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AN EVALUATION OF METHODS TO DETERMINE THE THICKNESS OF FREE PRODUCT IN A SHALLOW WATER TABLE AQUIFER

by

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AN EVALUATION OF METHODS TO DETERMINE THE THICKNESS OF FREE PRODUCT IN A SHALLOW WATER TABLE AQUIFER

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Western Michigan University, 1996

Estimates of the volume of recoverable free phase petroleum product in soils are frequently based on poorly understood empirical methods. These methods, in the form of field tests and/or equations, require simplifying assumptions and apparent product thickness to calculate the thickness or specific volume of free phase product. The purpose of this study was to compare the available methods against each other to cross validate them.

The field methods evaluated at a well with an apparent product thickness of 1.69 feet were: Yaniga's bailer test, split-spoon soil sampling, a test pit excavation and a new tool developed for direct measurement of the free phase product thickness in the soil. Equations proposed by Schiegg, Parker and Lenhard, Hall et al. and CONCAWE were also evaluated.

The results of the evaluation showed that Yaniga's bailer test, the modified CONCAWE equation, sampling soils from a test pit, and the new tool produced comparable results of approximately 0.5 feet thickness.

TABLE OF CONTENTS

Table of Contents--Continued

LIST OF TABLES

LIST OF FIGURES

List of Figures--Continued

CHAPTER I

INTRODUCTION

Background

Despite decades of industry experience in recovering spilled hydrocarbons (product) from the subsurface (e.g., Williams and Wilder, 1971), many of the methods used to determine the amount of spilled product in the subsurface sediments are strictly empirical, and are poorly understood. One reason that these methods are poorly understood is the increased complexity once free phase product is added to the system of sediments, air, and water. For example, the standard approach for determining the extent of free product in the subsurface sediments at a contamination site is to install monitoring wells with their screen intervals set to straddle the water table. Free phase product is then allowed to accumulate in the well and the thickness measured. Since it is generally well known that the petroleum product thickness measured in a monitoring well greatly exceeds the "actual thickness" in the surround subsurface sediments (e.g., Hampton and Miller, 1988), various direct and indirect methods in the form of field tests and/or equations are then applied to estimate the actual thickness or more appropriately specific volume from the thickness in the monitoring well. None of these methods has been shown to work in a controlled laboratory experiment or in a comparison test; yet costly remedial actions are often based upon the results of these unproven methods.

Previous Investigations

Some authors reported measuring the "actual" product thickness at field sites. Yaniga (1982) and Yaniga and Demko (1983) gave actual thicknesses determined using a bailer test, but the details of this method were not given. Yaniga (1984) described a core analysis technique to determine the location of hydrocarbon-contaminated sediments. Gruszczenski (1987) described a bailer test which is supposed to measure the actual thickness. Hughes, Sullivan and Zinner (1988) presented several methods, including a bailer test, a recovery well recharge test, and sediment coring of the aquifer. Kimberlin and Trimmell (1988) used an optoelectronic sensor down a well to determine the depth at which hydrocarbon droplets were entering the well screen. Keech (1988) used a dielectric well logging tool to measure the hydrocarbon thickness in formations. None of these papers report an actual product thickness measured in the field by more than one method simultaneously.

Various techniques have been used to calculate or estimate the thickness of the free product layer at a spill site. Several authors have formulated equations relating the apparent product thickness measured in a monitoring well with the actual thickness in the surrounding soil. Hampton and Miller (1988) found that none of the equations worked correctly for all of the laboratory experiments they reported, but that the Schiegg (1985) equation worked well in some cases and the CONCAWE (1979) equation produced an estimate with the proper order of magnitude. Hampton (1988, 1989) reported that the Lenhard and Parker (1990) approach worked well for these laboratory tests, but that conclusion was based on an incorrect assumption about their method which offset the values by a factor of 1.0/(porosity). Hence, none of these indirect methods could be trusted in the field without further validation.

Purpose

The purpose of this study is to evaluate the existing field methods and equations for estimating the thickness or specific volume of free phase product in soils from apparent product thicknesses in monitoring wells. Each of the methods was evaluated for accuracy, reliability, and practicality. The identification of a method or methods with these attributes will reduce the cost, time, and uncertainty associated with the free product recovery phase of remediation as well as facilitate research efforts in this area.

Scope

Four field methods for detecting and measuring free phase product were evaluated and compared in the vicinity of monitoring well No. 18 during the first of two field investigations conducted during the summers of 1988 and 1989 (see Figure 1). The methods evaluated during the first field investigation were Yaniga's bailer test, Gruszczenski's bailer test, soil sampling and analysis via split-spoon sampling, and soil sampling and analysis via a test pit excavation. Apparent product thicknesses obtained from measurements taken during the investigation were used to evaluate the CONCAWE, Schiegg, and Lenhard and Parker (1990) equations. After observing the inadequacies of some of the methods used during the first field investigation, the scope of the investigation was expanded to include the design, development, and testing of a new tool capable of taking a direct free phase product thickness measurement from the soils above a shallow water table. The new tool, dubbed the reconnaissance probe, was tested during the second field investigation along with Yaniga's bailer test, and soil sampling via a test pit excavation. Soil sampling via split-spoon sampling was not

Figure 1. Site Map.

included during the second field investigation due to its poor performance. The CONCAWE, Schiegg, and Lenhard and Parker's equations were also evaluated using apparent product thicknesses obtained during the second field investigation.

Site Description

Geology

The site is located in a rural farming area on a field with relatively flat topography. The surficial sediments to a depth of 60 to 65 feet consist of unconsolidated, thin to thick beds of silty, medium to coarse sands mixed with discontinuous thin lenses of fine to coarse gravel. These surficial sediments are believed to be primarily of glacial fluvial origin and were deposited on an outwash plain during the Wisconsin in glacial stage.

Hydrogeology

Ground water occurs under water table conditions approximately 6 to 10 feet below ground surface. Prior to the initiation of free phase product recovery the ground water flow direction at the site was west-southwest towards the St. Joseph River under a hydraulic gradient of approximately 0.0006. Hydraulic conductivities calculated from a pump test range from 0.01 to 0.001 cm/sec. Minor water table elevation fluctuations occur locally due to pumping for irrigation.

Environmental History

A release of petroleum distillates was reported at the site in mid 1987. The release occurred in the subsurface above the water table from a pipeline used to

transfer light petroleum distillates. An undetermined amount of light petroleum distillates was released; however, the volume released into the subsurface is estimated to be on the order of 1 million gallons.

As is the standard response to a release of product into the subsurface, many soil borings and monitoring wells were installed to delineate the lateral extent of the free phase product floating on top of the capillary fringe of the water table. Monitoring wells No. 17, No. 18, and No. 19, were installed at the northwestern portion of the site to determine the direction and extent of free phase product migration in that area. Each of these monitoring wells was installed to a depth of 12.5 feet below ground surface and constructed with 2-inch PVC casing and 9 foot long 2-inch diameter 0.010-inch mill-slotted PVC screens. The screen interval for each screen was set to straddle the water table.

As part of the on-going remediation efforts being conducted at the site, three 24-inch diameter recovery wells equipped with oil skimmers were installed to recover the free phase product. A water treatment system employing carbon-filtration was built at the site to remove hydrocarbon contamination from the ground water collected during the free phase product recovery operation.

CHAPTER II

METHOD EVALUATION

Field Investigation 1988

In the late summer of 1988 a field investigation was conducted adjacent to monitoring well No. 18 to measure the free phase product thickness in the soils. At the beginning of the investigation and prior to collecting a round of apparent product thicknesses, a comparison of the methods used to measure apparent product thickness was conducted at monitoring well No. 18. The comparison test included electronic product measuring devices from two manufacturers, a clear bailer, and a weighted tape with hydrocarbon and water indicator pastes. Upon completion of the comparison test, soil sampling at discrete depth intervals via split-spoon soil sampling and a test pit excavation were evaluated. Bailer tests were also performed at monitoring wells No. 17 and No. 19, located in close proximity to monitoring well No. 18. Data obtained during the field investigation was also used to evaluate the equations proposed by CONCAWE, Schiegg, Lenhard and Parker, and Hall et al.

Apparent Product Measurements

Apparent thickness measurements were taken in monitoring wells No. 17, No. 18 and No. 19. Three devices were used to collect measurements and the results compared to the indicator paste on tape method to determine the most accurate device.

The first device tested was the Oil Recovery Systems (ORS) interface probe

7

(see Figure 2). This electronic device determines the position of the two fluid interfaces based on the optical and electrical resistance characteristics of the three fluids (air, product, and water). The infrared optical component of the system detects the air/product interface and the resistivity component of the system detects the product/water interface. The ORS probe is lowered into the monitoring well until it comes into contact with the first fluid interface. Depending on which interface is encountered the probe issues a select audio signal consisting of a series of beeps. If product is present in the well, the probe is lowered further until the audio signal changes. The measurements taken when the audio signal begins and changes are used to calculate the apparent product thickness in the monitoring well.

Figure 2. A Photograph of the ORS Probe.

The second device tested was the Keck probe. This electronic device uses the fluid density and resistance to detect the two fluid interfaces. A float is used to determine the top of fluids interface and electrical resistance is used to measure the product/water interface elevation. The interface elevations are collected based on different audio signals in a similar manner to the ORS probe.

