG, 1994).

This site was chosen for this research based on three criteria. First, there are two distinct free product hydrocarbon plumes at the site. Second, the water table in this area is relatively close to the surface ranging from fourteen feet below grade to two feet below grade, making possible hand-augering as well as using a drill rig. Finally, the abundance and location of free product contamination at this site are well documented increasing the likelihood of encountering free product.

The field experiment was conducted to determine how the design and development of monitoring wells affected the appearance of fuels in monitoring wells. Three sets of wells were used to analyze different variables of well installation and design; these were, percent open area in the well screen, gravel pack grain size and wettability, and well development methods. A final experiment was established to determine the rates of appearance of product in monitoring wells in two different plumes.

Filter Pack Experiment

Methodology

In order to evaluate what effects different types of gravel packs have on the appearance and productivity of product in monitoring wells, a field experiment was conducted similar to the laboratory experiment. Five filter packs were tested. Previous work by Hampton et al. (1995), at this site indicated that wells with a hydrophobic/oleophilic material mixed with a sand, proved most productive. The preliminary laboratory experiment indicated that when a hydrophobic filter pack was used, filter packs with a finer grain size than the traditional industry filter pack that is 4-6 times as coarse as the 70 per cent retained portion of the formation material, resulted in a faster appearance or a better long-term productivity with respect to product in the well.

With this in mind, two of the five filter packs were a mixture of hydrophobic Teflon chips and sand. GP-5 was a mixture of a 12/40 sand, distributed by Flat Rock, and Teflon chips. This pack was mixed in a volumetric ratio of 43% Teflon chips and 57% 12/40 sand and was intended to be finer than Well GP-3. GP-3 was also a mixed filter pack with a volumetric ratio of 46% Teflon, and 54% 70/80 (Red Flint) sand. This pack was intended to be more coarse than well GP-5's filter pack. Well GP-2 was a 10/20 (Milan) sand and was intended to represent the industry standard typically used by environmental consultants. Well GP-4's filter pack was a 70/80 (Red Flint) sand, the same sand used in the mixture in well GP-3's filter pack.

Finally, a naturally packed well was installed. This is actually not a filter pack at all, rather the borehole was installed and the formation material was allowed to collapse back onto the well screen.

Every attempt was made to ensure that all of the wells were constructed of the same materials (other than the filter pack) and in the same fashion as one another. All of the wells in the filter pack experiment well nest used 20 slot, mill-slotted screens with a 0.125 inch spacing between slots except well GP-1, the naturally packed well, which had a 7 slot, mill-slotted screen with a 0.125 inch spacing. All wells were 2 inch diameter PVC pipe with 5 foot screens, drive-points to facilitate well installation, and PVC riser to finish the wells to above ground level. A hollow-stem auger drill rig was used to install all of the wells. The screens were set such that they were approximately bisected by the water table. After the filter pack was installed, bentonite chips were used to fill the annulus from the top of the filter pack to ground level. In an attempt to minimize the effect of the local hydrogeology on the rate of appearance and long-term productivity, all of the filter pack wells were placed as close to each other as possible. The wells were placed in two adjacent rows approximately 3 feet apart.

The grain size analysis of all the filter packs and formation materials can be seen in Appendices B-G. In order to generate a grain size analysis curve for wells GP-5 and GP-3, it was necessary to separate the Teflon chips from the sand. This was done because Teflon and sand have different densities and therefore cannot be mixed in order to do a grain size analysis. After the two materials were separated, a separate grain size analysis on each of the materials was performed. Once this was accomplished, the two curves were summed through their volumetric ratios to produce one curve.

The initial hypothesis for this experiment was similar to that of the laboratory experiment. It was simply that wells with a hydrophobic filter pack, which had a finer grain size than that of the "industry standard," would have a faster rate of appearance of product and a better long-term productivity than those wells filter-packed with a coarser grain size, and that were hydrophilic.

Results From Filter Pack Experiment

The results of the filter pack experiment are given below. Figure 3 shows the product thickness with respect to time. Table 3 shows the order of appearance of product within the filter pack well nest. Similar to the preliminary laboratory experiment, the "industry standard" hydrophilic well (GP-2) was the first well to have an appearance of product in the well. The natural packed well (GP-1) was second, followed by the finer-grained hydrophobic well (GP-5). The remaining two wells are even more difficult to evaluate. Both the 70/80 sand--Teflon mix (well GP-3) and the 70/80 sand filter pack (well GP-4) had extremely late arrival times and low productivities. The detection limit of the oil/water interface probe is on the order of 0.1 cm. Since the product thicknesses in wells GP-3 and GP-4 never exceeded 0.1 cm., it is questionable whether product ever appeared in these wells. As a result, these wells will not be used in the conclusions of this paper.

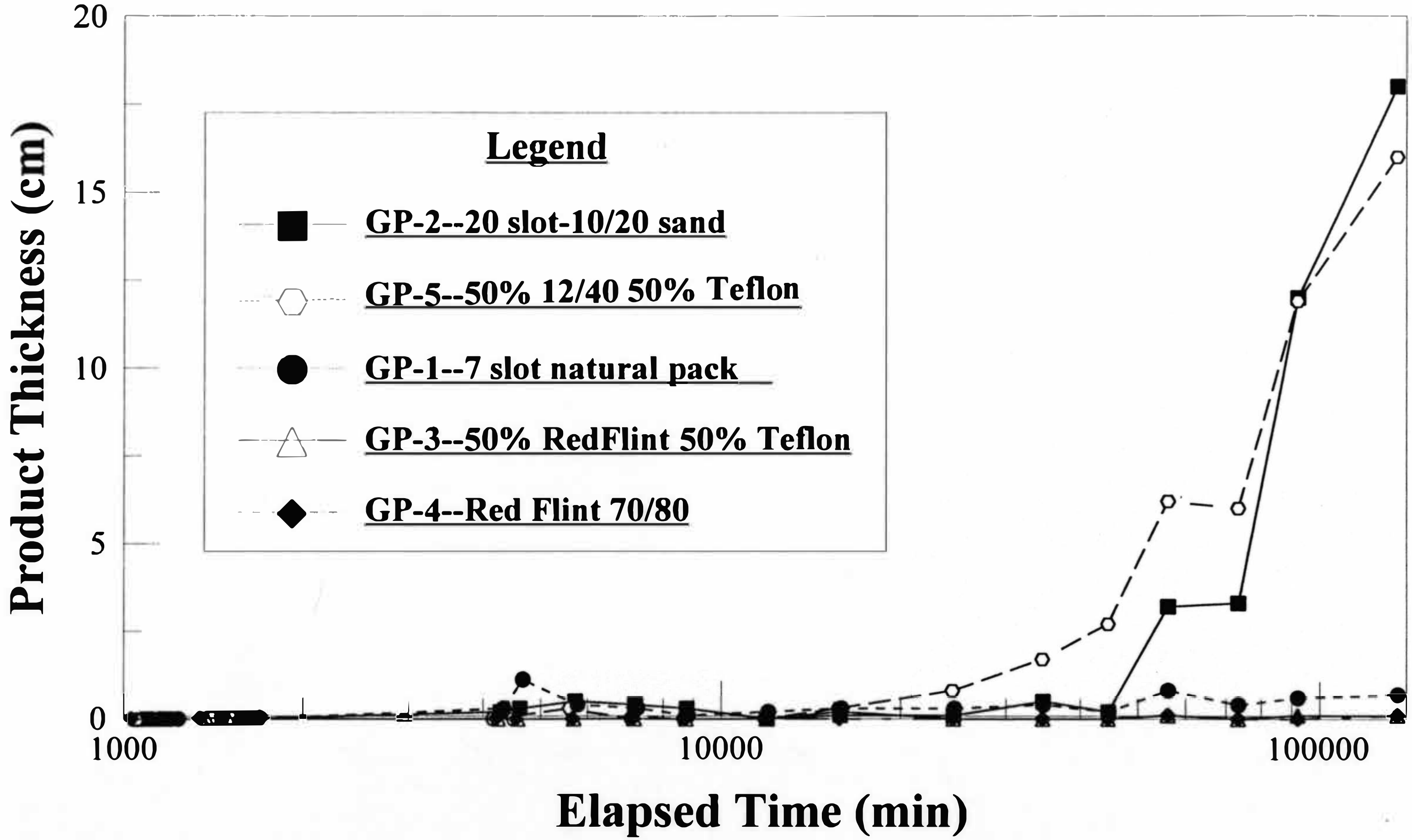


Figure 3. Rate of Appearance of Fuels in Gravel Pack Wells.

Table 3

Order of Appearance of Product in Filter Pack Wells

Well	Filter Pack	Time of Appearance, x
GP-2	10/20 Milan Sand	1634 ≤ x ≤ 4,275 min.
GP-1	Natural Pack	1687 ≤ x ≤ 4,327 min.
GP-5	12/40 Flat Rock Sand--Teflon Mix	11,750 ≤ x ≤ 15,724 min.
GP-3	70/80 Red Flint Sand--Teflon Mix	44,536 ≤ x ≤ 56,041 min.
GP-4	70/80 Red Flint	44,505 ≤ x ≤ 135,147 min

Table 4 shows the productivity of the filter pack well nest on 10/2/97 at the end of the experiment. The long-term productivity of the wells shows that ultimately the 10/20 sand (well GP-2) is most productive, followed by the 12/40 sand--Teflon mix (well GP-5) followed by the natural packed well (well GP-1). The remaining two wells are so unproductive that they will not be discussed and the natural packed well was not much better. During most of the experiment, the 12/40 sand--Teflon mix well (well GP-5) was more productive than the 10/20 sand (well GP-2).

<u>Conclusions From Filter Pack Experiment</u>

The rate of product appearance in these wells may at first seem a mystery. It was originally hypothesized that product would appear first in the wells that had hydrophobic/oleophilic treated filter packs, and then in wells with hydrophilic material as their filter packs. When the results are compared to the preliminary laboratory experiment and Hampton et al. (1995) previous results, it isn't surprising that it took longer for the hydrophobic/oleophilic filter packs to have product appear in these wells. It is possible that as the product enters the filter pack for the first time, that the product wets the oleophilic surface of the filter pack; hence, the delay in appearance of product in the Teflon mixture wells compared to wells with a hydrophilic material.

Table 4

Productivity of Filter Pack Wells on 10/2/97

Well	Filter Pack	Product Thickness
GP-2	10/20 Milan Sand	18 cm.
GP-5	12/40 Flat Rock Sand--Teflon Mix	16 cm.
GP-1	Natural Pack	0.7 cm.
GP-3	70/80 Red Flint Sand--Teflon Mix	0.1 cm.
GP-4	70/80 Red Flint Sand	0.1 cm.

The productivity of these monitoring wells was not consistent with the original hypothesis. Table 4 shows that the most productive well on 10/2/97 proved to be the well with the hydrophilic pack that was intended to represent the industry standard grain size. This was inconsistent with Hampton et al. (1995) previous findings that more productive wells had filter packs that were hydrophobic rather than hydrophilic. It is possible that hydrogeologic heterogeneities could have greatly complicated the results of this experiment and the interpretation of those results. These heterogeneities could include textural variations, stratigraphic variations, or differences in the product thickness due to well location within the gravel pack well nest. Regardless, these heterogeneities cannot be ignored as a driving force in the productivity and rate of appearance of fuels in these monitoring wells. This is evidenced by the fact that there is a relatively large discrepancy between the product thicknesses of wells GP-1, GP-3, GP-4, and wells GP-2 and GP-5, which are similar in all other important aspects.

