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Laura L. Krol

EVALUATION OF BAIL-DOWN TEST METHODS FOR CHARACTERIZING FREE PRODUCT RECOVERABILITY FROM AN AQUIFER

by

Laura L. Krol

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Laura L. Krol, M.S.

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Determination of the occurrence and recoverability of free product impacting the subsurface environment has been an on-going challenge in the environmental industry. A simple and relatively inexpensive test to perform in the field is the free product bail-down test. Many authors have proposed various analysis methods using these data for the determination of different free product characteristics.

The purpose of this project was to determine the comparability and possible validity of bail-down test interpretation methods for predicting hydrocarbon hydraulic conductivity/transmissivity and true free product thickness. Bail-down test data collected from two sites were analyzed and interpreted using methods from the following authors for this comparison: (a) Bouwer and Rice, (b) Jacob and Lohman, (c) Yaniga, (d) Gruszczenski, and (e) Hughes, Sullivan, and Zinner.

A consistent trend was noted in the calculated values from all three compared wells. The Bouwer and Rice hydraulic conductivities were consistently lower than the Jacob-Lohman conductivities by at least one order of magnitude. The Yaniga calculated product thickness was consistently the largest value; the next was the Gruszczenski thickness; while the Hughes et al. thickness was the smallest value.

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CHAPTER I

INTRODUCTION

Background

Light non-aqueous phase liquids (LNAPLs) which include aromatic hydrocarbon compounds, such as gasoline, diesel, and oil, are common contaminants found in the subsurface environment. LNAPLs have a lower density than water and are slightly soluble in water. When LNAPLs impact the soil, they tend to migrate through the vadose zone and collect above the water table. In the past, it was assumed that the LNAPLs accumulated on top of the water table as a separate mobile phase. This layer was considered to be one hundred percent saturated with LNAPLs. The LNAPLs that saturate this layer are commonly referred to as mobile free product, free product ,or simply, product. Determination of repeatable, usable, accurate, free product characteristics in the subsurface has been an on-going challenge in the environmental industry.

It has been found that free product thickness measured in monitor wells, commonly referred to as apparent free product thickness, does not represent the true free product thickness in the subsurface. Yaniga (1983) proposed the apparent free product thickness was observed to be 2 to 3 1/2 times greater than formation product thickness. Most authors (Ballestero et al. (1994), Hampton (unpublished 1990), Yaniga and Demko (1983), Hughes et al. (1988), Sullivan et al. (1988), Gruszczenski (1987), Farr et al. (1990), Lenhard and Parker (1990), Wagner et al. (1989), and Huntley et al. (1994)) agree that the apparent product thickness measured in a monitor well is generally greater than the actual product thickness in the adjacent formation. Farr (1990), Lenhard and Parker (1990), and Huntley et al. (1991) demonstrated that variable product, water, and air saturations coexist in the formation at depths above the measured product/water interface. The mobile free product layer is therefore not one hundred percent saturated with LNAPLs which further complicates the characterization of free product in the subsurface.

The determination of various aquifer and free product characteristics in the subsurface, such as thickness, volume, mobility, hydraulic conductivity, transmissivity, and percent saturation, using field methods is an on-going battle. Several methods of (a) testing, (b) data analysis, and (c) interpreting results have been suggested by authors in an attempt to aid in the accurate determination of free product characteristics in the subsurface. One method of testing which is simple and relatively inexpensive to perform in the field is the free product bail-down test. Results and interpretation of this type of test have been published by several authors, including de Pastrovich et al. (CONCAWE, 1979), Gruszczenski (1987), Farr et al. (1990), Hampton and Heuvelhorst (1990), Hampton and Miller (1988), Hampton et al. (1991), Hughes et al. (1988), Huntley et al. (1994), Lenhard and Parker (1990), Sullivan et al. (1988), Testa and Paczkowski (1989), Wagner et al. (1989), and

Yaniga and Demko (1983). Review of these documents has indicated that the basic free product bail down test procedures followed by each author were essentially identical. However, data analysis and result interpretation methods varied significantly.