The third device used in the comparison test was the ORS clear acrylic bailer. To measure the apparent product thickness, the bailer is lowered slowly into the monitoring well to allow the product to flow into the bailer without displacing large amounts of the product out of the well and into the formation. The bailer is then retrieved rapidly and the apparent product thickness measured visually from the bailer.

The fourth device was a weighted fiberglass tape coated with product indicator on one side and water indicator paste on the other side. The indicator pastes react with their respective fluids to show the air/product and product/water interfaces by color changes. Although it is messy and inconvenient, this is the most direct measure of product thickness in a well and was assumed to be the most accurate measurement. It was determined from this test (see RESULTS section) that the ORS interface probe produced the most accurate results when compared to the fiberglass tape and indicator paste method. Subsequently, the ORS probe was used for all of the apparent product measurements and bailer tests.

Bailer Test

One of the methods frequently cited for measuring actual free phase product thickness in the soils above the water table is the bailer test. There are many different bailer test methods. They are used because in most cases they are quick and easy to perform and they report a smaller free phase product thickness than the apparent

thickness observed in the monitoring well. However, the use of bailer tests to determine the "actual" free phase product thickness in soils has not gained total acceptance primarily because there is no published basis clearly explaining why or how they work. Gruszczenski (1987) has documented his approach. Yaniga and Demko (1983) briefly refer to their method.

The bailer test procedure used during the field investigation consisted of rapidly bailing product from the monitoring well without removing large quantities of water as shown in Figure 3. The bailing was continued until the product thickness in the bailer reached a minimum. The air/product and product/water interface elevations in the monitoring well were then measured using the ORS probe until they nearly recovered to their starting elevations.

Yaniga and Gruszczenski have different ways of analyzing the resulting data. Yaniga (personal communication, 1988) suggests plotting the air/product and product/water interface elevations versus log time. Two straight lines are fit to the product/water interface curve. The product thickness observed in the monitoring well at the time where the fitted lines intersect is taken to be the "true" free phase product thickness in the soils.

Gruszczenski (1987) suggests plotting the top of product (air/product interface) and product/water interface elevation versus time. He observed that one of two types of curves is produced by plotting the data in this manner. Type 1 curves show a rising top of product and product/water interface and is typical of a soil type with coarser particle size distribution and therefore smaller capillary fringe. The "true" product thickness for Type 1 curves is the apparent product thickness measured in the monitoring well. The Type 2 curves obtain a maximum height (minimum depth) during the early portion of the oil/water interface recovery. He suggests that for Type

2 curves the product thickness observed in the monitoring well at the time of the maximum height is the "true" free phase product thickness in the soils.

Figure 3. A Photograph of the Bailer Test Procedure.

Split-spoon Soil Sampling

The objective of the split-spoon soil sampling was to collect soil samples at depth intervals corresponding to top, middle, and bottom of the free phase product

zone. Continuous split-spoon soil sampling was conducted from the ground surface to directly below the water table elevation using Western Michigan University's (WMU) drill rig as shown in Figure 4. Soil samples were collected from each split-spoon at various intervals as small as 2 inches for laboratory analysis as shown in Figure 5. The soil samples collected for analysis were sealed in an appropriate air-tight containers,

Figure 4. A Photograph of the WMU Drill Rig.

cooled with ice, and transported to Western Michigan University for laboratory

analysis. Each soil sample was analyzed for total petroleum hydrocarbons (TPH) using the Soxlet extraction method and infrared spectroscopy. This analysis is only semi-quantitative because roughly one-half of the more volatile hydrocarbons is lost during the extraction process.

Figure 5. A Photograph of the Split-spoon Sampling.

Test Pit Excavation Soil Sampling

The test pit method consists of excavating a test pit to just below the water table elevation, collecting soil samples at discrete depth intervals from the side wall and base of the pit, and analyzing the soil samples for TPH. A pit was excavated with a backhoe on 9/1/88 approximately 10 feet west of monitoring well No. 18 as shown in Figure 6. The depth to the fluid surface from the ground surface was determined by

dropping a plumb line from a board stretching across part of the excavation.

Figure 6. A Photograph of the Test Pit Excavation.

Soils from the pit walls were sampled the next day with a thin 2 foot length of metal tube which was driven approximately one foot into the side wall to collect the soil sample as shown in Figure 7. The soil in the metal tube was then extruded into a small vial with an air tight seal. Soils below the fluid surface were sampled vertically with a split-spoon sampler driven by hand and immediately inverted upon withdrawal to prevent spreading of hydrocarbons.

Figure 7. A Photograph of the Test Pit Excavation Sample Collection.

Apparent Product Equations

Equations proposed by CONCAWE, Hall, Schiegg, and Lenhard and Parker, were evaluated at monitoring well No. 18. During the field investigation, two sets of soil samples were collected from the vicinity of monitoring well No. 18 to calculate the soil properties for the Schiegg, and Lenhard and Parker equations. One set by well No. 18 was collected during the split-spoon soil sampling and the other by hand augering to a depth of approximately 6 feet below ground surface next to well No. 19. These soil samples were then used to estimate two sets of the parameters required in the above equations. The formation factor for the Hall equation was derived by grain size analysis of both sets of soil samples collected and then applying the appropriate formation factor obtained from Hall et al. (1984). The soil retention parameters

required for the Schiegg (1985) and Lenhard and Parker (1990) equations were estimated using Parker's software program SOILPROP. The saturated thickness corresponding to the specific volume from Lenhard and Parker's equation was estimated assuming a porosity of 40% and a product saturation of 70%. The reader is referred to Hampton and Miller (1988) or Hampton (1989) for a more detailed description of the theory and application of the previously mentioned equations.

The New Tool

The new tool, dubbed the reconnaissance probe, was designed primarily to avoid the limitations of the methods evaluated during the first field investigation. The primary limitation of most of these methods is they are indirect measurements of a very complex system involving multiphase flow. The assumptions concerning the characteristics of multiphase flow and/or the soil parameters necessary to apply these methods often can not be met or limit the accuracy of the results. Direct methods, such as soil sampling via split-spooning and test pit excavations, are expensive, time consuming, and not always feasible. The reconnaissance probe is designed to be operated without a drill rig by one or two people to obtain direct measurements of the free-phase product zone from shallow water table aquifers.

Design

The reconnaissance probe is designed to delineate the saturated floating product zone by the combination of two systems. The first system employs two electrodes of dissimilar metals and a voltage comparator circuit, to locate the capillary fringe based on the soil moisture content. The second method, used to measure the free-phase product thickness, is a hydrocarbon-sensitive indicator strip extending

along the length of the probe. By locating the probe in the proper position above the capillary fringe using the first system, the second system can be used to measure the thickness of free-phase product as shown in Figure 8.

The first system consists of a small piece of insulated brass which forms an electrode near the tip of the probe. The stainless steel of the drive point is used as the second electrode. Both electrodes are connected to a comparator circuit by a series of holes and channels cut into the drive point as shown in Figures 9 and 10.

The presence of moisture in the soil creates a redox reaction between the metal redox pairs in the soil and/or groundwater and the drive point. As the reaction proceeds in the presence of saturated soils, ions at the electrodes are consumed and form a electro-chemical gradient. The movement of ions in response to the electro-chemical gradient between the electrodes forms a galvanic cell. As the soil moisture content increases, the abundance of ions and their ability to migrate towards the electrodes increases; therefore the output of the galvanic cell also increases. Based on the laboratory results the galvanic cell formed between the electrodes is capable of producing a voltage of 0.6 volts in a fully saturated sand.

Another type of current in addition to the above diffusion current is produced when the probe is driven through moist sediments. This is the result of the movement of water introducing an additional source of ions to the electrodes. This phenomenon is termed a convection current and can be observed by stirring the probe when it is submerged in water and connected to a volt-ohm meter (VOM). The result of the stirring is a surge in the output of the galvanic cell as the speed of stirring is increased.

Figure 8. Probe Application Schematic.

Figure 9. The Reconnaissance Probe Components.

The combination of the two previously mentioned phenomena should in theory allow for the detection of the capillary fringe by a comparator circuit. By calibrating the comparator circuit to a reference voltage obtained from a desired moisture content, a warning can be issued when that soil moisture content is exceeded.

The second system is used to measure the product thickness. It consists of an oil and organic solvent sensitive indicator strip running along the length of the reconnaissance probe (see Figure 9). The hydrocarbon indicator is constructed from a dimethylsiloxane-based polymer and a hydrophobic blue dye. The polymer is permeable to hydrocarbons but not to water. Hydrocarbons in contact with the indicator strip will diffuse into the polymer and dissolve the dye causing a change in

Figure 10. Probe Design Schematic.

color intensity on the indicator strip. By changing the composition of the indicator strip the color change can be delayed to allow the indicator strip to pass through the free-phase product zone without immediately reacting. When the indicator strip is removed from contact with the hydrocarbons, the hydrocarbons which have diffused into the indicator volatilize causing the color to revert to its original intensity.

Laboratory Testing

A series of laboratory experiments was conducted to test the components and predict the performance of the reconnaissance probe in the field. Although these experiments were only qualitative in nature, they were useful for determining if the application would be successful and provide insight to potential problems which might be encountered during the field investigation. These experiments were performed in a large 4 ft x 4 ft x 1 ft sand tank as shown in Figure 11 and two 3-ft tall, 6-inch diameter acrylic cylinders sealed on the bottom. Each container was packed with either coarse or fine sand, or a mixture of the two. A quantity of water sufficient to fully saturate the column was added and allowed to equilibrate.