Another possible complicating factor was gravel pack grain size. Examining the gravel pack grain size curves in Appendices D,E,F and G shows that the two wells that were productive, GP-2 and GP-5, were fairly similar in grain size. GP-2 was coarser than the other sand, GP-4. GP-5 was finer than the other hydrophobic gravel-packed well, GP-3. Coarser sand packs and finer hydrophobic packs perform better. In general, hydrophobic packs perform better when they are finer than the industry-standard sand pack. This was not achieved in this experiment.

Finally, it is possible that the spatial placement of the wells within the filter pack well nest in relation to the overall plume configuration and the groundwater flow direction, could have complicated the results of this experiment. Appendix H shows the well configuration of the filter pack well nest. Placing the wells relatively close to one another was done to minimize the effect of the placement of wells on the rate of appearance and productivity of the monitoring well. It is possible that the reason well GP-1 had a faster rate of appearance than GP-3 was because GP-3 is further down-gradient of well GP-1. Whether or not this is true, it cannot be ignored that this is a potential compounding factor in the interpretation of the results of this experiment.

Percent Open Area Experiment

Methodology

The site chosen to conduct the open area test was within the refined product plume in a city park south of the refinery as shown in Figure 2. The water table in this area is approximately three feet below grade; therefore, a hand auger was used to install these wells. Six wells were installed using PVC screens with various slot sizes and spacings, resulting in different percent open areas. Well OA-2 has a number 7 slot size with a 0.125 inch spacing between milled slots. Well OA-3 has a number 10 slot size with a 0.25 inch spacing between milled slots. Well OA-4 has a number 20 slot size with a 0.125 inch spacing between milled slots. Well OA-5 has a number 6 slot size with a 0.125 inch spacing between slots and is a wire-wrapped screen. Well OA-6 has a number 10 slot size with a 0.125 inch spacing between slots and is a wire-wrapped screen. Well OA-7 has a number 20 slot size with a 0.125 inch spacing between slots and is a wire-wrapped screen. Table 5 summarizes this information and shows the percent open area within each respective well screen.

In order to minimize the effect of hydrogeologic heterogenieties, the wells were placed relatively close to one another. The wells were installed using a hand auger. All of the wells had five-foot screens with a drive-point on the end to facilitate installation. The well screen was emplaced such that the screen is bisected by the water table. Above the screen a P.V.C. riser was used to finish the well to above ground level. No well development method was used on the open area wells. Once the wells were installed, the time of product appearance was monitored using an oil/water interface probe. After product appeared, the product thickness was monitored at increasing time intervals.

Table 5

Screen Type vs. Open area

Well	Slot Size, Type, and Spacing	Per Cent Open Area
OA-3	10 slot, mill-slotted, 1/4 in.	2.5
OA-2	7 slot, mill-slotted, 1/8 in.	4.0
WD-3	10 slot, mill-slotted, 1/8 in.	5.0
OA-5	6 slot, wire-wrapped, 1/8 in.	5.5
OA-6	10 slot, wire-wrapped, 1/8 in.	9.0
OA-4	20 slot, mill-slotted, 1/8 in.	9.6
OA-7	20 slot, wire-wrapped, 1/8 in.	16.8

The hypothesis that was established before the experiment was that wells with a larger open area would allow product to enter the well at a faster rate and would also prove the most productive.

Results of Open Area Experiment

The order of appearance of product in the open area well nest is shown in Table 6 and the long-term productivity is shown in Table 7. Figure 4 shows the rate of appearance and the long-term productivity with respect to time for each well.

Table 6

Order of Appearance of Product in Open Area Experiment

Well	Percent Open Area	Time, x
OA-2	4.0	$34 \leq x \leq 44$ min.
OA-7	16.8	$255 \leq x \leq 1{,}418$ min.
OA-6	9.0	$272 \leq x \leq 1{,}427$ min.
OA-5	5.5	$281 \leq x \leq 1{,}444$ min.
OA-4	9.6	$1{,}727 \leq x \leq 1{,}743$ min.
OA-3	2.5	$1{,}741 \leq x \leq 1{,}757$ min.

Product appeared first in OA-2. OA-2 has 4 percent open area within the screen. Product appeared in OA-2 between 34 and 44 minutes from the time of installation. OA-7 has 16.8 percent open area and was the second well in which product appeared. Product appeared in well OA-7 between 255 and 1418 minutes from the time of installation. OA-7 was followed by OA-6 which has 9 per cent open area and appeared between 272 and 1427 minutes from the time of installation. OA-6 was followed by OA-5 which has 5.5 per cent open area. Appearance in well OA-5 occurred between 281 and 1427 minutes from the time of installation. OA-5 was followed by OA-4 which has 9.6 per cent open area. Product appeared in well OA-4 between 1727 and 1743 minutes from the time installation. Finally, product appeared last in well OA-3. OA-3 has 2.5 per cent open area and had product appear between1741 and 1757 minutes from the time of installation.

Table 7

Productivity of Open Area Wells On 10/2/97

Well	Per Cent Open Area	Product Thickness (cm)
OA-2	4.0	11.5
OA-6	9.0	10.2
OA-7	16.8	6.9
OA-4	9.6	5.1
OA-3	2.5	1.2
OA-5	5.5	0

The long-term productivity of the open area wells is shown in Table 7. OA-2 has the greatest product thickness reaching up to 11.5 cm. in thickness. The second most productive well proved to be OA-6, which had up to 10.2 cm. of product. OA-6 was followed by OA-7, which had 6.9 cm. of product. Well OA-4 was next with 5.1 cm. of product, followed by OA-3 with 1.2 cm. of product. Finally, the least productive well was OA-5, which had no product for the entire experiment.

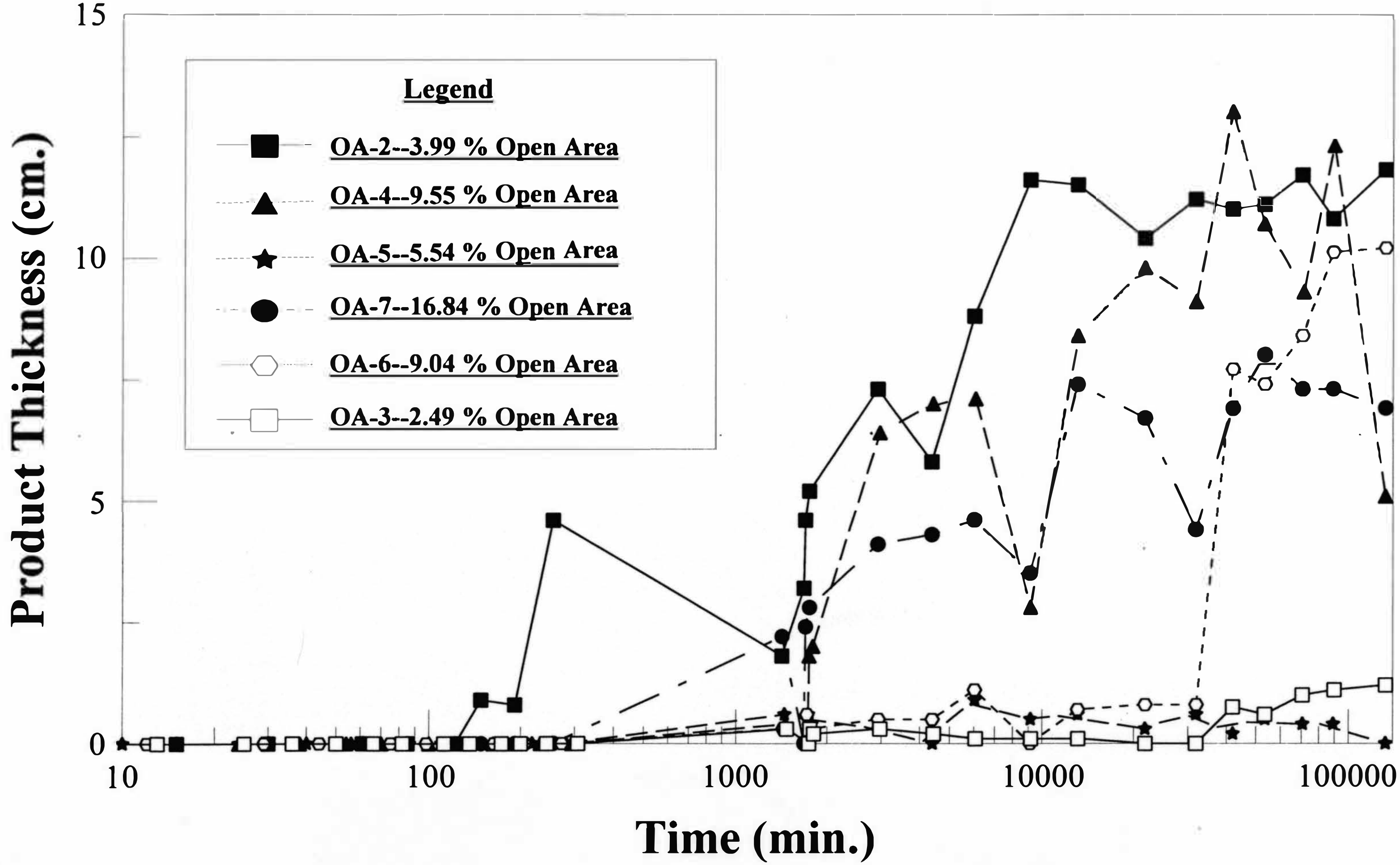


Figure 4. Appearance of Product in Open Area Wells.

Conclusions From Open Area Experiment

The results from the open area experiment seem relatively inconclusive. No discernible pattern could be interpreted from the data obtained from the open area experiment. There are several possible explanations for this. One possible explanation why there was no discernible pattern is that the hydrogeologic conditions vary considerably over the area of the open area well nest. It is probable that the geology of this area cannot be considered homogeneous or isotropic; therefore, this will ultimately affect the product appearance and productivity of each monitoring well differently, thus giving ambiguous results. Differences such as textural variations, non-uniform stratigraphic layering, and sorting variations of the geologic materials could ultimately prove more important in the efficency of the monitoring well than does the percent open area. . The combined effects of these inhomogeneities could be called hydrogeologic heterogeneities, and could greatly complicate the results of this experiment and the interpretation of those results

Another possible explanation of the inconclusive data is that the product thickness over the area of the open area well nest varies from well to well even if the geology were homogeneous. In other words, well location relative to the free product plume could determine product thickness and the product appearance rate. Appendix I shows the configuration of the open area well nest. Although the wells were intended to be close enough to one another that the location of the wells was not an important factor in the results of this experiment, it is possible that well placement within the plume configuration was relevant even on a relatively small scale. For example, as seen in Table 6, wells OA-7 and OA-5 had a faster rate of appearance than did wells OA-6 and OA-4. Appendix I shows that wells OA-6 and OA-4 are further down-gradient than wells OA-7 and OA-5. This hypothesis is not consistent for all of the wells in the open area well nest, but it cannot be ignored as a possible complicating factor in the rate of appearance of product within these monitoring wells.