Objective

The purpose of this project was to determine the comparability of select bail-down test methods, results, and interpretations. Methods which predict hydrocarbon hydraulic conductivity, transmissivity, and/or true product thickness in the formation were selected for comparison using data sets collected from wells at two different locations.

Bail-down test methods, data analysis, and result interpretation procedures presented by the following authors were used for this comparison:

1. Bouwer and Rice method as published by Bouwer and Rice in 1976 and updated by Bouwer in 1989. This method was developed for analyzing slug tests performed in a monitor well for ground water applications. Hydraulic conductivity and transmissivity values can be determined using this method. Mr. Donald Lundy (personal communication, 1995), suggested using this method to analyze free product bail-down tests to determine the hydrocarbon hydraulic conductivity and transmissivity values.

2. Jacob-Lohman method as utilized by Huntley, Hawk, and Corley in a paper published in 1994. This method was developed for testing flowing artesian wells for ground water applications. Ground water hydraulic conductivity and transmissivity values can be determined using the Jacob-Lohman constant drawdown, variable rate, straight-line method (Lohman ,1979). Huntley et al. (1994) used this method to analyze free product bail-down tests and produced hydrocarbon transmissivity and hydrocarbon hydraulic conductivity values. Dr. David Huntley (personal communication,1995), suggested also applying the Jacob-Lohman variable drawdown, variable rate straight line method (Lohman, 1979) for comparison.

3. Yaniga method as utilized by Wagner, Hampton, and Howell (1989). This method was developed for bail-down tests performed in a monitor well containing free product. The true oil thickness reportedly can be ascertained using this method.

4. Gruszczenski method as given in by Gruszczenski (1987). This method was developed for bail-down tests performed in a monitor well containing free product. The true oil thickness, the capillary fringe thickness, and the depths to the top and bottom of these features reportedly can be ascertained using this method.

5. Hughes, Sullivan, and Zinner method as published by Hughes et al. (1988). This method was developed for free product bail-down tests performed in a monitor well. The true oil thickness and the depth at which it occurs in the subsurface can reportedly be determined using this method.

Data sets collected from wells at two different sites were analyzed using each of the selected bail-down test methods. The first set was collected from a monitor well (MW-18) located in Constantine, Michigan (Constantine site). The second and third data sets were collected from monitor wells (CR-3A and CR-3B) located in Carson City, Michigan (Carson City site).

Scope of Project and Report Organization

The project scope of work included an extensive literature review, field work, data acquisition, data analysis, result interpretation, and result documentation. This paper documents the process and results of this project. It has been divided into several chapters as follows: Introduction; Literature Review; Field Test Methods; Data Analysis and Result Interpretation; Discussion; and, Conclusions.

The Introduction includes project background, objective, and this scope of work. The Literature Review chapter has been subdivided by method and is an overview of the theory and application of the each of the compared methods. The Field Test Method chapter has been subdivided by site and describes the bail-down test procedures and data acquisition performed in the field. The Data Analysis and Result Interpretation chapter has been subdivided by site and details the application and results of each individual method. The Discussion chapter has been subdivided by site and the results are discussed. Finally, the Conclusion chapter assesses the overall validity of each method.

CHAPTER II

LITERATURE REVIEW

General

An extensive literature review was performed as a part of this project. The basic theory and application of each of the compared bail-down test methods have been summarized by method in the following chapter.

Bouwer and Rice Method

Bouwer and Rice published a straight-line method in 1976 to evaluate slug tests performed on ground water monitor wells. Their method calls for an almost instantaneous lowering or rising of the ground water level in a monitor well by removing or inserting, respectively, a slug of water, then measuring the depth to water in the well over time as the water reaches equilibrium. The slug test analysis methods described by Bouwer and Rice can be used to determine the hydraulic conductivity of an aquifer and are applicable to partially or fully penetrating wells in either unconfined or confined aquifers.

In the Bouwer and Rice method, the water level in a well should be raised or lowered essentially instantaneously using a slug, a bailer, or a pump. As the water level returns to equilibrium, the depth to water is measured using either a static water level tape or a pressure transducer and recorded along with the time of the readings. The drawdown in the well is determined by subtracting the initial, static, pre-slug test, water level in the well from the measured depth to the water at time, t. A straight-line plot of the log drawdown versus elapsed time data is prepared for use in analysis of the test.