The water level was then lowered for the addition of kerosene and allowed to equilibrate again. After a sufficient capillary fringe developed, between 700 and 800 ml. of kerosene mixed with a fluorescent dye was added to the acrylic columns. Nine liters of kerosene mixed with a blue dye was added to the sand tank. After the kerosene in the columns reached equilibrium, its upper and lower boundaries were marked using a wax pencil and a fluorescent light.

Figure 11. A photograph of the Large Sand Box.

In addition to the reconnaissance probe, several smaller versions were constructed for use in the laboratory. These laboratory probes were constructed using 1/4-inch diameter stainless steel rods 3 feet in length. The indicator and electrodes were placed on these probes in a similar manner to the reconnaissance probe (see Figure 12). The first step in the experiments was to check the electronics and then calibrate the probe to a reference soil moisture. A continuity check was performed to eliminate potential short circuits of the electrodes. The probe was then connected to a VOM meter and placed in a container of water. The voltage was observed and the probe removed and dried. It was then calibrated to a previously saturated soil sample obtained from the soil column that had been allowed to drain for a short period of

time. The comparator circuit alarm was then set slightly above the point where the alarm sounded in the partially saturated soil sample. The probe was then driven into the column until the alarm sounded and marked at a reference point at the top of the column as shown in Figure 13.

Figure 12. A Photograph of a Laboratory Equipment.

After the probe was allowed to sit for a period of ten to fifteen minutes it was removed and compared to the hydrocarbon thickness marked on the column. It was concluded from these tests that the electronics were not always capable of locating hydrocarbon-water interface. This may have been due in part to interference from ac electrical sources in the room that caused feedback to occur in the circuit and the alarm to sound prematurely. To prevent the probe from acting as an antenna, a resistor was connected across the inputs of the circuit. At times the resistor interfered

with the probe's performance if an improper value of resistance was selected. When the resistance across the inputs was too low, feedback was merely delayed; when the resistance was too great, the circuit was prevented from receiving a signal and the capillary interface was not detected. The difficulty and uncertainty of calibrating the reference voltage caused the probe to miss the interface in some cases during the laboratory experiments. A filter stage capable of removing interference should be employed to increase the probe's ability to locate the capillary fringe.

Figure 13. A Photograph of Laboratory Experiment.

In an attempt to investigate the ac interference problem, the probe was connected to a VOM to observe the voltage as it was driven into the columns. It was observed that as an impact occurred on the probe a corresponding surge of voltage occurred. As the tip of the probe neared the capillary fringe the surge in voltage

increased beyond the voltage setting for the reference soil moisture. This surge was less abrupt and smaller in magnitude for slightly moist soils and was barely perceptible for soil contaminated with hydrocarbons. The most abrupt and largest amplitudes occurred at or near the hydrocarbon-water interface where the soil was water saturated. Not knowing this may have also contributed to the difficulty in locating the capillary fringe. However, a technique applying the voltage surge phenomenon was used on several occasions to accurately place the probe at the hydrocarbon-water interface in the 6-inch columns. This technique was not as successful in the large tank.

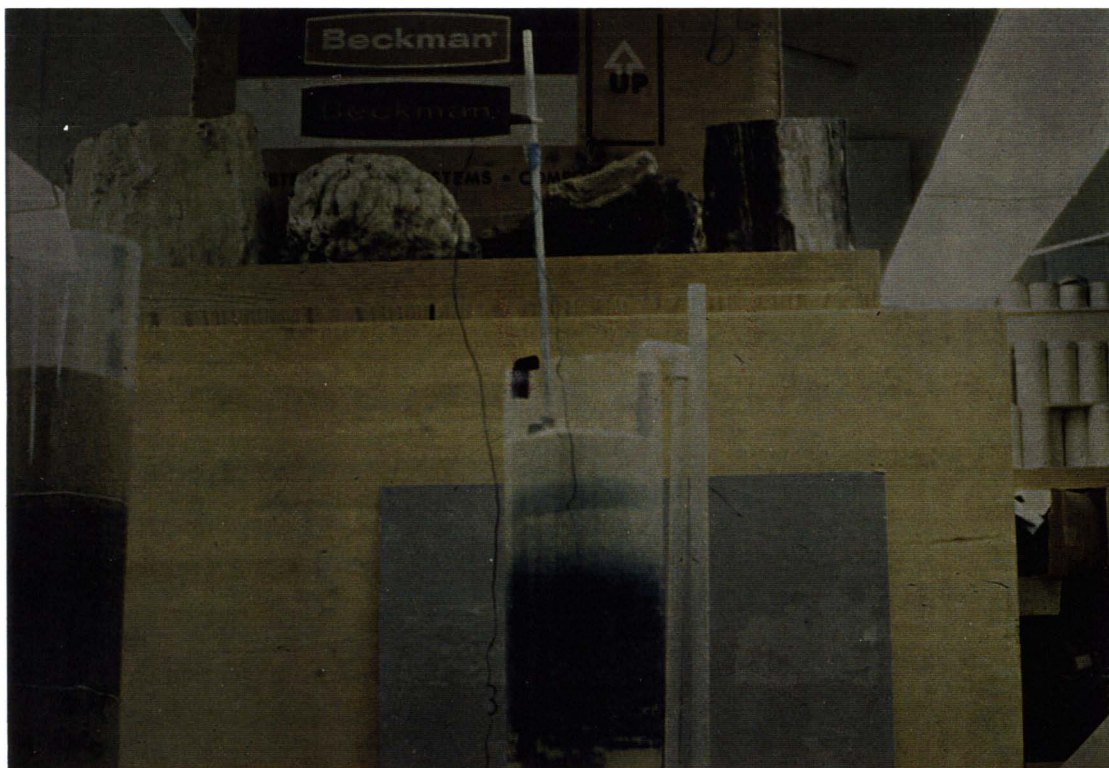The indicator strip gave accurate and reliable measurements of the air/product interface through all of the tests conducted in the 6-inch columns. However, if the water-hydrocarbon interface was overshot due to a failure of the capillary detection mechanism, an exaggerated thickness was measured in the smaller columns. This is probably due to the sediments in the small diameter columns being tightly packed which allowed the build up of hydrostatic pressures during the driving of the probe. The increased hydrostatic pressures would force the mobile product onto the probe and create a color change as it passed through mobile product zone or possibly distort the free-phase product zone. In contrast, during some tests in the large sand tank, the probe produced poor color changes. The lack of color change was attributed to loosely packed sediments in the larger tank which allowed for the creation of an annulus during the driving of the probe. In loosely packed sediments the indicator strip did not make sufficient contact with the sediments. Further tests were conducted in the large sand tank to evaluate the effects of sediment packing.

The sand tank test shown in Figure 13 was a particularly difficult one for the probe. The tank was filled with fine sand with a coarse sand layer in the middle. The water table was in the lower fine sand. When product was added to the top of the

sand, it pooled temporarily on a perched capillary fringe on top of the coarse sand until it penetrated to the fine sand below. The result was a product layer in the lower fine sand above the capillary fringe, with another perched product layer above the coarse sand. The perched layer was fairly thin, however, and in most places appeared to be at residual saturation. When the probe was inserted in the tank, we expected it to change color in both product layers. When it was removed 15 minutes later, the only color change was in the lower portion of the lower layer. That interval is shown in Figure 14 by two black lines marked on the probe. Upon reflection, we concluded

Figure 14. A Photograph of the Large Sand Box Experiment.

that both the upper layer and the upper portion of the lower product layer are oil-air capillary fringes instead of being part of the mobile product zone. This unexpected result calls in question some earlier observations in this sand tank (e.g., Hampton and

Miller, 1988), where similar product layers were included in the actual product thickness measurements.

We reached two conclusions about using the reconnaissance probe during the field investigation. The first conclusion is that the water detection system was not totally reliable. If the comparator circuit failed, it might be possible to use a VOM to detect voltage surges and place the probe at the capillary fringe. In either case, a water level from nearby monitoring wells would be needed to evaluate the free-phase product measuring system. The second conclusion is that the degree of sediment packing could greatly influence the indicator strip's ability to measure the free-phase product thickness. A shim which could adjust the degree of formation contact with the indicator strip was developed for the field investigation.

<div align="center">Field Investigation 1989</div>

In the late summer of 1989 a second field investigation was conducted adjacent to monitoring well No. 18. Apparent product thicknesses measured in monitoring wells No. 17, No. 18, and No. 19 indicated that a small reduction of product thickness had occurred in this area from the last field investigation conducted in the late summer of 1988. Bailer tests were performed on monitoring wells No. 17, No. 18, and No. 19. A test pit for collection of soil samples at discrete depth intervals was excavated approximately 10 feet south of the previous test pit location. After completion of these tasks, the reconnaissance probe was tested 9 times at 4 different locations. A record of the water table elevations compiled over the four day period of the field investigation show the water table to be falling slowly.

<u>Apparent Product Thicknesses</u>

Apparent product thickness measurements were collected from the

surrounding wells using the ORS probe in a manner similar to the 1988 field investigation.

Bailer Tests

Bailer tests were performed on monitoring wells No. 17, No. 18, and No. 19 in the same manner as described for the 1988 field investigation.