Well Development Experiment

Methodology

In order to identify the effects of well development on the rate of appearance of fuels in monitoring wells and the long-term productivity of a monitoring well, a separate experiment was conducted. In this experiment all of the wells were installed in the same manner, with the same material, and with the same type of well screen. The site chosen for the well development experiment was approximately 30 ft. south of where the open area experiment was conducted as shown in Figure 2.

Once again, a hand auger was used to install these wells. The process of installation and development went as follows. All boreholes were drilled before any of the monitoring wells were installed. Once this was accomplished, all wells were installed in their respective boreholes. Measurements were taken to determine if product had entered the well and then development was started on the three selected wells that were to be developed.

Three methods of development were chosen for this experiment that are common to the environmental consulting industry; a bailer method, a surge block method, and finally an overpumping method (Wilson, 1995). Well WD-5 was developed by the bailer method. The bailer method of development was accomplished by using an acrylic bailer to draw water and product out of the well in order to develop the well. The bailer was lowered into the well and allowed to fill through the check valve at the bottom of the bailer. The bailer was then removed and emptied and the process was repeated until approximately 10 gallons of water/product were removed from the well.

Well WD-4 was developed by the overpumping method. The overpumping method was accomplished using a peristaltic pump to remove water and product from the well, in order to remove fines and develop the well. A tube was lowered into the well and was used to pump out the water/product in the well. A total of 28 liters of liquid was removed from the well at an approximate pumping rate of 0.8 L/min.

Well WD-2 was developed by the surge block method of development. The surge block method was accomplished by using a piston-like apparatus that was moved up and down within the well screen to develop the well. Since the well development well nest was installed by hand, no drill rig was present to operate the surge block, as is typically the case in the consulting industry. Hence, the surge motion was accomplished by hand. This motion was performed for approximately 30 min., during which time the well was occasionally bailed to remove fine material and water. A total of 10 gallons of water was removed from the well.

The initial hypothesis for this experiment was that the well developed with the surge block method would prove most productive and have a faster rate of appearance than either the overpumping or the bailer method. This was based on the fact that water is forced in and out of the near-well zone by the surging motion of the surge block. Hence, the well should be better developed due to the bi-directional movement of water through the near well zone, as opposed to the nearly unidirectional movement of water in the overpumping and bailer methods of development.

Results From the Well Development Experiment

Table 8 shows the order of appearance of product in the wells that were developed. This table indicates that facilitating product to enter a well is best accomplished by overpumping the well for development purposes. The second best option seems to be the bailer method, followed by the surge block method. The long-term productivity of the experimental wells is shown in Table 9. Figure 5 and Table 9 show that well WD-5 (bailer method) proved most productive in terms of product thickness. Well WD-4 (overpumping method) was second, followed by a very unproductive well WD-2 (surge block method).

Conclusions From Well Development Experiment

It is difficult to explain why well WD-2 (surge block method) didn't have a faster rate of appearance or higher productivity rate than the other two developed wells. One would expect that the back and forth motion of the water moving in and out of the well screen would only help to develop the well better than the one way motion of the overpumping and bailer methods. This was not the case in this experiment. The overpumping method proved fastest in the rate of appearance of product in the monitoring well. One possible explanation is that water was removed at a faster rate from this well than from either of the other two developed wells. This could have caused the well to be unidirectionally developed more quickly than the bailer method, however, in terms of long term productivity, the bailer method proved more productive.

Table 8

Order of Appearance of Product in Well Development Wells

Well	Development Method	Time of Appearance, x
WD-4	Overpumping	$168 \leq x \leq 1{,}365$ min.
WD-5	Bailer	$1{,}366 \leq x \leq 2{,}804$ min.
WD-2	Surge block	$40{,}320 \leq x \leq 51{,}702$ min.

At first glance, one would expect that the bailer method and the overpumping method are actually the same, in that they both remove water/product and fine material from the well as a result of their development procedure. It could be possible, however, that the bailer actually produces a surging motion when it is lowered into the well; thus, the bailer method is actually a subdued replica of a surge block. As a result, the bailer method actually develops the well bi-directionally as opposed to the unidirectional development of the overpumping method.

Table 9

Productivity of Well Development Wells on 10/2/97

Well	Development Method	Product Thickness
WD-5	Bailer	14.6 cm.
WD-4	Overpumping	8.5 cm.
WD-2	Surge block	0.1 cm.

There are several possible explanations for well WD-2's poor performance. First, Driscoll (1989) points out that surging may force fine material back into the formation before the fines are removed from the well if the well is not pumped or bailed frequently. It is entirely possible that when developing well WD-2, inadequate bailing was performed in order to ensure removal of the fine material from the near well zone, thus rendering well WD-2 inefficient. This could have been compounded by the bacterial growth often found in free product plumes further clogging the near well zone as a result of inadequate bailing.

Finally, it is also possible that the hydrogeologic conditions such as textural variations, stratigraphic layering differences, and sorting variations could have contributed to the rate of appearance and amount of product within each well. As with the other experiments, it is possible that the spatial location of each well within the well nest was a complicating factor in the results of this experiment. Appendix J

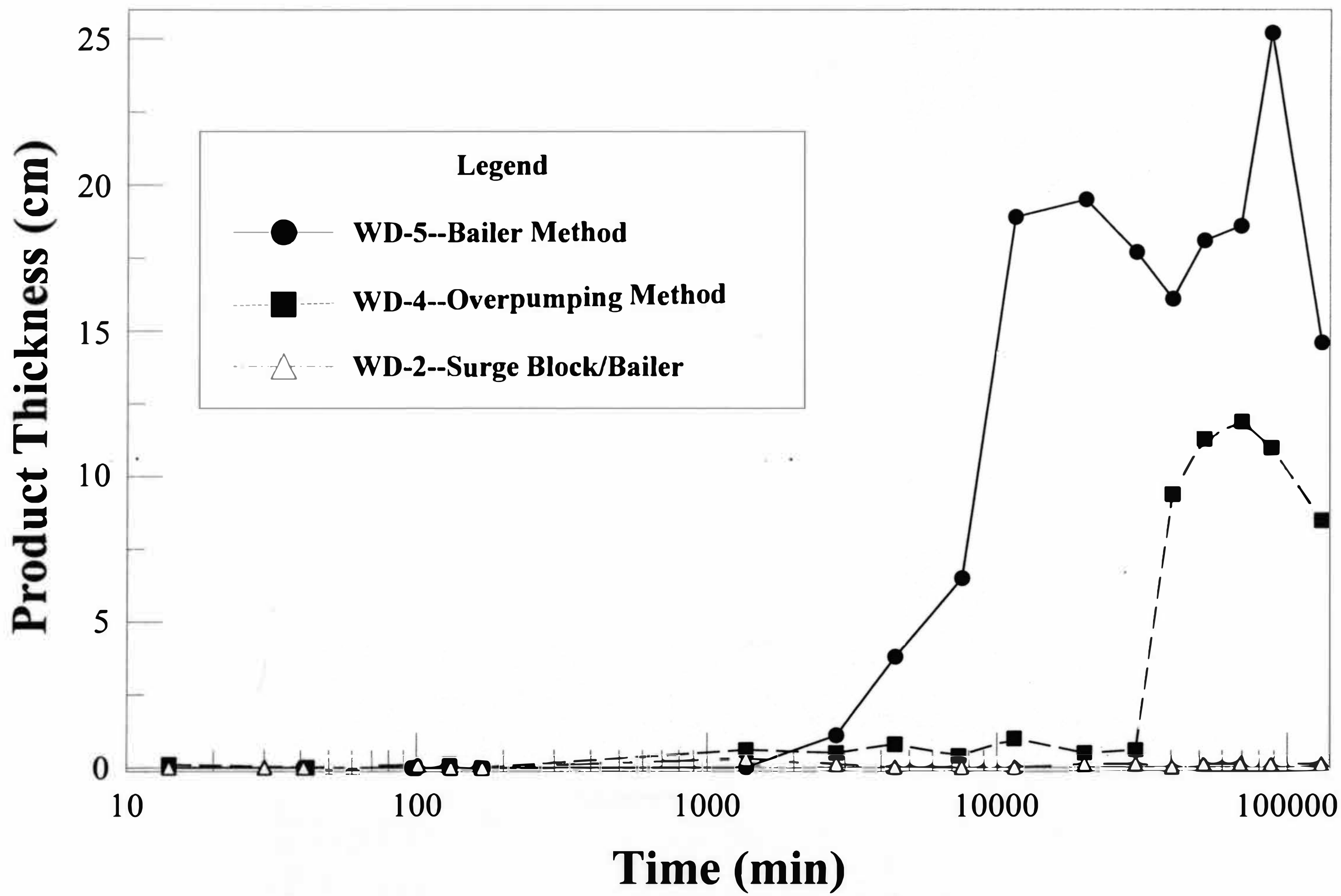


Figure 5. Appearance of Product in Well Development Wells.

shows the location of each well in the well development experiment, within the experimental well nest. Plume thickness due to well location could have also been a contributing factor in the long-term productivity and the rate of appearance of product within the well.

Plume Comparison Experiment

Methodology

As mentioned previously, the site at which this research was performed has two distinct contaminant plumes, a refined product plume in the City Park, and a crude oil plume in the cemetery north of the refinery. Two wells were placed in each of the respective plumes in order to gain a better understanding of how different contaminant plumes affect the rate of appearance of product in monitoring wells and the long-term productivity within these wells. Wells PC-1 and PC-2 were used for this purpose in the crude oil plume. Wells WD-3 and WD-1 were used as plume comparison wells in the refined product plume.

Every attempt was made to ensure that the well sets were installed with similar materials and by similar means. Both sets of monitoring wells had one well that was a 10 slot, mill-slotted well with a 0.125 inch spacing (wells WD-3 and PC-2). The other well in each set was a 7 slot, mill-slotted well with a 0.125 inch spacing (wells WD-1 and PC-2). All of the wells have 5-foot screens, which were set to be bisected by the water table. All were fitted with a drive-point in order to facilitate well installation, and all were fitted with a PVC riser to finish the wells to above ground level. Installation of these wells was performed with a hand auger. After the wells were installed, they were monitored for rate of appearance of product, after which they were monitored for product thickness with respect to time.

The initial hypothesis for this experiment was that wells within the refined product plume would have a faster rate of appearance than would wells in the crude oil plume. This was based on the assumption that the refined product plume had a lower viscosity than the crude oil plume. Therefore, since fluids with a lower viscosity move faster than fluids with a higher viscosity, product would appear in wells in the refined product plume faster than it would in wells in the crude oil plume (Fetter, 1994).

Results From Plume Comparison Experiment

Consistent with the original hypothesis, Table 10 shows that a faster rate of appearance occurs in the wells placed in the refined product plume (WD-3, and WD-1) than in wells within the crude oil plume (PC-2, and PC-1). The productivity of these two well sets cannot be compared due to the fact that each set was placed in a different contaminant plume. Tables 10 and 11 show that wells with a greater percent open area have a faster rate of appearance, and better long-term productivity, than do similar wells with a smaller percent open area.