The slope of the line is used to determine the hydraulic conductivity of the aquifer using the following equations:

$$K = [(r_c^2 \ln (R_e/r_w)) / 2L] (1 / t) \ln (y_o / y_t)$$

$$\ln (R_e/r_w) = [[1.1 / [\ln (H / r_w)]] + [[A + B \ln [(D - H) / r_w]] / (L / r_w)]]^{-1}$$

where K = hydraulic conductivity

r_w = radius of well borehole

r_c = radius of well casing

R_e = effective radius of influence

L = saturated screen length

H = static height of water in a well

D = saturated thickness of the aquifer

t = time

y_o = y intercept of fluid drawdown, at t=0

y_t = fluid drawdown at time t

A & B = dimensionless coefficients which are a function of L/r_w

Further details concerning the development of the Bouwer and Rice theory and or the application of this slug test method can be found in their 1976 paper and in the updated paper by Bouwer (1989).

Application of this method to free product bail-down tests was suggested by Mr. Donald Lundy, of Remediation Technologies Inc. located in Fort Collins, Colorado (personal communication, 1995). For purposes of this project, a slug of product was removed from the subject well at a constant rate. Product removal was quick relative to the time required for product recovery and equilibration. Product recovery was monitored using an Oil Recovery System (ORS) interface probe or a KECK KIR-89 interface probe to measure the depth to product and to the product/water interface, and was recorded with respect to time.

The free product slug tests were analyzed using the product recovery data in place of water recovery data by calculating and plotting the log product drawdown versus time as opposed to log water drawdown versus time. The following methods were considered for calculating the product drawdown for the Bouwer and Rice method:

1. Mr. Lundy suggested using the change in product thickness relative to the initial product thickness as the product displacement. The product drawdown would be calculated by subtracting the thickness of the product at each reading from the initial product thickness using the following equation:

$$y_p = o_i - o_t$$

where y_p = product drawdown

o_i = initial product thickness measured in the well

o_t = product thickness at time t

Even though drawdown is not depth-dependent, this method was not used to determine the product drawdown because the calculated drawdown does not appear to correlate with the drawdown proposed by Bouwer and Rice.

2. Convert the oil thickness in the well at each reading to an equivalent water thickness and subtract the equivalent water thickness from the product/water interface depth at that time. This method was not used because the values calculated at each reading represented the instantaneous potentiometric surface in the formation. This value essentially did not change as a result of this test because little to no water was removed from the aquifer during the product removal stage of the experiment.

3. A third method proposed to calculate the product drawdown was as follows. Calculate the potentiometric surface in the formation by converting the initial oil thickness to equivalent water thickness using the specific gravity of the free product. Subtract the equivalent water thickness from the initial depth to product/water interface to get the formation potentiometric surface. Then at each reading convert the above calculated product drawdown to equivalent water drawdown in the well. Plot the calculated log equivalent water drawdown versus time and use the plot for analysis. This method was not used because the determined hydraulic conductivity and transmisivity values may be representative of the ground

water and not the free product in the aquifer.

4. A final method was considered to calculate the product drawdown using essentially the same way Bouwer and Rice proposed for ground water. This method consisted of subtracting the initial product depth from the product depth measured at time 't' as the well recharged, basically using the following equation:

$$y_p = D_{pt} - D_{pi}$$

where y_p = product drawdown

D_{pt} = product depth at time 't'

D_{pi} = initial product depth

The fourth method was used to calculate the product drawdown as a part of this project.

The AQTESOLV v.1.1 computer program was used to analyze the results of the bail down tests using the Bouwer and Rice slug test equations. Since the program was set up for ground water applications, the required input parameters had to be modified to represent free product applications. The parameters required to run the program include the following: time versus drawdown data, initial drawdown in well (y_o), radius of well casing (r_c), radius of well (r_w), saturated thickness (D), screen length (L), and static height of water in well (H). The time versus calculated product drawdown was entered in a spread sheet type format within the program.