Test Pit Excavation Soil Sampling

A second test pit was excavated adjacent to well No. 18 to the northwest. The dimensions of the test pit were approximately 10 x 20 ft. The sample collection method was modified from the one previously used. The pit wall was sampled using prelabeled 4-inch sections of 0.5-inch diameter conduit pipe. These sections were inserted into the pit wall until an adequate sample was retrieved. The ends of the sections were then wiped clean and sealed with rubber corks, bagged and placed in a cooler. Thus, decontamination was not required this time between samples. The soil samples were stored and analyzed for TPH in the same manner as the previous field investigation.

Apparent Product Equations

Apparent product thicknesses measured in monitoring well No. 18 were used with the soil parameters obtained from the first field investigation to calculate the actual free-phase product thickness using the same equations as the first investigation.

Reconnaissance Probe

The reconnaissance probe was tested a total of 9 times during the 1989 field investigation. Six of these tests were conducted at short distances from monitoring well No. 18. One test was conducted half way between monitoring well No. 17 and monitoring well No. 18. The other two tests were next to wells No. 17 and No. 19.

The field procedure for the probe started with the selection of a suitable location for measurement. At this location a continuity check and general inspection of the probe was completed. An indicator strip was placed in its slot and attached to the probe with screws. Two inputs to the ground water detection system were connected to the probe by clips. A drive hammer was positioned on top of the coupling and attached by a bolt functioning as a set pin (see Figure 15). The probe was then driven into the ground approximately 6 to 8 inches. The reference voltage was adjusted to just above the point where a warning is issued from the water detection circuit.

After the initial setup, the probe was driven into the ground until the water detection circuit beeped or the flight was nearly buried. If the circuit issued a warning, the depth of penetration was determined and compared with the expected depth to water as determined from a nearby monitoring well. If the probe was located at the correct depth, it was allowed to sit for approximately twenty minutes. Otherwise, an attempt to recalibrate was made and driving continued. If the end of the flight was reached without a detection warning, an extension flight was connected to the probe and the process was continued as above.

Upon locating the top of the capillary fringe, the reconnaissance probe was left in position for a period of about 20 minutes. The probe was then withdrawn and a measurement was taken from the indicator strip.

Figure 15. A Photograph of the Reconnaissance Probe in the Field.

CHAPTER III

RESULTS

Apparent Product Thickness Measurements

The results of the comparison test between the apparent product thickness measurement methods evaluated during the first field investigation are presented in Table 1.

Table 1

Comparison of Apparent Product Thicknesses
at Monitoring Well No. 18

WELL # AND DATE	EQUIPMENT USED	DEPTH TO PRODUCT (FT)	DEPTH TO WATER (FT)	PRODUCT THICKNESS (FT)
18 8/25/88	Keck probe	9.98	11.95	1.97
	ORS probe	9.98	11.67	1.69
	Keck probe	9.935	10.065	0.13
33B	ORS probe	9.94	10.03	0.09
8/30/88	paste/tape	9.945	10.025	0.08
34 8/30/88	Keck probe	9.765	11.615	1.85
	ORS probe	9.79	11.19	1.40
	Keck probe	10.095	12.045	1.95
18	ORS bailer			1.96
8/30/88	ORS probe	10.04	11.76	1.72
18 8/18/89	ORS probe	10.21	11.59	1.38
	paste/tape	10.20	11.51	1.31

ORS = Oil Recovery Systems

31

The results show a considerable amount of discrepancy between the various methods. One explanation for the difference in these readings is that each device displaces different volumes of oil when placed in the monitoring well. Devices with a large volume displace larger volumes of oil and produced the larger readings when compared to the weighted fiberglass tape. The ORS interface probe is about the size of a 70-ml VOA bottle. The stone used as a weight for the fiberglass tape displaced about 25 ml. The Keck probe is 17 inches long and 1.5 inches in diameter and displaces about 470 ml. (Keck subsequently redesigned the probe and reduced its size, but that model was not tested.) The ORS bailer is about 40 inches long and 1.75 inches in diameter and displaces 490 ml.

The distribution of apparent product thicknesses on August 30, 1988, as shown in Figure 16, forms a lens with the highest apparent product thickness occurring in the area of monitoring wells No. 5, No. 6 and No. 7 adjacent to the road. The thickness decreases more gradually in the direction of ground water flow towards the west and southwest indicating that it has spread more rapidly in that direction. This is probably the result of the regional gradient to the west and drawdown from the product recovery operations being conducted at three wells to the west and south (see Figure 1). The opposite is true for the free product pancake in the easterly direction. The apparent product thicknesses measured in monitoring wells No. 17, No. 18, and No. 19 during the first field investigation were 1.79, 1.72, and 1.79 feet, respectively.

A product sample was collected from monitoring well No. 18 to determine its density. The product density was calculated by adding aliquots of product to a graduated cylinder, weighing it and recalculating the density at each new volume. The product density was taken to be the limiting value from the density calculations. The
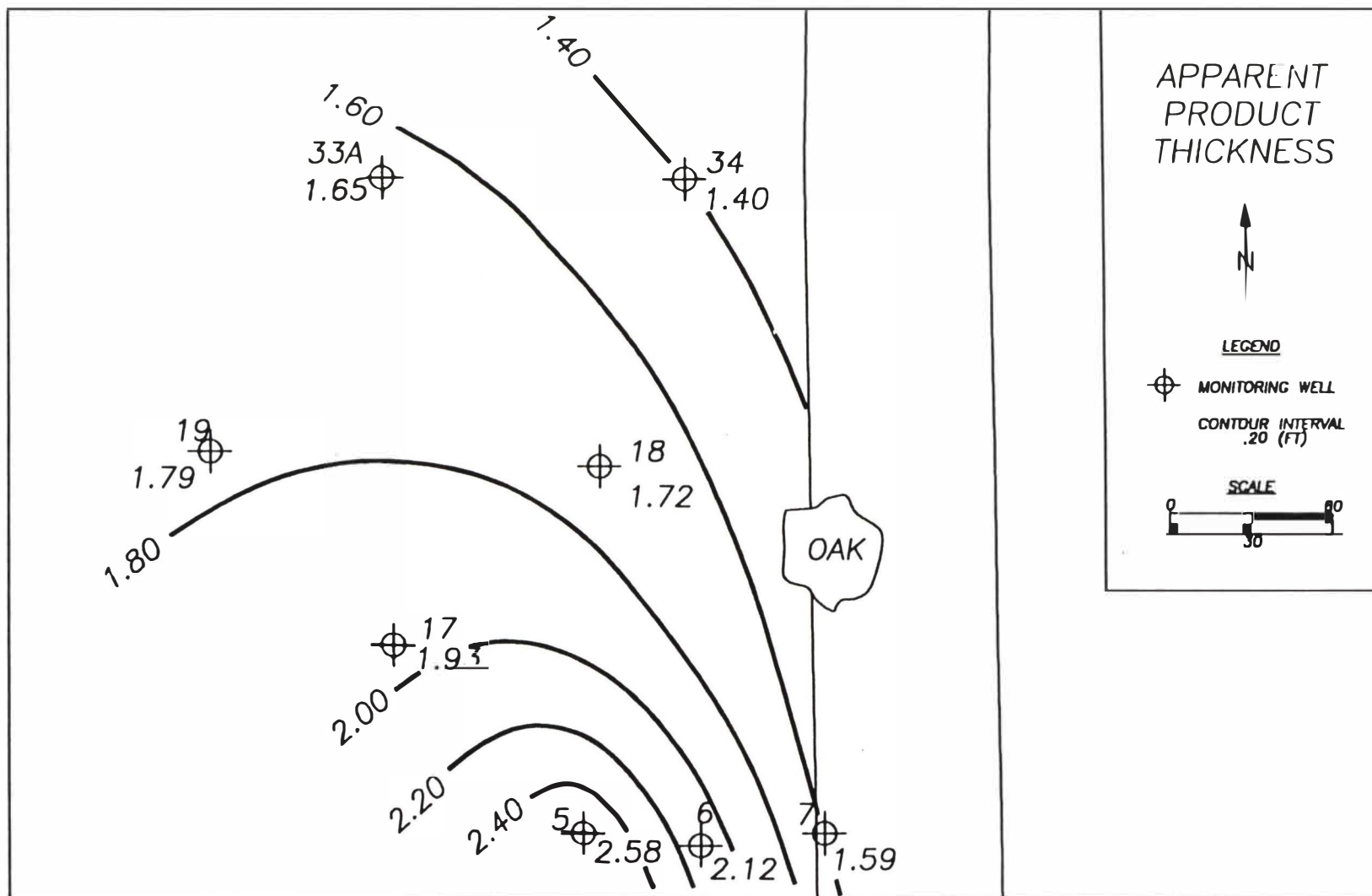
Figure 16. Distribution of Apparent Product Thickness.

density determined by this method was 0.75 grams per ml, characteristic of light hydrocarbons similar to gasoline. This product density was subsequently used for all of the product thickness equations as well as to correct the water table elevations of monitoring wells containing free phase product.

Bailer Tests

The results of the bailer tests performed at monitoring wells No. 17, No. 18, and No. 19 during the first field investigation are shown in Figures 17 through 21. The first bailer test was done at well No. 18 on 8/30/88. The oil-water interface elevation data shown in Figure 17 could be nicely fit by three straight lines, one more than Yaniga prescribed. These lines intersect at more than one point, so it is not clear which thickness is the true value. The intersection point of the two longest lines is at a thickness of 0.71 ft. Due to the ambiguity in interpreting this data set, another bailer test was performed at monitoring well No. 18, together with tests at monitoring wells No. 17 and No. 19, on 9/2/88. All three tests were easily fit by two straight lines (e.g., see Figure 17). The bailer tests resulted in actual product thicknesses of 0.54 ft at monitoring well No. 18, 0.8 ft at monitoring well No. 17, and 0.5 ft at monitoring well No. 19.