Table 10

Rate of Appearance of Product in Plume Comparison Wells

Well	Slot Size, Type and Spacing	Time of Appearance, x
WD-3	10 slot, mill-slotted, 1/8th in.	0 min.
WD-1	7 slot, mill-slotted, 1/8th in.	$0 \leq x \leq 20$ min.
PC-2	10 slot, mill-slotted, 1/8th in.	$55 \leq x \leq 149$ min.
PC-1	7 slot, mill-slotted, 1/8th in.	$284 \leq x \leq 909$ min.

Table 11

Productivity of Plume Comparison Wells on 10/2/98

Well	Slot Size, Type and Spacing	Product Thickness
WD-3	10 slot, mill-slotted, 1/8th in.	14.3 cm.
WD-1	7 slot, mill-slotted, 1/8th in.	12.4 cm.
PC-2	10 slot, mill-slotted, 1/8th in.	32.3 cm.
PC-1	7 slot, mill-slotted, 1/8th in.	28.5 cm.

Conclusions From Plume comparison Experiment

There are a variety of reasons why the refined product plume could have appeared faster in the monitoring wells. First, Fetter (1994) states that fluids with higher viscosities travel at a slower rate than fluids with lower viscosities. Presumably, the refined product plume has a lower viscosity than the crude oil plume. This would facilitate product entering wells in the refined product (WD-3, and WD-1) faster than wells in the crude oil plume (PC-1, and PC-2). Second, the hydrogeologic conditions such as the conductivity and the hydraulic gradient could have affected the rate of appearance of the product in the monitoring wells. If either of these was greater in the refined product wells than in the crude oil wells, product would be encouraged to enter the refined product wells at a faster rate than the crude oil wells.

The productivities of the monitoring well sets in each plume are shown in Table 11. While it may seem from the data above that wells PC-2 and PC-1 are more productive than their similar counterparts in the refined product plume, it is impossible to compare the productivities of the two well sets. These are two entirely different plumes that are compared; they have different thicknesses, viscosities, and flow rates making a meaningful comparison impossible.

Ultimately, these data prove most useful in evaluating the effects of open area on the rate of appearance of the product in the wells and the long-term productivity of the monitoring wells. Tables 10 and 11 and Figure 6 show that a faster rate of appearance of product occurs in the wells with a greater open area. It also shows that the most productive wells proved to be those wells with the greatest per cent open area. When we compare the two well sets individually, it is clearly seen that well WD-3 and PC-2 outperform wells WD-1 and PC-1 in terms of rate of appearance and long term productivity.

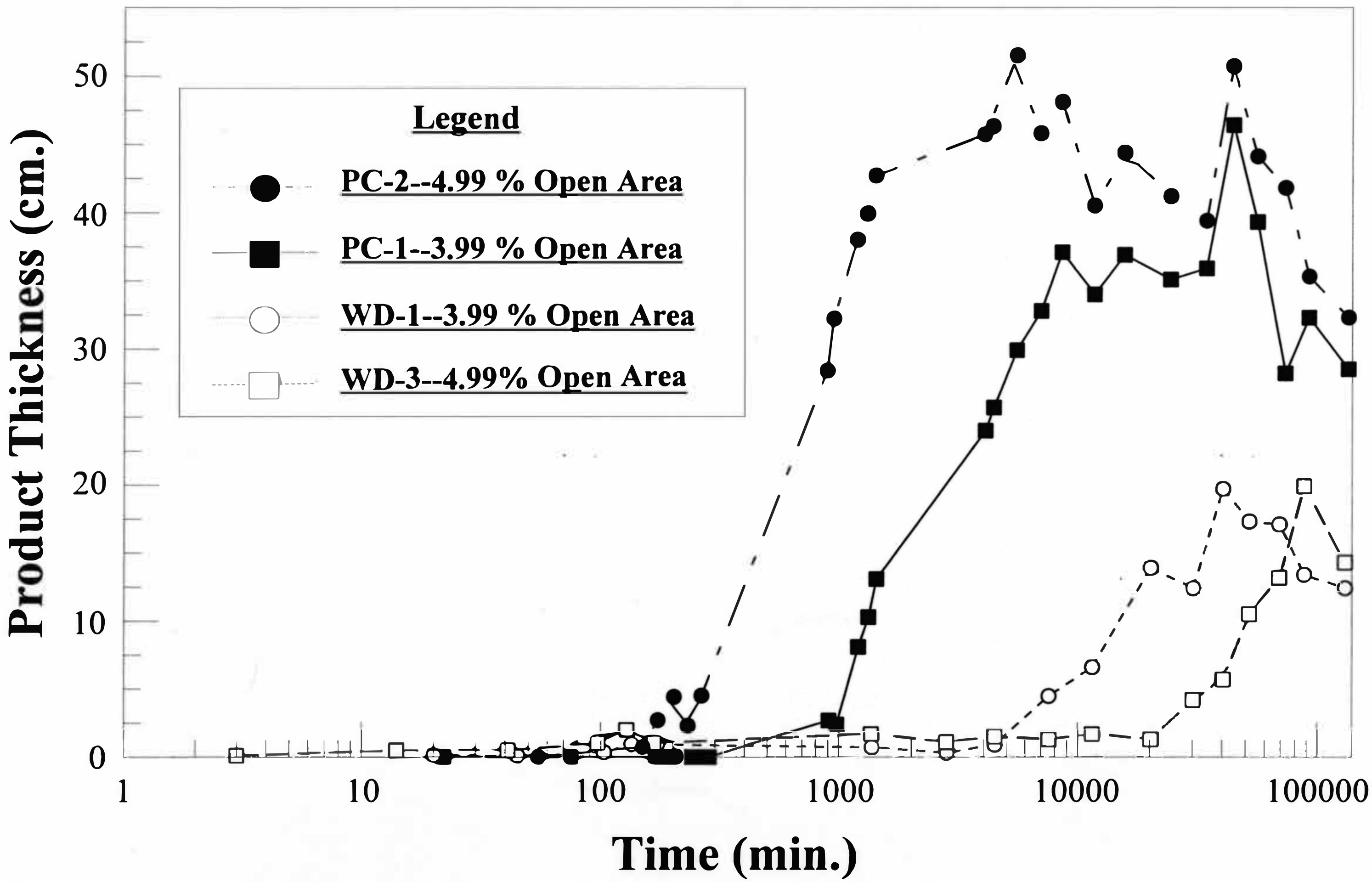


Figure 6. Appearance of Product in Plume Comparison Wells.

CONCLUSIONS

Hastening the appearance of fuels in monitoring wells may be facilitated by their design and installation procedures. This research attempted to understand how per cent open area, filter pack selection, and well development methods affected the rate of appearance of fuels in a monitoring well. The results are somewhat ambiguous as to how much influence the above factors have in the rate of appearance and long-term productivity of a monitoring well.

The laboratory experiment was consistent with the findings of Hampton et al. (1995) that hydrophobic filter packs, with a grain size finer than that of the “industry standard,” were more productive than hydrophilic filter packs, with a grain size 4-6 times that of the formation material. The rate of appearance of fuel in the monitoring well may be inhibited by hydrophobic filter packs. This may be due to the hydrophobic material holding the fuel within the filter pack until the pack is saturated with respect to product. This delays the appearance of fuel within the monitoring well.

The results of the first field experiment were intended to test the filter packs’ effects on the rate of appearance of fuels in a monitoring well. The results were consistent with the results of the laboratory experiment in terms of rate of appearance. The productivity of these wells was not consistent with the laboratory experiment or Hampton et al. (1995) previous findings. The effects of hydrogeologic heterogeneities and the spatial placement of the wells within the plume configuration are thought to be factors interfering with the productivity and rate of appearance of fuels in the monitoring wells.

The effect of open area on the rate of appearance of fuels in a monitoring well, was not demonstrated by the second field experiment. Once again, the hydrogeology of the site could have interfered with the results of this experiment. It is also possible that the spatial placement of the wells in relation to the plume configuration was a complicating factor in the results of the open area experiment. The plume comparison experiment better demonstrated how open area affected the productivity and rate of appearance of fuel in a monitoring well. The two well nests used in the plume comparison experiment both indicated that wells with a larger per cent open area hastened the appearance of fuels in a monitoring well, and improved the productivity of the monitoring well.

The well development experiment indicates that wells developed with a bailer were more productive than wells developed by overpumping or surge block. The surge block method was extremely unproductive in this experiment. It is possible that the surge block method of development proved ineffective due to infrequent removal of water/fine material from the well. The overpumping method proved faster in its rate of product appearance. This could be due to the faster removal of water in the overpumping method as compared to the bailer method. It also could be due to hydrogeologic hetergeneities over the experimental area and the spatial placement of the wells in relation to the plume configuration. It is also possible that the bailer method proved most productive due to a development action that is a subdued replica of the surge block method, which facilitates removal of water and fine material from the well.

The plume comparison experiment indicates that wells placed within a refined product distillate plume will have a faster rate of appearance than will wells placed in a crude oil plume. This could be due to the lower viscosity of the refined product plume compared to the viscosity of the crude oil plume. The plume comparison experiment also adds credence to the theory of a large percent open area facilitating a more productive well, with a faster rate of appearance of product.

In summary, this experiment has shown that percent open area, filter pack selection, and well development methods are possible factors to be considered in the design and installation of monitoring wells that can affect free product appearance and productivity. Perhaps more important in determining the product entry into a well is the well location relative to the free product plume and the local hydrogeology, factors difficult to control and evaluate.

RECOMMENDATIONS FOR FUTURE RESEARCH

In hindsight, the experimental methodology of this project could have been improved. First, it would have been useful to perform controlled laboratory experiments aimed at determining how well development and percent open area factor into the rate of appearance of fuels within a monitoring well. The results from the field experiment are somewhat ambiguous due to the uncontrolled nature of field conditions. Hydrogeologic heterogeneities such as textural variations, stratigraphic layering, and product thickness in relation to well placement are all uncontrollable conditions that cloud the results of this experiment. Laboratory tank experiments similar to the filter pack experiment conducted in this research could help to eliminate the above compounding factors.