The Bouwer and Rice option in AQTESOLV 1.1 was used in the following way. The y_0 intercept value extrapolated from the log product drawdown versus time plot was entered as the initial drawdown in the well. The initial, static product thickness measured in the well above the potentiometric surface was entered as the static height of water in well parameter. The program requires the saturated thickness value to be greater then the static height of water in well parameter for the program to run. That makes perfect sense for water wells, but in free product wells the static height of product is likely to exceed the product-saturated thickness in the aquifer. The actual product saturated thickness was entered if it was known and was greater than the static height parameter value, or an artificial value slightly greater than the static height parameter was inputted as the saturated thickness. According to Bouwer (1989) the saturated screen length in a well should be used for the screen length in the equations. Therefore, the product saturated screen length was inputted as the screen length.

The potentiometeric surface was determined using the following equations:

$$w_e = o_i\,(SGhc)$$

$$D_{ps} = D_{p/w} - w_e$$

where: w_e = equivalent water thickness

o_i = initial product thickness

SGhc = specific gravity of the hydrocarbon

D_{ps} = depth to the potentiometric surface

$D_{p/w}$ = initial depth to the product/water interface

AQTESOLV provides a data plot showing log drawdown versus time. The data points are fitted by the computer with a best fit straight line. This line can be modified by the operator. The slope of this line, along with the parameters entered are used to calculate the hydraulic conductivity. The transmissivity can then be calculated using the following equation:

$$T = K\,D$$

where T = transmissivity

K = hydraulic conductivity

D = saturated aquifer thickness

Jacob-Lohman Method

The Jacob-Lohman method for analyzing slug test or bail-down test data was developed for ground water applications. Huntley, Hawk, and Corley (1994) applied the Jacob-Lohman (1979) variable discharge, constant drawdown equations to hydrocarbon slug removal test data to calculate the hydrocarbon hydraulic conductivity. The slug test results presented were used by Huntley et al. to validate their method to predict saturation and mobility of non-aqueous phase hydrocarbons in fine grained sandstone. The actual equations and values utilized to calculate the example hydrocarbon hydraulic conductivity presented in the paper were not cited. Dr. David Huntley confirmed the analysis procedures detailed in Lohman (1979) using the variable discharge, constant rate straight-line equations were used to calculate these values (personal communication, 1995).

Prior to performing the free product bail-down test, the initial product and product/water interface depths were measured and recorded. The bail-down test was performed by removing a slug of free product from the well until a constant minimum oil thickness remained in the well. The product depth and product/water interface depth were measured and recorded with respect to time as the well recovered to equilibrium conditions.

The collected data was analyzed using constant-drawdown, variable discharge test equations per Jacob-Lohman methods published in Lohman (1979). The transmissivity was calculated using the following equation (based on Lohman 1979, equation 72):

$$T = 2.3 \;/\; [4 \pi y_p \; \Delta(1/Q) / \Delta\log_{10}t]$$

where T = transmissivity

y_p = fluid drawdown in discharging well

$\Delta(1/Q)$ = time-weighted discharge

t = time

The instantaneous oil discharge into the well, Q, was calculated by dividing the calculated instantaneous volume of oil entering the well between readings by the length of time between readings. The reciprocal of the discharge, 1/Q, was plotted versus log time and a straight line was fitted to the late-time data points, per Dr. David Huntley. The slope of the line, which is the change in 1/Q value over one log cycle, was used as the $\Delta(1/Q)/\Delta \log_{10} t$ value in the above transmissivity equation.

By definition, the drawdown in the well has to be constant in order to apply this method. Dr. Huntley indicated that an average product drawdown was calculated and used as the constant drawdown in his publication. The product drawdown values calculated for the Bouwer and Rice method section of this project were used for this calculation. The average constant drawdown in the well was estimated from the drawdowns represented by the straight line portion of the 1/Q versus log time graph.