The bailer test results at monitoring well No. 18 for the second field investigation are shown in Figure 17. This figure shows the measurements taken from two separate bailer tests conducted on consecutive days. The bailer test results at monitoring well No. 18 appear to be reproducible, while those at monitoring well No. 19 as shown in Figure 22 shows more variation. In neither case, however, are the curves as easy to divide into two or three straight line segments as in Figures 17 and

Figure 17. First Bailer Test Results from Monitoring Well No. 18 8/30/88.
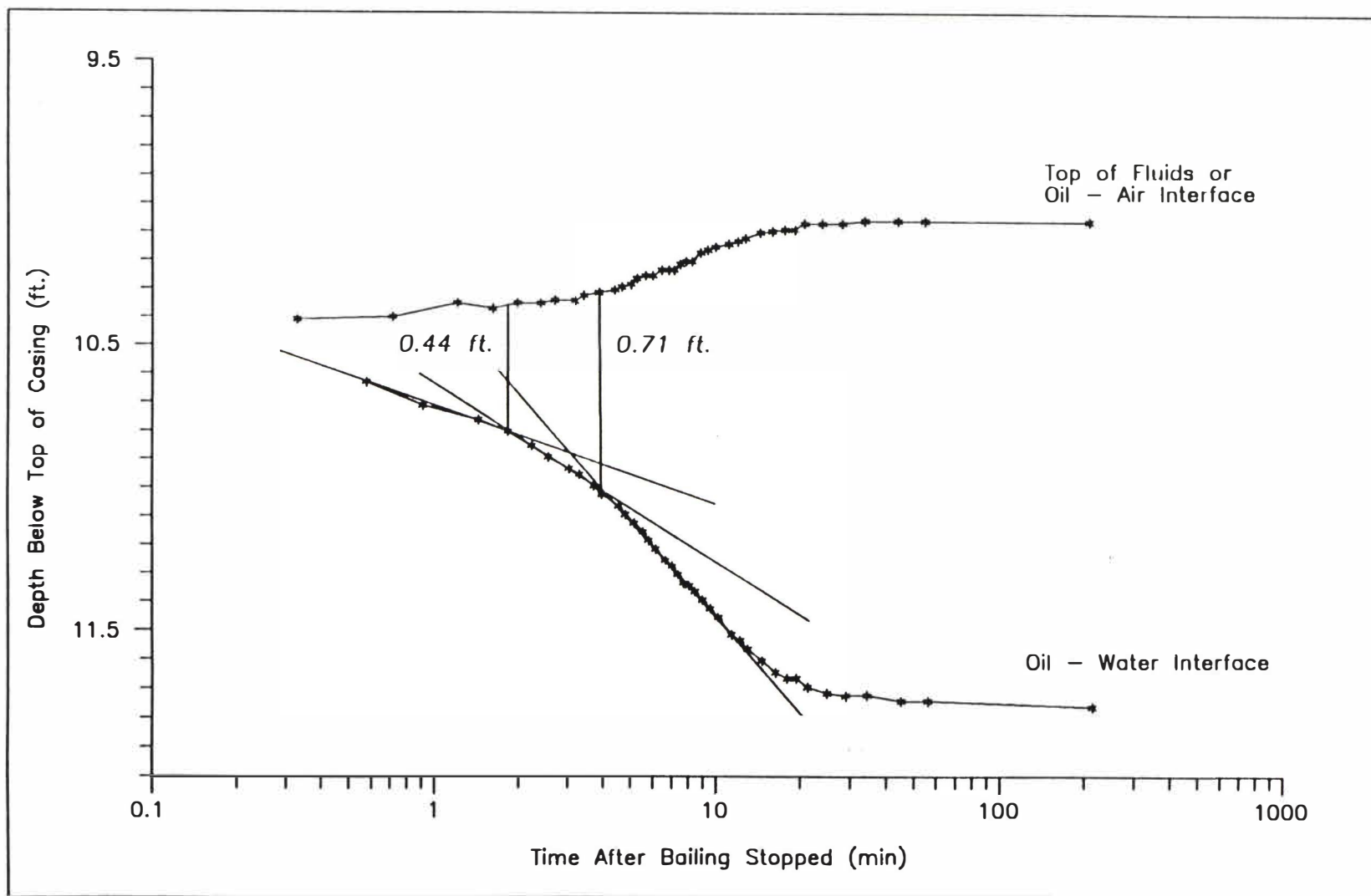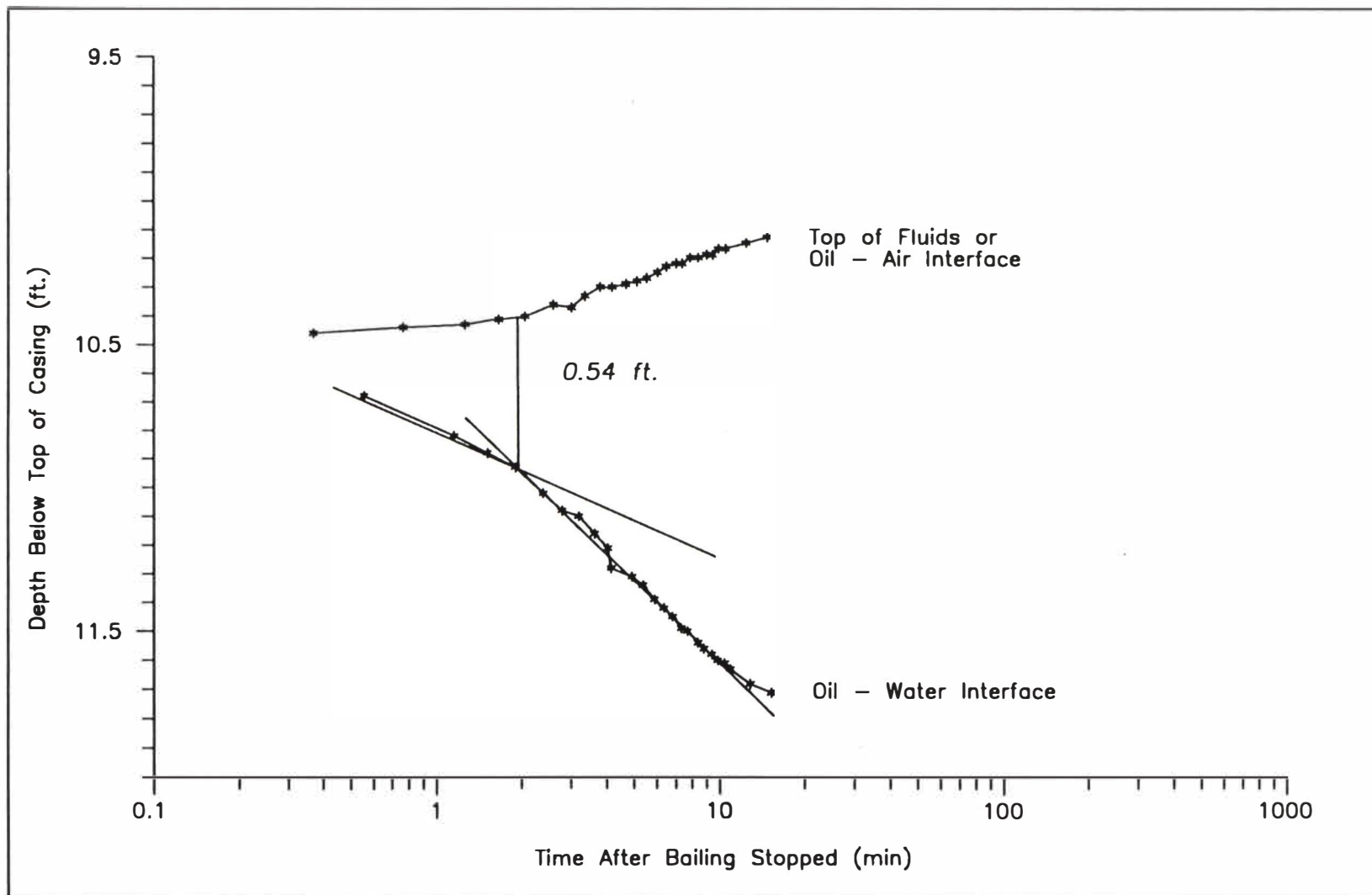
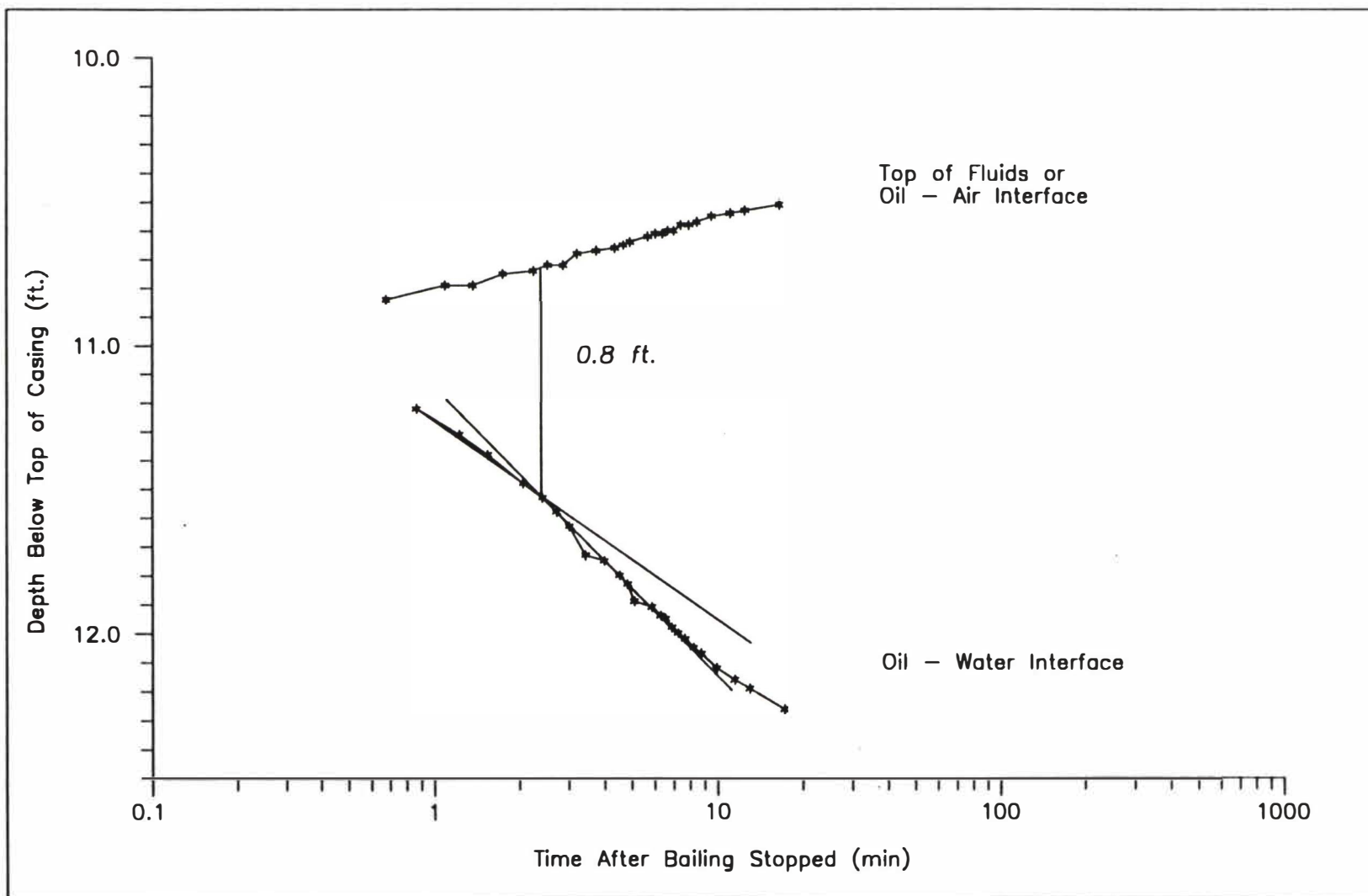Figure 18. Second Bailer Test Results from Monitoring Well No. 18 9/2/88.