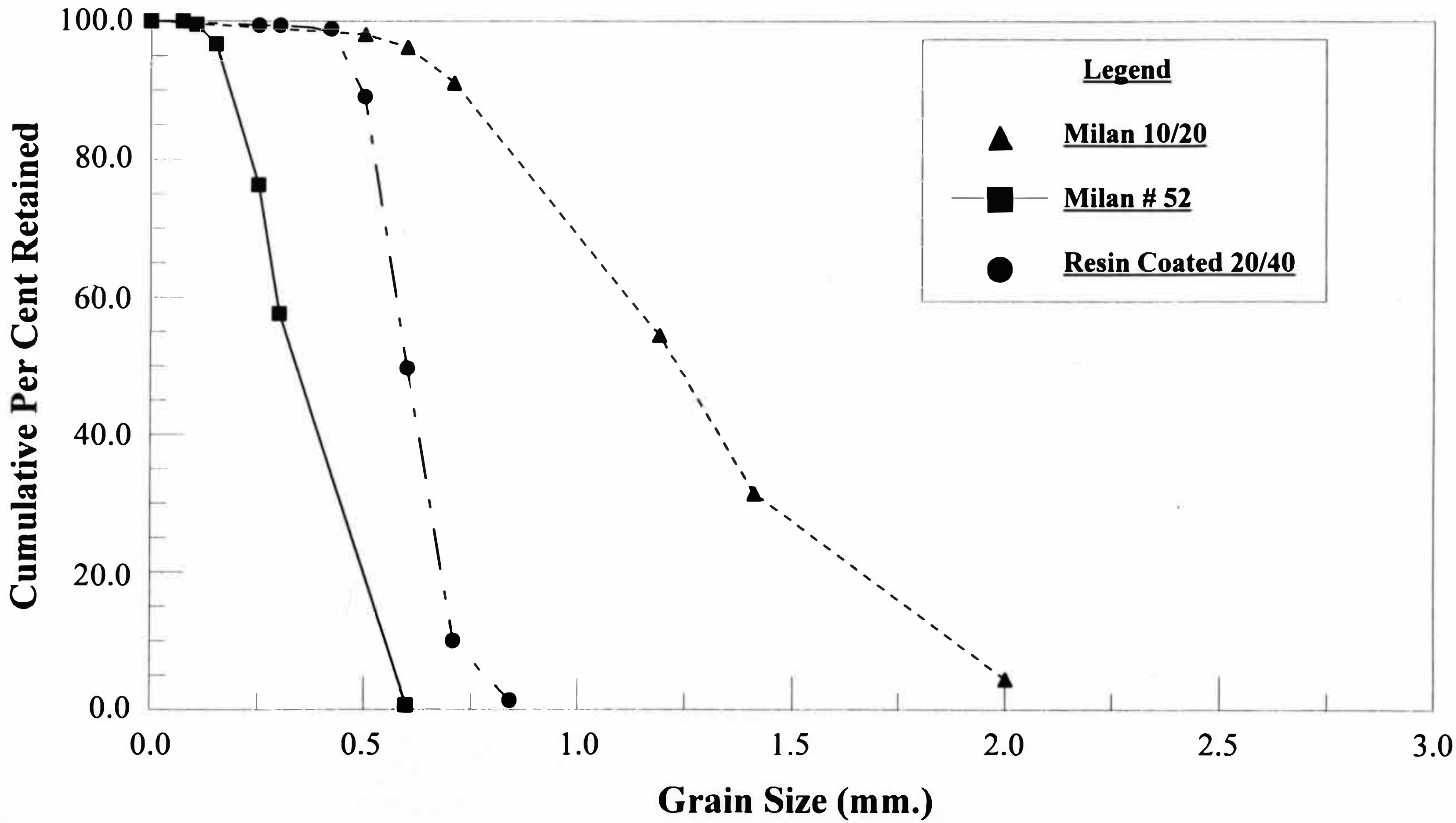
Another possible improvement on this research would be to conduct experiments in the field and laboratory that contained duplicate tests of the same parameter being tested. For instance, if one was conducting an experiment to determine how percent open area affected the rate of appearance of fuels in a monitoring well, it would be useful to have two or more wells of the same open area located in the same relative location. This would aid in the final interpretation of the data and could also help to eliminate the effects of hydrogeologic heterogeneites on the results of the experiments.

Possibly the most exciting results obtained from this experiment came from the well development experiment. The inconsistency between the initial hypothesis of this experiment and the results obtained in the well development experiment were surprising. Free product hydrocarbons pose an interesting problem for the environmental consultant. Chemical and biological breakdown of fuels produce bi-products that can complicate the development process. Understanding how these bi-products affect the development process will aid in producing more productive wells. The surge block method is very commonly used as a development method in areas of free product hydrocarbon contamination. The results of this experiment indicate that this method as we employed in this experiment was relatively ineffective as a development method when compared to the bailer or overpumping method of development. Continued research in the laboratory and the field will help to verify the conclusions of this study.

Appendix A

Laboratory Grain Size Analysis of
Formation and Filter Packs

Laboratory Grain Size Analysis of Formation and Filter Packs

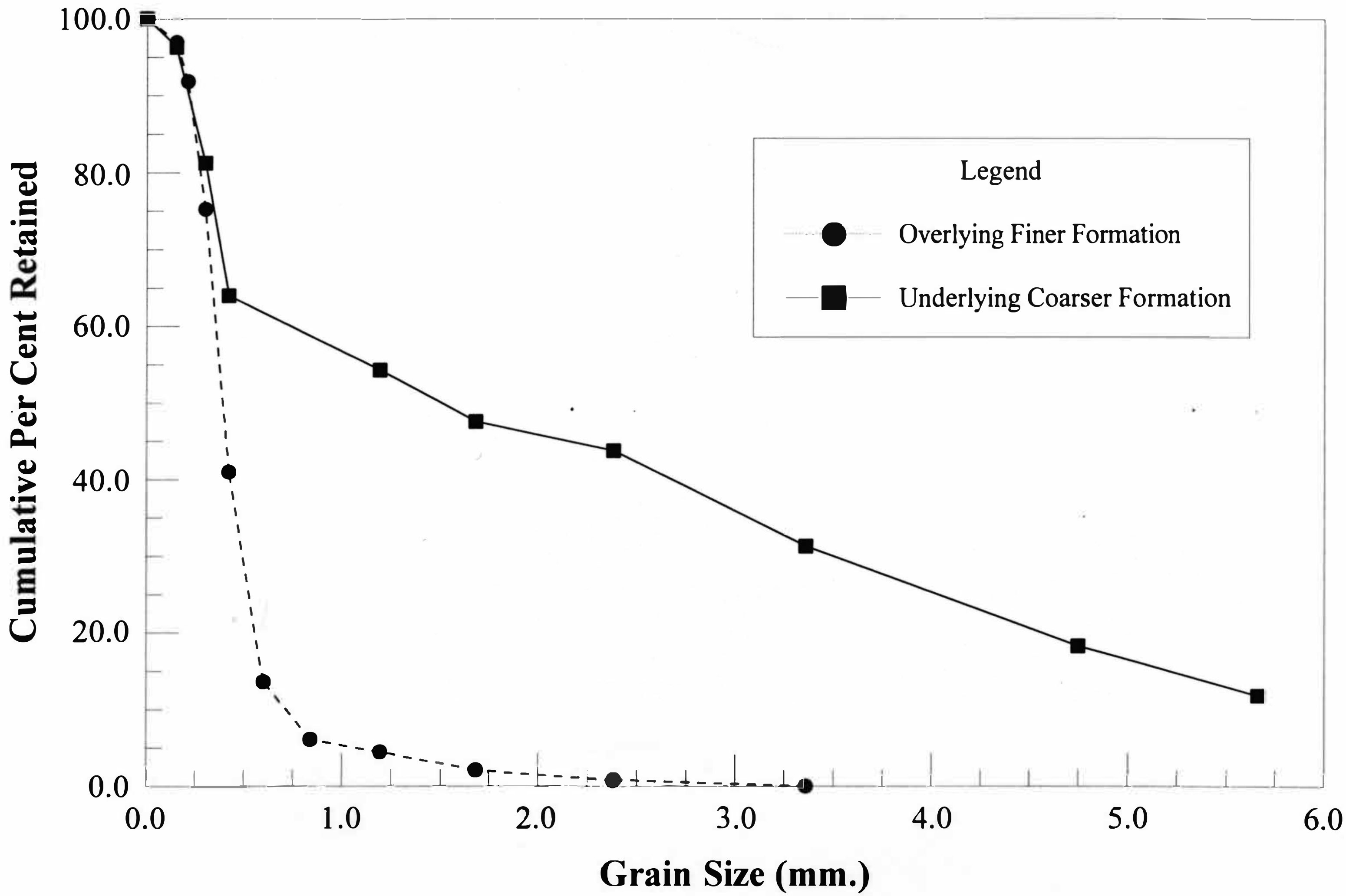


Appendix A. Laboratory Grain Size Analysis of Formation and Filter Packs

Appendix B

Well GP-1, Formation Grain Size Analysis

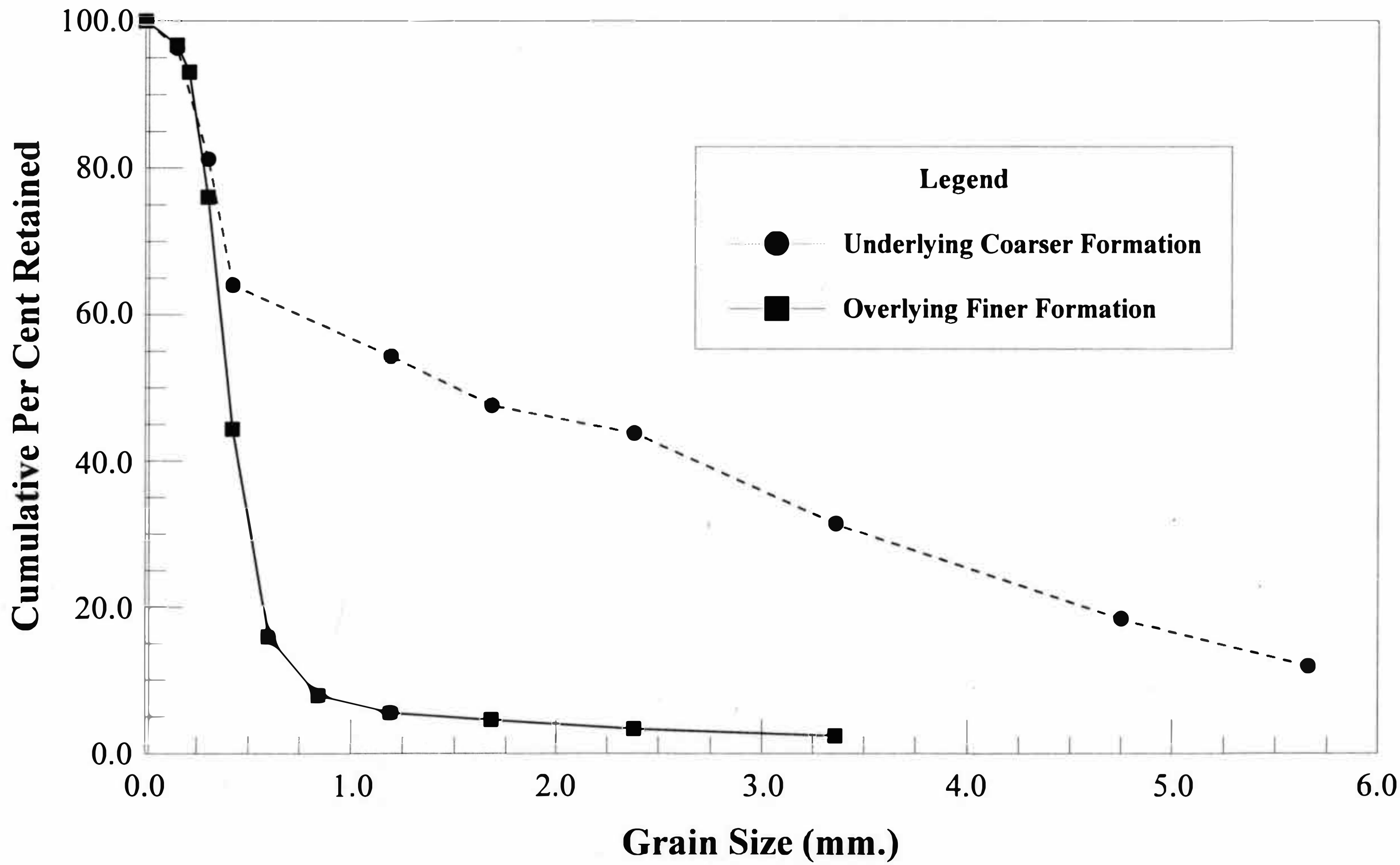
Well GP-1, Formation Grain Size Analysis