Dr. Huntley also indicated that the data could be further modified in order to use the Jacob-Lohman variable discharge, variable rate straight-line method as follows (based on Lohman 1979, equation 71):

$$T = 2.3 \ / \ [4 \pi \ \Delta(y_p/Q) \ / \ \Delta \log_{10} t]$$

The instantaneous product drawdown divided by the product discharge into the well was calculated and plotted against log elapsed time. A straight line was fitted to the data points. The slope of the line, which is the change in y_p/Q over one log cycle of time, was then used as the $\Delta(y_p/Q) / \Delta\log_{10}t$ value to calculate the above transmissivity.

Yaniga Method

Yaniga and Demko (1983) reportedly determined the true free product thickness by performing "fuel pumping test and data assessments". The actual bail-down test method and analysis was summarized briefly in the question and answers section of their 1983 paper, as follows:

1. Measure initial static product depth and product/water depth. The difference between these two depths is the apparent oil thickness.
2. Remove at least one full well volume of free product from the well.
3. Measure the rate of product recharge into the well.
4. Recalculate the product thickness using the product depth and product/water depth measurements.

The actual procedure to determine the true product thickness was not outlined in their paper.

Wagner, Hampton, and Howell (1989) outlined and applied the Yaniga free product bail-down test method to determine the actual free product thickness in the formation of interest. The Yaniga method as detailed by Wagner et al (1989) was utilized for this project.

The free product bail-down test procedures were the same as the previous two methods. The initial, static, pre-test, depth to product and product/water interface was measured. Free product was removed from the well at a constant rate by bailing or pumping. A minimum of one well volume of free product was removed per Yaniga and Demko (1983). Once the free product was removed from the well, the product and product /water interface depths were measured and recorded relative to time after bailing or pumping ended.

The depth to product versus log time and depth to product/water interface versus log time was then plotted. Two straight lines reportedly can be fitted to the product/water interface plot. The vertical distance between the intersection of the two lines on the product/water curve and the top of product curve reportedly represents the true free product thickness in the formation. Thus, the true product thickness is measured directly off the graph.

Gruszczenski Method

Mr. Thomas Gruszczenskis' (1987) method for estimating the actual free product thickness in a formation uses the results of the field bail-out tests performed on monitor wells containing free product. His general bail-out test method is the same as the previously described bail-down test methods; however, he adds a few more details to his method.

Prior to performing the bail-out test, the initial, static depth to product and product/water interface has to be measured and recorded. Then one must bail water/product out of the well until the product thickness in the well is constant. One measures and records the depth to product and product/water interface versus time. Gruszczenski suggests taking readings every 30 seconds for the first 5 minutes; taking readings every minute for the next 5 minutes; taking readings every 2 minutes for the next 20 minutes (from elapsed time of 10 minutes to 30 minutes); taking readings every 10 minutes until an hour had elapsed; finally, taking readings as needed to help define the slope of the product recovery curve. These recommended intervals must be adapted to the site in question, of course.

Analysis using this method begins with plotting the product depth versus time and the product/water interface depth versus time on cartesian graph paper. The corrected water depth, the potentiometric surface, should also be plotted on the graph as a horizontal line. One determines the corrected water level in the well (which represents the potentiometric surface in the formation) by converting the free product thickness in the well to equivalent water thickness, using the equation outlined in the Bouwer and Rice method section of this report.

The vertical distance between the top of product and product/water interface curves at the inflection point along the product/water curve reportedly represents the true product thickness. The inflection point is chosen where the slope becomes negative along the product/water interface curve.

The sum of the true product thickness and the underlying capillary fringe is estimated by measuring the vertical distance between the corrected water level, the potentiometric surface, and the static, initial, stabilized top of product off the graph. The thickness of the capillary fringe is calculated by subtracting the actual product thickness from the sum of the product thickness and the capillary fringe thickness.

The true product thickness and capillary fringe thicknesses can then be used to determine the depth at which the free product and the capillary fringe will be encountered. Gruszczenski apparently uses an average of the corrected water levels, calculated from the initial and inflection point depth measurements, as a reference for determining the depths. If no water was removed during the product removal stage of the test, these values should be essentially the same. The depth to the capillary fringe is calculated by subtracting the calculated capillary fringe thickness from the corrected depth to water. The depth to the top of the actual free product is calculated by subtracting the actual oil thickness from the calculated depth to the top of the capillary fringe. Additional information and examples using this method can be found in Gruszczenski (1987).