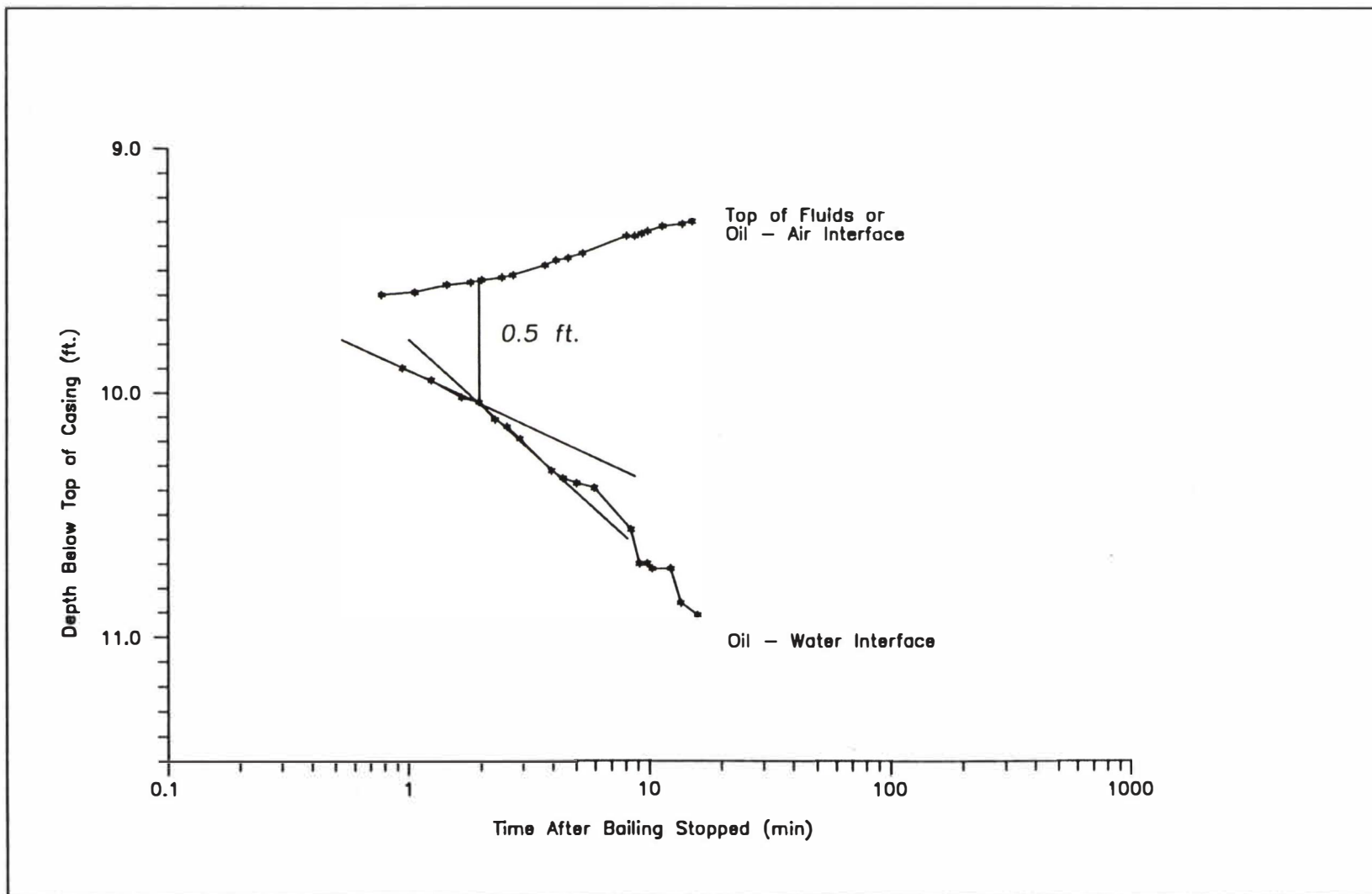Figure 19. Bailer Test Results from Monitoring Well No. 17 9/2/88.

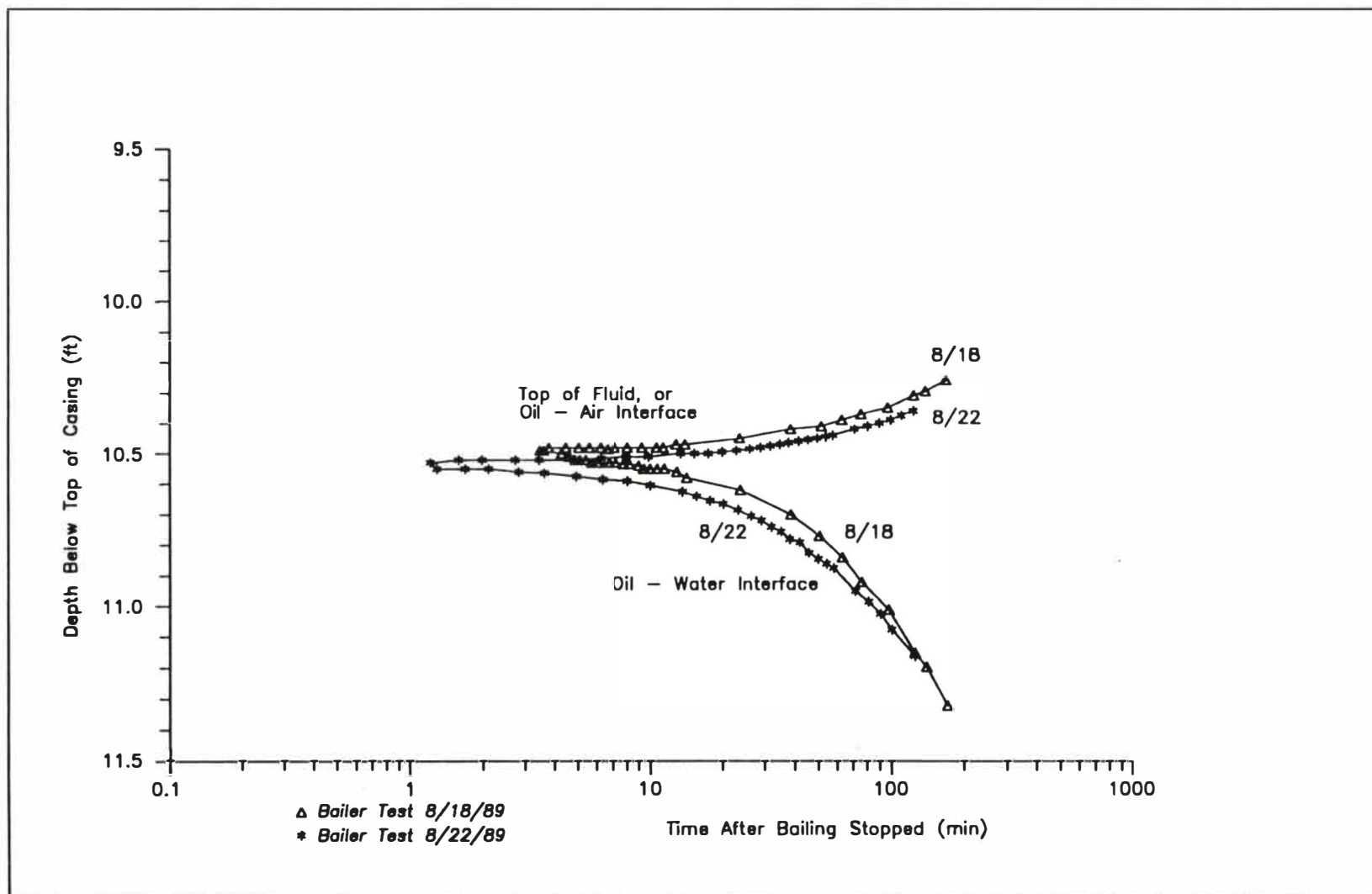Figure 20. Bailer Test Results from Monitoring Well No. 19 9/2/88.