Appendix C

Well GP-5, Formation Grain Size Analysis

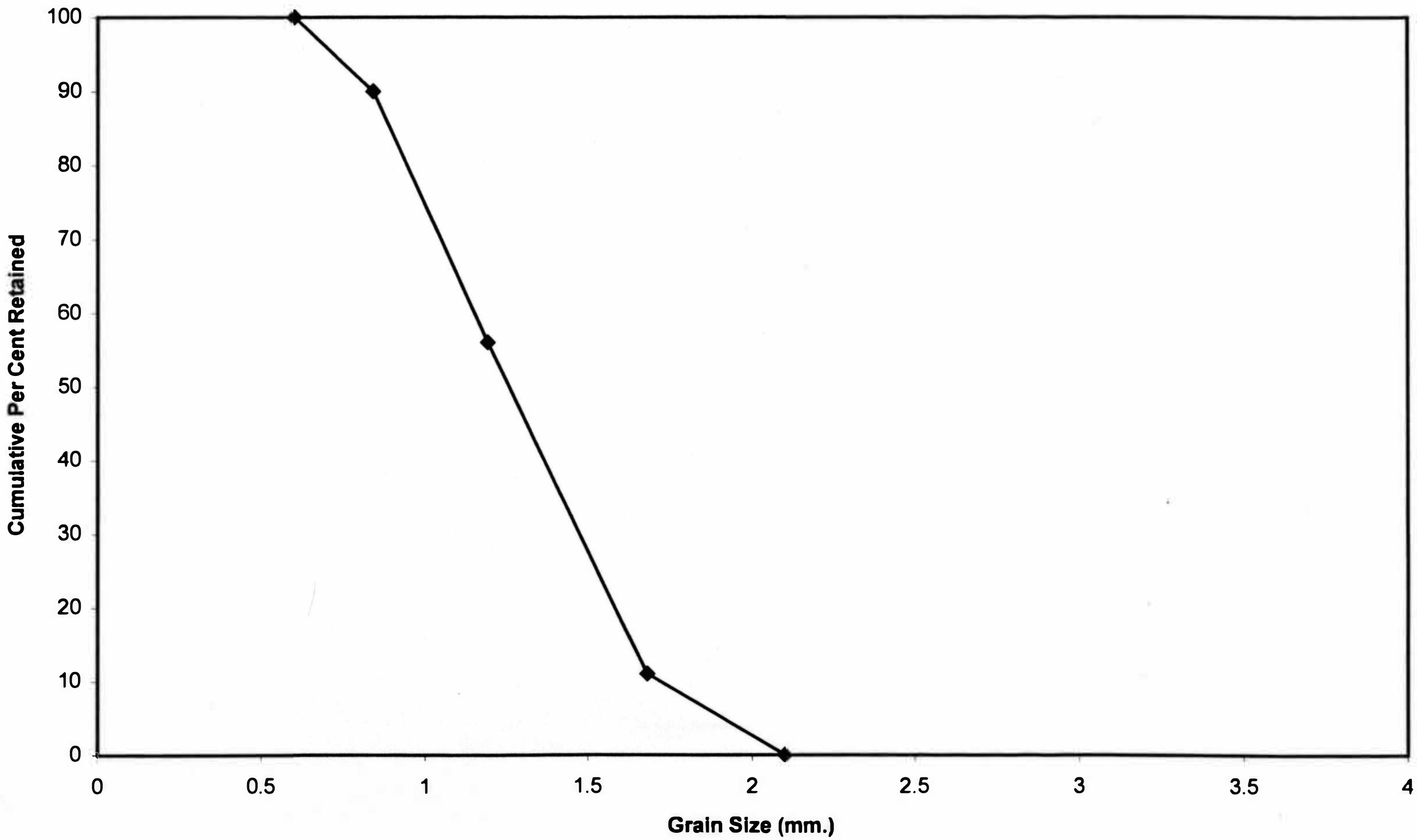
Well GP-5, Formation Grain Size Analysis