Hughes, Sullivan, and Zinner Method

Hughes, Sullivan, and Zinner (1988) discussed two test methods, a recharge test and a bail-down test, in their paper which could be used to determine the true free product thickness in the subsurface. For the purposes of this project, only the bail-down test method, analysis, and interpretation of the results will be discussed.

For successful use of the bail-down test results for the determination of the true mobile free product thickness in the formation, certain conditions must be met. These conditions are as follows: (a) the hydrocarbon/water interface in the formation must be above the potentiometric surface in the formation, and (b) the hydrocarbon recharge rate into the well must be relatively slow. If these conditions are met, the free product will enter the well at a constant rate until the product level in the well is at the same depth as the base of the free product layer in the formation. The product entry rate will steadily decrease as more product accumulates in the well above this surface. Reportedly, the entry rate of the product into the well would continuously decrease if the product/water interface was below the potentiometric surface. Details of the theory behind this test method, analysis and interpretation can be found in the 1988 paper by Hughes et al.

The bail-down test procedures are the same as the previously discussed methods. Prior to removing the free product from the well, the initial, static product depth and product/water interface depth must be measured and recorded. The potentiometric surface should be calculated using the equation presented in the Bouwer and Rice method section of this report. The free product is rapidly bailed or pumped out of the well until the hydrocarbon thickness remaining in the well is constant and is between 0.1 and 1.0 feet. The potentiometric surface should be recalculated using the bailed down depths to product and product/water interface and should be within 0.05 feet of the initially calculated surface, before beginning to record the recharging free product and product/water elevations in the well. The depths to product and to the product/water interface are measured and recorded relative to time as the well recharges. One should continue taking and recording depth measurements relative to time until the well has fully recharged or it has recovered to approximately 10 percent of initial conditions.

The product depth versus time data is used for analysis and is plotted on cartesian graph paper. The calculated potentiometric surface is included as a horizontal line on this graph. The linear segment at the begining of the product curve represents mobile free product entering the well at a constant rate. The point where the product curve becomes nonlinear, the inflection point, is thought to correspond to the hydrocarbon entry point into the well which reportedly represents the base of the free product layer in the formation.

The depth at which the inflection point occurs on the curve thus represents the depth to the base of the free product layer in the formation. The initial product level in the well is assumed to correlate with the top of product level in the formation. Therefore, the vertical distance between the inflection point and the initial product level is the true product thickness in the formation.

CHAPTER III

FIELD TEST METHODS

General

Free product bail-down tests were performed at two sites, one located in Constantine, Michigan, and the other one located in Carson City, Michigan. Site description, testing methods, and data collecting procedures were essentially the same at both sites and are delineated in detail below.

Constantine Site

A release of petroleum distillates was discovered in mid 1987 at the Constantine site. The site is located on flat lying, sandy, heavily irrigated farming land. The water table is at 6 to 10 feet below the ground surface. The aquifer is made up of medium to coarse grained, glacial outwash sands and gravels which extend to a depth of 60 to 65 feet. Reportedly (Wagner et al., 1989), the gradient is approximately 0.0006 towards the west/south-west and the hydraulic conductivity of the aquifer ranges from 0.01 to 0.001 cm/sec (0.02 to 0.002 ft/min). The free product thickness observed in soil samples taken from the side of a test pit in the vicinity of the well was 0.6 feet and the specific gravity of the hydrocarbon was 0.75 (Wagner et al, 1989).

The borehole for monitor well MW-18 was drilled using a truck mounted drill rig equipped with 6 5/8-inch outer diameter hollow stem augers and a 7 1/4-inch diameter bit. The well was constructed using 9 feet of 2-inch diameter, 0.010-inch slotted polyvinyl chloride (PVC) screen and 2-inch diameter PVC well casing. The annular space around the screen was allowed to collapse forming a natural gravel pack. The total depth of the well was 12.5 feet below the ground surface. The well casing was left sticking up approximately 2 feet above the ground surface.