Figure 21. Bailer Test Results from Monitoring Well No. 18 8/18/89 and 8/22/89.

Figure 22. Bailer Test Results from Monitoring Well No. 19 8/18/89 and 8/22/89.

18. In each test for monitoring well 19, the oil-water elevation curve can be divided into four line segments. As in Figure 2, the choice of which thickness is the true thickness is ambiguous. However, since the apparent thickness of 1.74 ft at monitoring well No. 19 is nearly as large as the previous year's value, and is about the same as the previous year's value at monitoring well No. 18, presumably the actual thickness should be about the same. Hence, the thickness which occurred at the intersection between the second and third lines, which varied from 0.525 to 0.55 ft in the two tests, was taken as the actual thickness value.

Split-Spoon Soil Sampling

Coring of the soils directly above and a short distance below the water table and analyzing the soil samples for total petroleum hydrocarbon content would appear to be the most logical way to determine the position and thickness of the mobile product zone. Yaniga (1984) mentions his core analysis method. Hughes et al. (1988) contains an excellent discussion on the pitfalls of coring. Many of these pitfalls were encountered during this field investigation. The results of the soil samples collected from the split-spooning conducted near monitoring well No. 18 are shown in Figure 23. The TPH analysis results of the soil samples are reported as grams of hydrocarbon extracted divided by the original wet weight of the soil. These values are useful as a qualitative gauge of the amount of hydrocarbon present, recognizing that about half of the product is usually lost during the extraction process.

During the split-spoon soil sampling considerable difficulty was encountered while trying to collect representative samples of the various target zones. The sand consolidated considerably during coring, resulting in an average sample retention of

Figure 23. Split-Spoon Sampling Results.

16.5 inches. The consolidation of the sediments probably caused fluids within the soil sample to migrate and destroy any distinct interfaces. Due to the fact that the top of the free phase product zone could only be estimated, we suspect that the spoon taken from the fourth interval may have been driven too far into the free phase product zone. After removing the split-spoon, product was observed draining from the split-spoon into the bore hole. The following split-spoon interval reached the water table after first passing through the product which had accumulated in the borehole. Furthermore, product mixed with ground water was also observed draining from this split-spoon interval. Hence, soil samples collected from the following spoon contained hydrocarbons, particularly near the top of the spoon.

While these split-spoon results are too sparse in the product zone and probably tainted below, there are a few interesting values. The top of the product zone was encountered near the top of the fourth split spoon. This is consistent with other depth measurements. Also, a relatively high hydrocarbon content was found at a depth of approximately 1 foot below ground surface, near the sharp interface between the plowed layer consisting of silty to clayey top soil and the underlying sandy soil. This zone of high hydrocarbon concentrations may be due to hydrocarbon contaminated soil vapors migrating up through the vadose zone until they reached the tilled layer which forms an impermeable barrier. Further sampling would be needed to verify this possible explanation.

Test Pit Excavation Soil Sampling

The results of the test pit excavation soil sampling for the first field investigation are shown in Figure 24. The product capillary fringe averaged 4 to 4.5

Figure 24. Schematic of Test Pit with Soil Sampling Results.
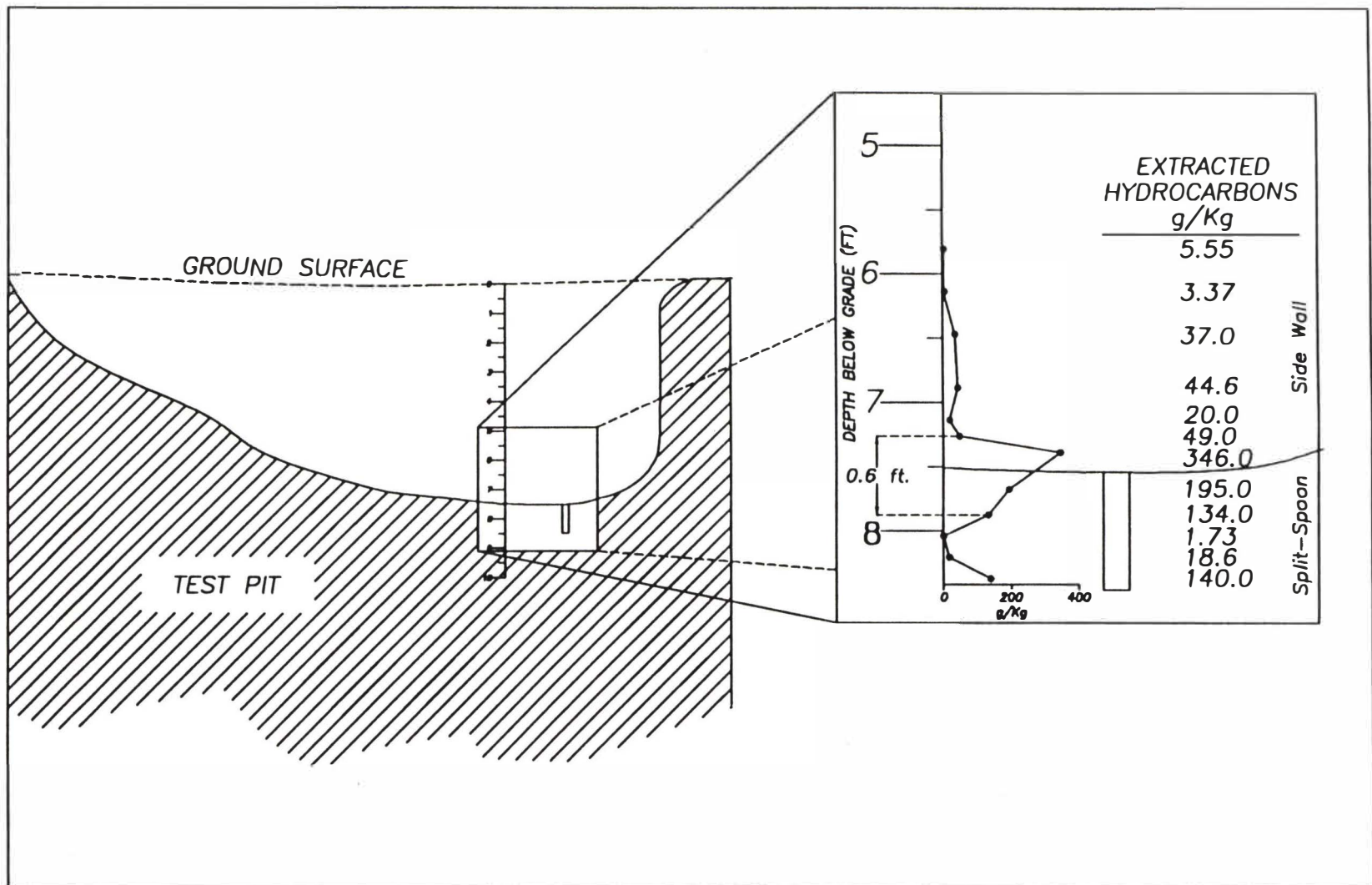
inches above the fluid surface located at a depth of approximately 7.5 ft below ground surface. Figure 24 shows the results: a product layer 0.6 ft thick with the free fluid surface near the top of that layer. Since the samples were obtained using different methods above and below the free fluid surface, the numbers for extracted hydrocarbons from those two zones are not comparable quantitatively.

Note also that a "hot" layer was sampled at the bottom of the split spoon. This may be a coarse layer that filled with product which was subsequently stranded when the water table elevation increased. Similar layering in laboratory experiments was depicted by Hampton and Miller (1988) and Hampton (1989).