Appendix D

10/20 Milan Sand

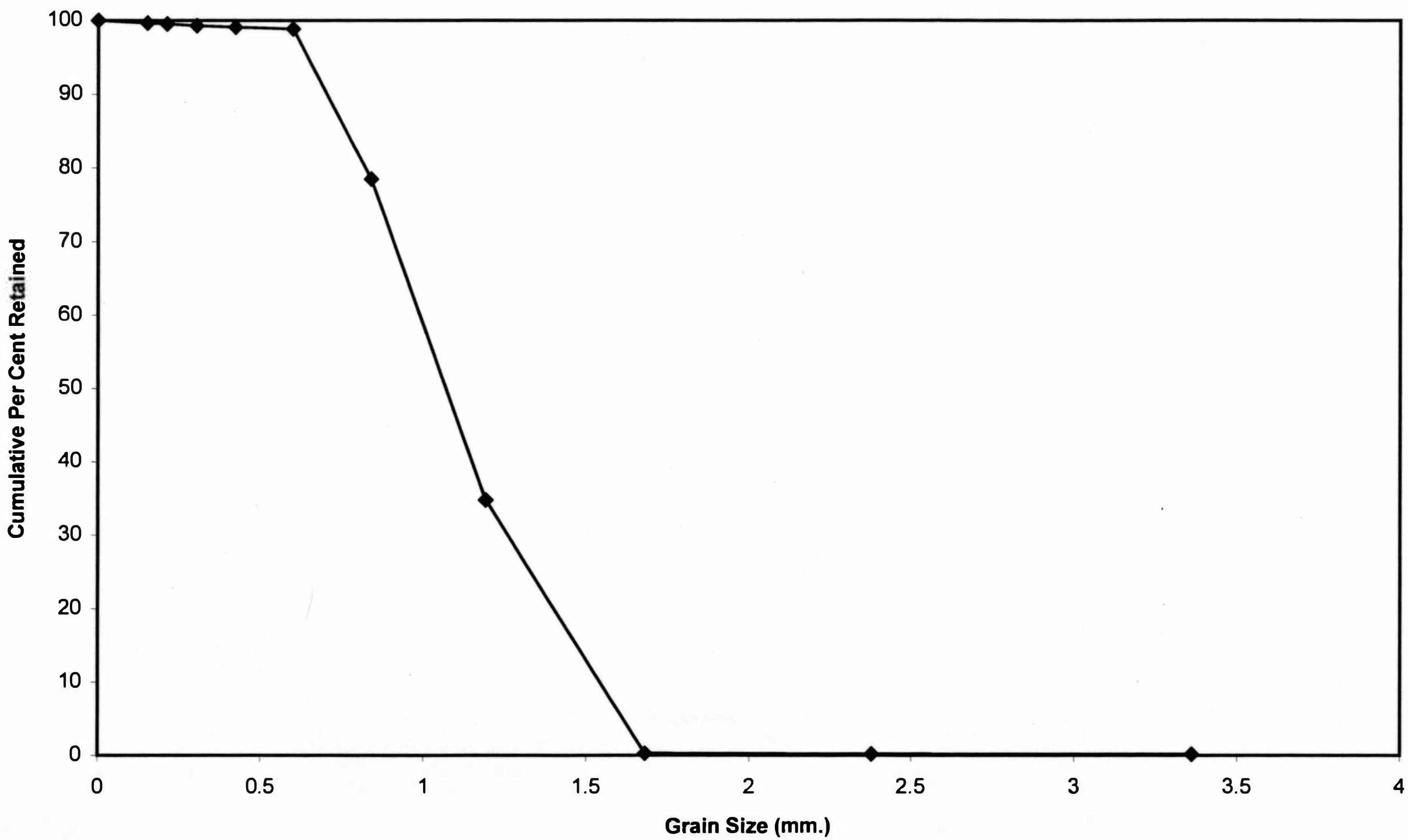
10/20 Milan Sand



Appendix E

70/80 Red Flint Sand

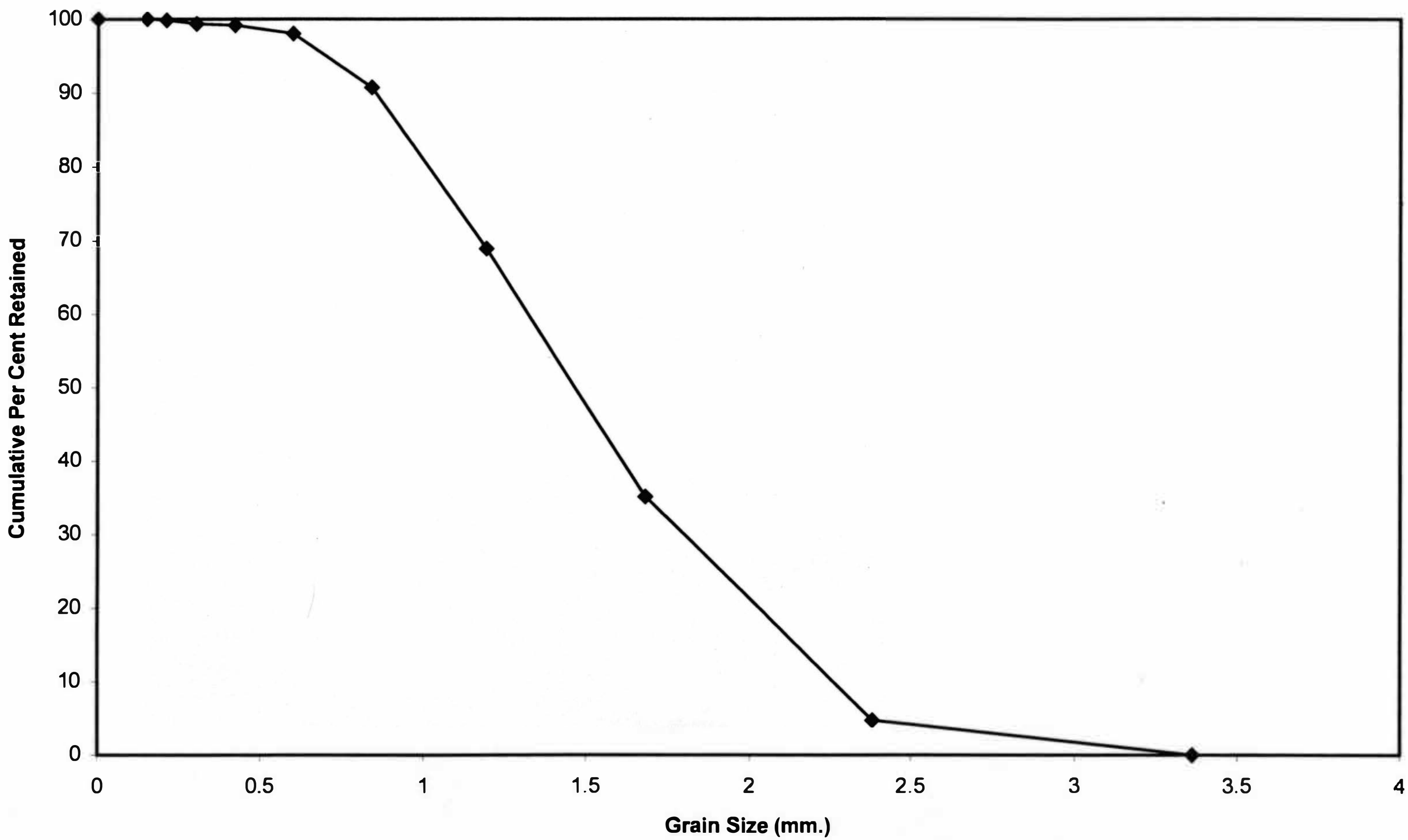
70/80 Red Flint Sand



Appendix F

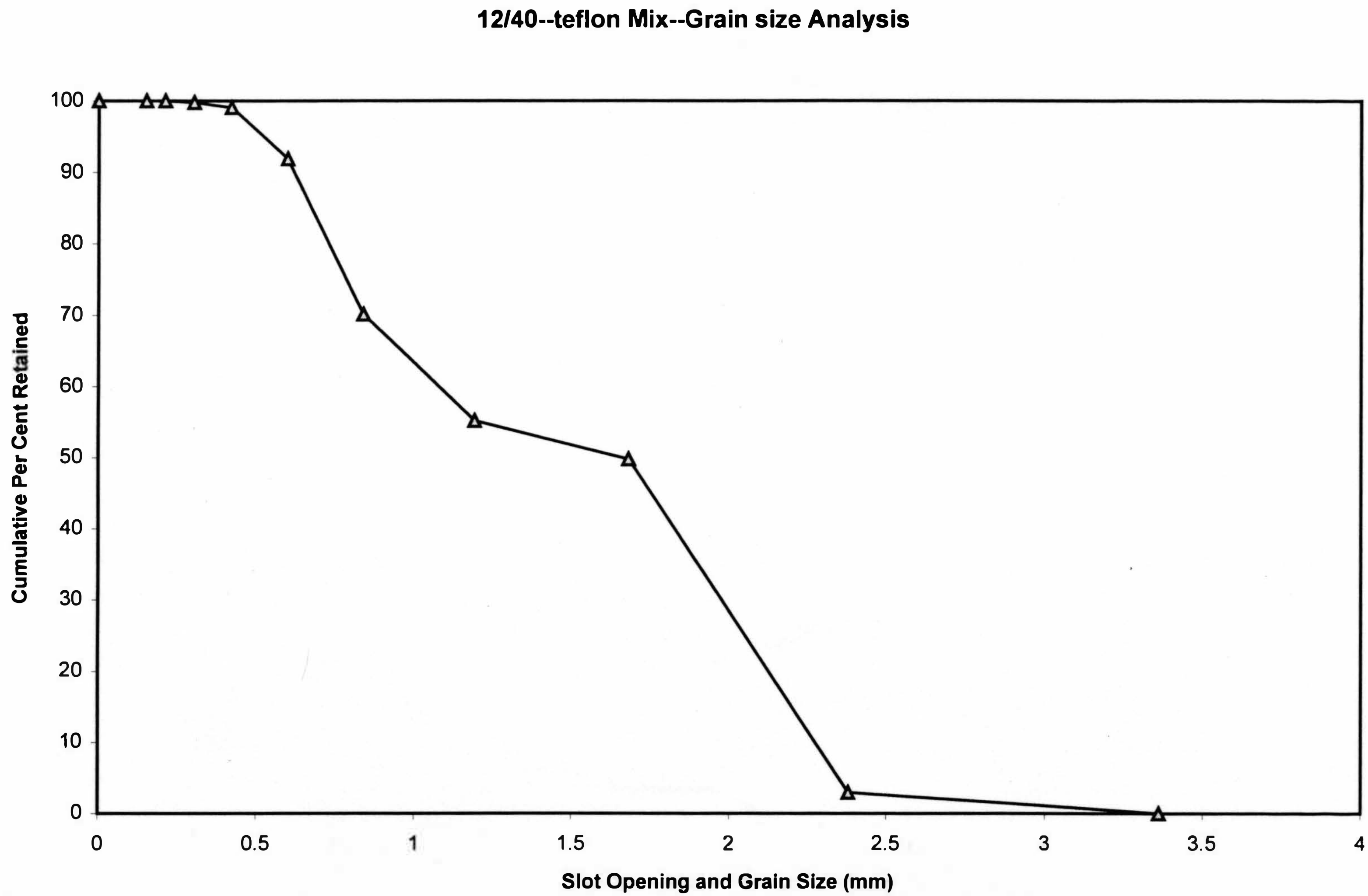
70/80--Teflon Mixture

70/80--Teflon mixture



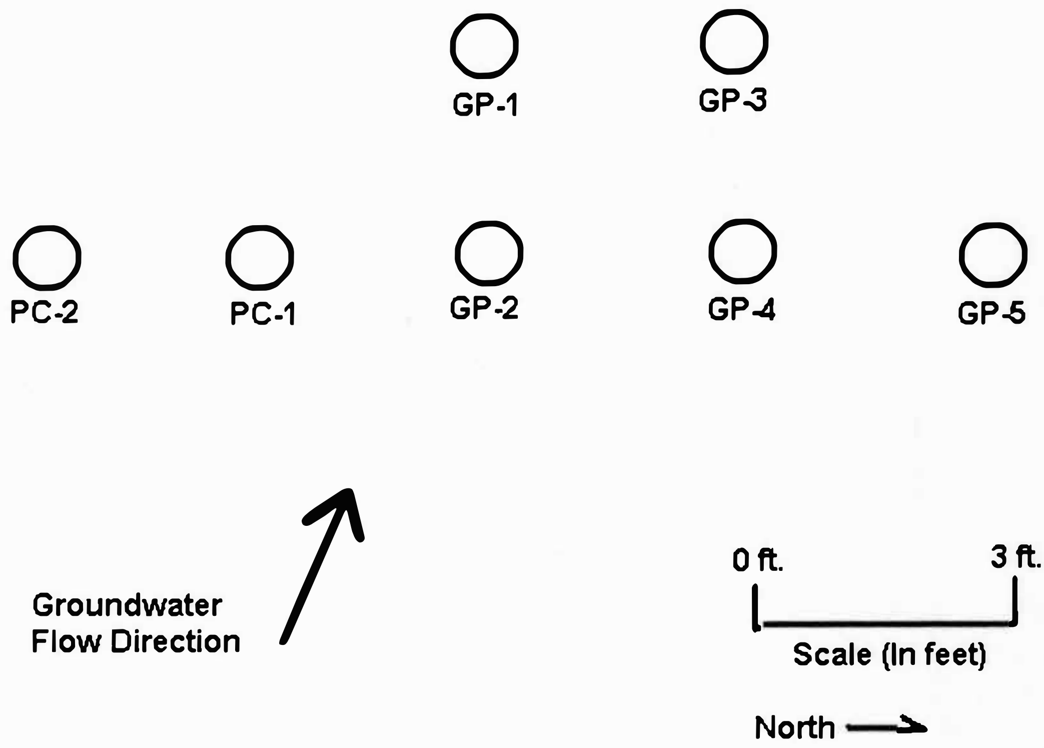
Appendix G

12/40--Teflon Mix--Grain Size Analysis


12/40--teflon Mix--Grain size Analysis
Cumulative Per Cent Retained
100
90
80
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Slot Opening and Grain Size (mm)

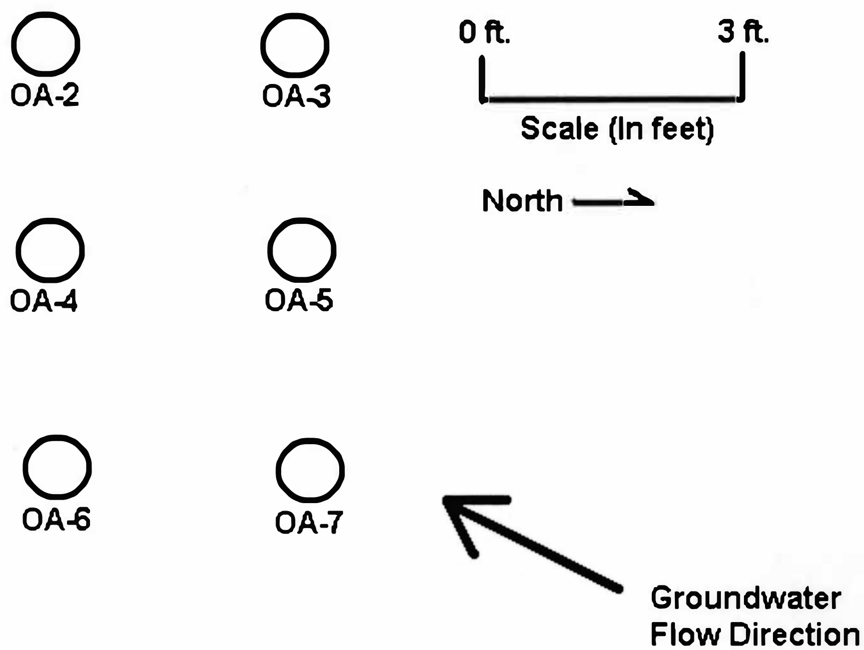
Appendix H

Gravel Pack Well Nest Well Configuration


GP-1
GP-3
PC-2
PC-1
GP-2
GP-4
GP-5
Groundwater
Flow Direction
0 ft.
3 ft.
Scale (In feet)
North

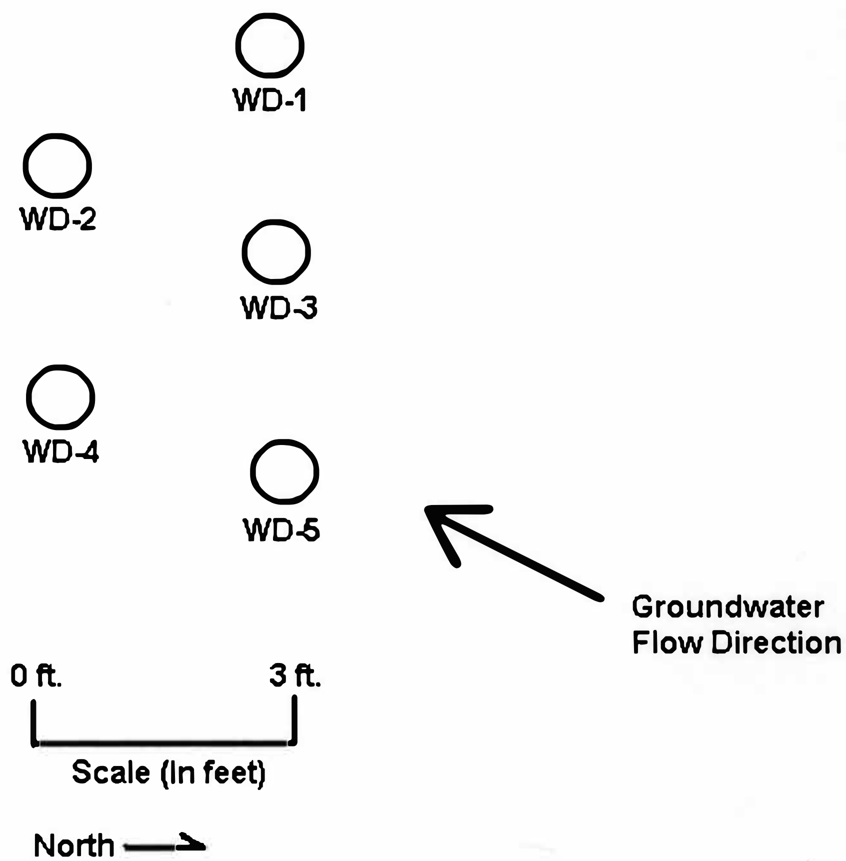
Appendix I

Open Area Well Nest Well Configuration


OA-2
OA-3
0 ft.
3 ft.
Scale (In feet)
North
OA-4
OA-5
OA-6
OA-7
Groundwater
Flow Direction