The bail-down test was performed on September 2, 1988. An ORS interface probe was used to measure the depth to product and product/water interface. The initial product thickness in the well was 1.69 feet.

Free product was removed from the well using a bailer as quickly as possible. Free product was bailed until several successibe bailers had the same small product thickness in them. Care was taken during bailing to remove free product with as little water as possible. A total of 1.3 liters (0.046 ft^3) of free product was removed from the well in 5 minutes at a relatively constant rate of 0.0092 ft^3/min.

When the product level was at a minimum thickness, bailing was stopped and the well was allowed to recover. The product and product/water interface depths were measured using an ORS interface probe and recorded relative to time at approximately 30 second intervals during the majority of the recovery test. The well fluid depths were essentially at pre-test conditions 15 minutes into the recovery test. Therefore, monitoring was stopped at this time. All depths were recorded to the nearest one hundredth of a foot relative to the top of casing. Field data collected for MW-18 is included as Table 1.

Table 1

Free Product Bail-Down Test Field Data for
MW-18, Located in Constantine, Michigan
(Test Performed on September 2, 1988)

Air/Free Product Interface		Free Product/Water Interface	
TIME, minutes	DEPTH, feet	TIME, minutes	DEPTH, feet
0	10.10	0	11.79
0.37	10.46	0.57	10.68
0.77	10.44	1.17	10.82
1.27	10.43	1.52	10.88
1.68	10.41	1.92	10.93
2.08	10.40	2.40	11.02
2.63	10.36	2.80	11.08
3.05	10.37	3.22	11.10
3.42	10.33	3.65	11.16
3.87	10.30	4.07	11.21
4.25	10.30	4.52	11.28
4.75	10.29	4.93	11.31
5.20	10.28	5.40	11.34
5.63	10.27	5.93	11.39
6.13	10.25	6.38	11.42
6.58	10.23	6.83	11.45
7.12	10.22	7.33	11.49
7.50	10.22	7.72	11.50
8.00	10.20	8.40	11.54
8.55	10.20	8.82	11.56
9.16	10.19	9.40	11.58
9.60	10.19	9.87	11.60
10.10	10.17	10.42	11.61
10.68	10.17	10.92	11.63
12.62	10.15	12.82	11.68
15.00	10.13	15.17	11.71

Carson City Site

The second site is a former oil refinery facility presently being used as an oil transfer station, which is located in Carson City, Michigan. Free product was being slowly pumped from an existing monitor well, MW-17, at the site in mid 1991. The facility is sited over a relatively thin sand aquifer situated adjacent to a stream. The water table is 10 to 15 feet below the ground surface and flows towards the north west. The thickness of mobile free product in the soil in the vicinity of the tested well is not known. The specific gravity of the product is 0.827 (Hampton et al., 1995).

Several experimental monitor wells were installed on site in 1992 using various construction techniques. The purpose of these wells was to demonstrate the effectiveness of geosynthetic sand packs for free product wells. A total of 6, 4-inch diameter, PVC wells were installed in a two row grid pattern 5.5 feet west of MW-17. The rows were oriented east-west and were approximately 4 feet apart. Each row had 3 wells installed approximately 8.5 feet apart.

Two rounds of free-product bail-down tests were performed on these wells in 1992. The results collected, unfortunately, did not appear to be repeatable. Therefore, the effectiveness of the geosynthetic sand packs was not established. The well placement, construction details, and bail-down test results can be refered to in Hampton et al. (1995). Hampton et al. suggested performing dual well free product bail-down tests on select well pairs in an attempt to gain repeatable results.

Dual well free product bail-down tests were performed on various pairs of wells on 8 separate occations during the summer and early fall, 1994. Preliminary review of the test data indicated the results appeared to be more repeatable than the single well tests previously performed. The dual free product bail-down test results. performed on the 6 wells at the site have been included in Appendix A.