The depth below grade to the fluid surface was measured to be approximately 7.36 ft during the second field investigation. The laboratory results for the soil sampling at discrete depth intervals do not compare favorably with the results of the first field investigation. The concentrations of TPH are extremely low for all of the depth intervals and call into question the sample preservation and/or laboratory holding time before analysis.

<center>Apparent Product Equations</center>

Table 2 compares the results obtained during the first field investigation using the apparent thickness measured in monitoring well No. 18 in the Hall et al., Schiegg, and Lenhard and Parker (using their OILEQUIL software) equations. The CONCAWE equation adjusted to use the field-measured density gave a value of 0.56 ft. The other equations were less successful. Schiegg's equation and Lenhard and Parker's method yielded both good and bad results, depending on the soil parameters used in them. These soil parameters were based on grain-size curves measured on samples taken from the split spoon and from a previous hand auger profile. The

Schiegg equation's results compared favorably to other values when it was based on the soil sampled by hand auger at well 19, but not when sampled by split-spoon. Lenhard and Parker's OILEQUIL program predicted an exaggerated thickness using either soil. The values in parenthesis in Table 2 are product specific volumes calculated by OILEQUIL. These were converted to the thickness values shown by assuming a porosity of 40% and oil saturation of 70% in the product layer. Assuming a lower porosity or saturation would further exaggerate the results.

Table 2

Values of Actual Product Thickness Near Well No. 18
With an Apparent Thickness of 1.69 feet

METHOD	VALUE (ft)
Test Pit	0.6
CONCAWE (1979)	0.42
Density-adjusted CONCAWE	0.56
Dietz (1971)	0.96 - 1.39
Hall et al (1984)	1.44
Schiegg (1985) - hand auger	0.52
split spoon	0.23
OILEQUIL - VG auger	0.68 (0.19)
OILEQUIL - BC auger	0.79 (0.22)
OILEQUIL - VG spoon	0.91 (0.255)
OILEQUIL - BC spoon	1.04 (0.29)

Reconnaissance Probe

The field reconnaissance probe produced six usable measurements of the product thickness and elevation out of nine trials (see Table 3).

Table 3

Measurements Taken by the Reconnaissance Probe

Trial No.	Well Area	Top of Color (ft.)	Bot. of Color (ft.)	Solid Thick- ness (ft.)	Mottled Thick- ness (ft.)	Total Thick- ness (ft.)	Test Time (min.)
Reconnaissance Probe							
1	18	---------------- No Color Change ----------------					5
2	18	7.00	?	0.13	0.00	0.13	10
3	18	7.50	8.00	0.00	0.50	0.50	10
4	18	7.44	7.84	0.00	>0.40	>0.40	20
5	18	7.23	7.79	0.29	0.27	0.56	20
6	19	6.52	7.04	0.39	0.13	0.52	25
7	18	---------------- Lost Indicator ------------------					25
8	17	7.85	7.64	0.27	0.31?	0.58?	25
9	17-19	7.60?	Lost Bottom of Indicator				30
Lab Probes in Test Pit							
1	NA	7.47	7.70	0.29	0.00	0.29	5
2	NA	7.30	7.90	0.29	0.31	0.60	5
3	NA	7.33	7.48	0.15	0.00	0.15	5

The color change observed on the indicator strips usually varied in intensity from a dark solid zone with a sharp interface at the top to a mottled zone with increasing depth (see Figures 25 and 26). Sometimes only one of the two types of

Figure 25. A Photograph of the Reconnaissance Probe Results for Trial No. 3.

color changes was observed. The difference in intensities is most likely related to the soil's hydrocarbon content. The solid region appears to indicate the location of the mobile product zone. The mottled region appears to show the location of the oil-water capillary fringe, with the mottled pattern being formed from contact with the hydrocarbons trapped in the larger pores; however, it could also result from quick color change as the strip is moved through the mobile product layer.

The smaller lab probes were used to measure the thickness in the test pit. Of the three trials, only one produced a thickness which can be compared with the other

Figure 26 A Photograph of the Reconnaissance Probe Results for Trial No. 6.

results. The first trial was done before the fluids in the pit and the surrounding soils had reached equilibrium. The third trial was located in an area of disturbed soils caused by a slump in the pit and may be invalid. The second trial was located on a step that was formed by digging out the pit wall. This trial is probably the most reasonable because the sediments were not disturbed and the fluid levels in the test pit were not changing. The results of the laboratory probes in the test excavation are shown in Table 3 with the results of the reconnaissance probe.

During the field test of the new probe many problems were encountered. The electronics used to detect the capillary fringe were unable to function due to feedback. The contacts between flights and on the drive coupling were damaged and had to be

replaced several times. After the first trial of the probe it was determined that the indicator strip was not making sufficient contact with the formation to react. The indicator strip was modified by the addition of a shim. This change, along with a longer period in the hole, improved readings considerably. However, on three occasions all or part of the indicator separated from its backing when the probe was being retrieved and was lost down the hole.

CHAPTER IV

CONCLUSIONS

Table 4 compares the results of all of the methods for the first and second field investigations at well No. 18.

Table 4

Method Results for 1988 and 1989 Field Investigations

Method	1988 (ft.)	1989 (ft.)
Yaniga's Bailer Test	0.54	0.43 - 0.45 ?
Split-Spoon Soil Sampling	?	NA
Test Pit Soil Sampling	0.6	?
Density Adjusted CONCAWE	0.56	0.40 - 0.49
Hall et al. (1984)	1.44	NA
Schiegg (1985)/Hand Auger	0.52	0.03 - 0.31
Schiegg (1985)/Split-spoon	0.23	NA
OILEQUIL/VG Auger	0.68 *0.19	NA
OILEQUIL/BC Auger	0.79 *0.22	NA
OILEQUIL/VG Split-Spoon	0.91 *0.255	NA
OILEQUIL/BC Split-Spoon	1.04 *0.29	NA
Reconnaissance Probe	NA	0.50 - 0.56

Bailer Test

The results from the Yaniga's analysis of the bailer test results were reproducible and correlated with the test pit soil sample analysis, the CONCAWE equation, and the reconnaissance probe methods evaluated at the site. However, the relation between the analysis method and the physical processes involved during the recovery of the product and water levels in the well are still not clearly understood. This method remains empirical and requires additional investigation and verification until a relationship between the physical processes and the analysis method can be established.

The inflection point for the Gruszczenski bailer analysis was not observed in any of the monitoring wells evaluated. If the inflection point was taken to be at an earlier time than the first data point taken during the recovery period, this method would estimate an order of magnitude smaller "actual" product thickness than the other methods. If the curves are interpreted as Type 1 curves the free-product thickness would be over estimated by a factor of 3 from the other methods. The explanation for the criteria of choosing the product thickness and the assumptions therein, have not been adequately explained or verified by the author proposing this method.

Split-Spoon Soil Sampling

The split-spoon soil sampling method was determined to be inadequate for measuring the free-phase product thickness. The major limitation to using split-spoon soil sampling for this purpose is cross-contamination. This is due to the small depth interval over which the sample is collected and compaction of the sample during collection which cause fluids to migrate and smear the free-phase product zone.

Another problem associated with this method is the difficulty of determining the depth from which to collect a representative sample.

Test Pit Excavation Soil Sampling

The results from the test pit excavation from the first field investigation correlate well with Yaniga's bailer test, the modified CONCAWE equation, and the reconnaissance probe. The poor results from the second test pit excavation can be attributed to poor sample preservation technique and an excessive holding time prior to performing the laboratory analyses. The laboratory procedure for analysis of the soil samples may have contributed to the poor results.

Apparent Product Thickness Equations

Of the equations evaluated, the density-adjusted CONCAWE equation correlated best with the bailer test, test pit excavation and reconnaissance probe methods. This equation, which accounts for fluid density alone and neglects soil properties, should work best in coarse media where capillarity is unimportant. It appears that this equation provides a qualitative estimate and should be used with caution. The other equations evaluated which did take into account the various fluid and soil properties did not perform as well when compared to the field methods evaluated. This is probably the result of the impossibility of collecting an undisturbed representative soil sample from which to measure the soil properties. In spite of these limitations, the equations, especially the Lenhard and Parker (1990) equation, could be calibrated to the site characteristics by adjusting the soil and other parameters provided enough data is available. The inability of these equations without calibration to match the methods which produced consistent thickness estimates limits their use as

a field screening tool.

Reconnaissance Probe

Given the absence of the soil sampling results for the second field investigation and the ambiguity surrounding the bailer test results for monitoring well No. 18, no definitive conclusions can be reached at this time about the accuracy of the new tool. However, there are correlations among the results of the bailer tests, the new tool, the density-adjusted CONCAWE equation, and depths to product measured in wells and the test pit. All this circumstantial evidence suggests that the new tool can be used to determine the location and vertical extent of free product in shallow aquifers.

The new tool, which might appropriately be called the Aquifer Dipstick, needs further refinements before commercialization. The electronics must be revised to overcome feedback and mechanical breakage of the contacts. The indicator strips need to resist mechanical abrasion better during insertion and removal. The drive hammer and coupling system needs improvement to avoid bending the couplers.

Nevertheless, this device, when refined, has potential as a screening tool to help delineate hydrocarbon plumes and site monitoring wells. It could also be used in deeper aquifers by coupling it to drive rods on a drill rig. Then it could be used in a hollow-stem auger rig like a split-spoon sampler or a Hydropunch to sample below the drill bit.

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