Appendix J

Well Development Well Nest Well Configuration


WD-1
WD-2
WD-3
WD-4
WD-5
Groundwater
Flow Direction
0 ft.
3 ft.
Scale (In feet)
North

Appendix K

Data From Laboratory Experiment

Control--untreated 10/20		Resin coated 20/40		Treated 10/20	
Time (min)	***Product Thickness (cm)***	***Time (min)***	***Product Thickness (cm)***	***Time (min)***	***Product Thickness (cm)***
0.00	0	0.00		0.00	0
12.00	0.1	14.75	0.1	14.75	0.1
17.62	0.8	18.07	1	18.70	0
19.52	1.7	20.10	2.6	20.53	0.5
21.15	1.8	21.55	3.3	22.08	0.9
22.63	2	23.30	4.4	23.95	1.5
25.65	2.3	25.23	5.9	26.82	2.2
28.97	2.7	29.77	7.9	30.68	3.3
32.87	3.3	33.63	8.9	34.40	4.3
36.10	4.1	36.80	10.1	37.55	5.4
40.73	4.3	41.60	11.9	42.30	6.4
49.42	5.4	50.13	13	50.97	8.1
58.90	5.9	59.75	15.1	60.48	9.1
78.83	6.9	80.08	17.4	81.83	10.7
120.08	9.5	122.48	20.7	123.92	14.3
191.50	11.1	192.67	22.7	194.00	17.2
294.00	12	295.33	24.1	296.50	19.2
431.00	12.5	433.00	25.7	436.00	20.8
1603.33	13.7	1604.83	28.4	1606.17	23.2
3194.33	13.7	3195.33	29	3196.50	23.9
4061.00	13.8	4062.38	28.9	4063.60	24
4575.00	13.9	8896.00	29.3	8897.00	23.6
10364.00	14	10366.00	29.3	10367.00	23.8
18987.00	14	18988.00	29.1	18990.00	23.9
29127.00	14	29128.00	28.4	29129.00	23.7
60640.00	13.7	60640.00	26.2	60640.00	23.1

Appendix L

Data From Filter Pack Experiment

GP-1 7 slot natural pack		GP-2--10/20 sand 20 slot		GP-3 Red Flint Teflon 50/50 mix		GP-4 70/80 Red Flint		GP-5 12/40 sand/Teflon mix	
Elapsed Time *(min)*	**Product Thickness** *(cm)*	**Elapsed Time** *(min)*	**Product Thickness** *(cm)*	**Elapsed Time** *(min)*	**Product Thickness** *(cm)*	**Elapsed Tim** *(min)*	**Product Thickness** *(cm)*	**Elapsed Time** *(min)*	**Product Thickness** *(cm)*
0	0	0	0	0	0	0	0	0	0
15	0	4	0	32	0	37	0	53	0
57	0	35	0	68	0	62	0	107	0
88	0	58	0	96	0	110	0	151	0
110	0	104	0	142	0	164	0	244	0
154	0	131	0	198	0	208	0	268	0
184	0	176	0	242	0	301	0	299	0
228	0	233	0	333	0	327	0	328	0
291	0	276	0	360	0	357	0	360	0
329	0	368	0	391	0	386	0	976	0
421	0	394	0	419	0	417	0	1053	0
447	0	426	0	451	0	1029	0	1400	0
479	0	454	0	1061	0	1112	0	1508	0
507	0	485	0	1145	0	1339	0	4140	0
538	0	1096	0	1371	0	1457	0	4481	0
1148	0	1179	0	1490	0	1566	0	5592	0.3
1232	0	1406	0	1599	0	4196	0	7073	0
1458	0	1525	0	4235	0	4539	0	8635	0
1577	0	1634	0	4572	0	5650	0	11790	0
1687	0	4275	0.2	5682	0	7130	0	15724	0.3
4327	0.3	4607	0.3	7163	0	8690	0	24387	0.8
4659	1.1	5719	0.5	8722	0	11849	0	34447	1.7
5772	0.4	7197	0.4	11881	0	15782	0	44449	2.7
7250	0.3	8755	0.3	15805	0.2	24445	0	55950	6.2
8804	0.1	11915	0	24477	0	34505	0	73128	6
11966	0.2	15850	0.1	34537	0	44505	0	91852	11.9
15903	0.3	24512	0.1	44536	0	56008	0.1	135087	16
24565	0.3	34571	0.5	56041	0.1	73185	0		
34623	0.4	44569	0.2	73217	0	91910	0		
44619	0.2	56075	3.2	91942	0.1	135147	0.1		
56127	0.8	73252	3.3	135183	0.1				
73312	0.4	92037	12						
92030	0.6	135227	18						
135282	0.7								

Appendix M

Data From Open Area Experiment

OA-7 20 Slot wire-wrapped		OA-6 10 Slot Wire-wrapped		OA-5 6 Slot Wire-wrapped		OA-4 20 Slot Mill-slot		OA-3 10 slot Mill-slot 1/4" spacing		OA-2 7 Slot Mill-slot	
Elapsed Time *(min)*	Product Thicknes *(cm)*	Elapsed Time *(min)*	Product Thickness *(cm)*	Elapsed Time *(min)*	Product Thickness *(cm)*	Elapsed Time *(min)*	Product Thickness *(cm)*	Elapsed Time *(min)*	Product Thickness *(cm)*	Elapsed Time *(min)*	Product Thickness *(cm)*
0	0	0	0	0	0	0	0	0	0	0	0
15	0	12	0	10	0	3	0	8	0	7	0
30	0	29	0	24	0	13	0	13	0	11	0
61	0	44	0	40	0	24	0	25	0	16	0
85	0	75	0	56	0	38	0	36	0	23	0
122	0	98	0	86	0	54	0	50	0	34	0
148	0	136	0	110	0	70	0	66	0	44	0.9
191	0	163	0	148	0	100	0	82	0	58	0.8
255	0	206	0	174	0	124	0	112	0	74	4.6
1418	2.2	272	0	218	0	162	0	136	0	91	1.8
1678	0	1427	0.3	281	0	189	0	173	0	121	3.2
1695	2.4	1697		1444	0.6	232	0	200	0	145	4.6
1747	2.8	1712	0.6	1711	0.5	294	0	243	0	181	5.2
2918	4.1	1763	0.3	1727	0.6	1453	0.4	307	0	208	7.3
4367	4.3	2934	0.5	1777	0.4	1727	0	1471	0.3	252	5.8
5996	4.6	4384	0.5	2948	0.3	1743	1.8	1741	0	316	8.8
9117	3.5	6015	1.1	4396	0	1793	2	1757	0.3	1474	11.6
13057	7.4	9133	0	6031	0.9	2964	6.4	1806	0.2	1753	11.5
21722	6.7	13077	0.7	9148	0.5	4413	7	2978	0.3	1768	10.4
31780	4.4	21736	0.8	13091	0.6	6051	7.1	4428	0.2	1817	11.2
41876	6.9	31798	0.8	21748	0.3	9164	2.8	6066	0.1	2989	11
53283	8	41888	7.7	31812	0.6	13107	8.4	9178	0.1	4437	11.1
70468	7.3	53301	7.4	41895	0.2	21762	9.8	13121	0.1	6078	11.7
89191	7.3	70482	8.4	53315	0.5	31829	9.1	21774	0	9189	10.8
132479	6.9	89207	10.1	70494	0.4	41907	13	31845	0	13133	11.8
		132493	10.2	89221	0.4	53330	10.7	41916	0.75	21783	11.7
				132505	0	71228	9.3	53344	0.6	31856	10.8
						89958	12.3	70520	1	41923	13.6
						132520	5.1	89972	1.1	53356	11
								132532	1.2	71246	11
										89983	14.1
										132540	11.5

Appendix N

Data From Well Development Experiment

Well WD-5 (Bailer only)		Well WD-4 (Overpumping)		Well WD-3 (No Development)		Well WD-2 (Surge Block and Bailer)		Well WD-1 (7-slot No Development)	
Elapsed Time (Min.)	**Product Thickness (cm)**	**Elapsed Time (min)**	**Product Thickness (cm)**	**Elapsed Time (min)**	**Product Thickness (cm)**	**Elapsed Tim (min)**	**Product Thickness (cm)**	**Elapsed Tim (min)**	**Product Thickness (cm)**
0	0	0	0	0	0.1	0	0	0	0
13.99999999	0	14	0.1	3.00000001	0.1	13.99999999	0	19.99999999	0.1
41	0	42	0	14	0.5	29.99999999	0	45	0.1
96	0	98.00000001	0	41.00000001	0.5	41	0	103	0.3
130	0	130	0.1	97	1	101	0.1	134	0.9
166	0	168	0	128	2	131	0	172	0.9
1366	0	1365	0.6	166	1	169	0	1368	0.7
2804	1.1	2803	0.5	1365	1.7	1364	0.3	2807	0.3
4460	3.8	4456	0.8	2803	1.1	2802	0.1	4455	0.9
7552	6.5	7371	0.4	4455	1.5	4451	0	7555	4.5
11495	18.9	11494	1	7551	1.3	7551	0	11499	6.6
20152	19.5	20153	0.5	11493	1.7	11495	0	20156	13.9
30222	17.7	30221	0.6	20152	1.3	20147	0.1	30225	12.4
40327	16.1	40324	9.4	30220	4.2	30220	0.1	40321	19.7
51721	18.1	51720	11.3	40322	5.7	40320	0	51722	17.3
68902	18.6	69621	11.9	51720	10.5	51720	0.1	68904	17.1
87629	25.2	87629	11	68901	13.2	68900	0.1	87632	13.4
130906	14.6	130906	8.5	87629	19.9	87626	0.1	130912	12.4
				130906	14.3	130906	0.1		

Appendix O

Data From Plume Comparison Experiment

PC-1 7 Slot Mill-slot		PC-2 10 Slot Mill-slot	
Elapsed Time *(min)*	Product Thickness *(cm)*	Elapsed Time *(min)*	Product Thickness *(cm)*
0	0	0	0
22	0	55	0
75.0	0	149	0.7
169	0	173	2.7
193	0	202	4.4
223	0	231	2.3
251	0	263	4.5
284	0	889	28.4
909	2.7	947	32.2
978	2.4	1185	38
1205	8.1	1305	39.9
1325	10.3	1412	42.7
1432	13.1	4050	45.8
4071	24	4383	46.4
4405	25.7	5495	51.5
5516	29.9	6977	45.8
6997	32.8	8543	48.1
8560	37.1	11693	40.5
11714	34	15628	44.3
15649	36.9	24291	41.2
24312	35.1	34351	39.4
34372	35.9	44357	50.7
44375	46.4	55855	44.1
55877	39.3	73031	41.8
73052	28.2	91756	35.3
91778	32.3	135002	32.3
135025	28.5		

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