The data sets were closely reviewed to determine which data could successfully be used as a part of this comparison study. The data collected during the dual-well bail down test performed on wells CR-3A and CR-3B on August 8, 1994, appeared to have the most extensive coverage over time. Therefore, these data sets were analyzed and have been included in this study.

Monitor wells CR-3A and CR-3B were drilled using a truck-mounted drill rig equipped with 9 5/8-inch outer diameter hollow stem augers and a 10 1/4-inch diameter bit. Monitor well CR-3A was constructed using 10 feet of 4-inch diameter, 0.020-inch slotted, PVC screen and 4-inch diameter PVC well casing. A sand gravel pack was installed around the screen. A 72-60 sand pack was placed from a depth of 9.6 to 19.6 feet; and a 50-60 sand pack was placed from a depth of 7.5 to 9.6 feet, below the ground surface. The remaining annular space was filled with holeplug to the surface. The total depth of the well was 19.6 feet below the ground surface. The well casing was left sticking up 0.54 feet above the ground surface. Well construction details were recorded in the site field book by Mr. Thomas Barrett (1992).

Monitor well CR-3B was constructed using 10 feet of 4-inch diameter, 0.020-inch slotted, PVC screen and 4-inch diameter PVC well casing. An experimental gravel pack was installed around the screen. A 70-80 sand pack was placed from a depth of 17 to 19.5 feet; a 50/50 sand/teflon mix pack was placed from a depth of 11 to 17 feet; a 50-60 sand pack was placed from 9.5 to 11 feet; and, a 70-80 sand pack was placed from 7.7 to 9.5 feet, below the ground surface. The remaining annular space was filled with holeplug to the ground surface. The total depth of the well was 19.5 feet below the ground surface. The well casing was left sticking up 0.67 feet above the ground surface.

The dual well bail-down test was performed on August 8, 1994. An ORS interface probe was used in CR-3A and a KECK KIR-89 interface probe was used in CR-3B to measure the depth to product and product/water interface to the nearest tenth of a centimeter. The initial, static fluid depths were recorded prior to performing the bail down test. The initial product thickness in CR-3A was 4.80 feet. The initial product thickness in CR- 3B was 4.39 feet.

Each well was equipped with a peristaltic pump. The free product was simultaneously pumped from each well at a relatively constant rate until a minimum product thickness remained in the well. A total of 12 liters (0.42 ft^3) of free product was pumped out of each well in 16 minutes at a relatively constant rate of 0.75 liters/minute (0.026 ft^3/min). When the minimum product level was reached, the tube from the pump was removed from the well, the pump was turned off, and recovery measurements were performed as quickly as possible. Depth to product and product/water interface measurements were recorded at approximately 30 second intervals for the first 10 minutes of the well recovery. Time between readings was increased to approximately 3 minute intervals for the next 15 minutes (to 25 minutes elapsed time). Time between readings was increased to approximately 10 to 20 minute intervals for the next hour. After that, time between readings gradually increased to every other day for the duration of the test. The total elapsed time for the well to recover within 5 % of the original, pre-test conditions was 8 days. The 16-minute pumping period was essentially instantaneous relative to the week-long recovery.

The measurements collected during the first 210 minutes of the test have been used for calculations in this report. All depths were recorded relative to top of casing. Field data collected for CR-3A and CR-3B have been included as Table 2 and 3, respectively. The depth measurements were converted from centimeters to feet for use in this paper. The converted data have been also included, to the thousandth of a foot, on the respective tables.

Table 2

Free Product Bail-Down Test Field Data for
CR-3A, Located in Carson City, Michigan
(Test Performed on August 8, 1994)

Air/Free Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	371.0	12.172	0	517.2	16.969
0.65	388.0	12.730	1.25	420.6	13.799
4.00	387.5	12.713	4.50	420.5	13.796
5.00	387.4	12.710	5.50	420.8	13.806
6.00	387.3	12.707	6.50	420.9	13.809
7.00	387.2	12.703	7.50	421.5	13.829
8.00	387.1	12.700	8.50	421.5	13.829
9.00	387.0	12.697	9.50	421.6	13.832
11.00	386.9	12.694	11.5	421.9	13.842
13.00	386.8	12.690	13.5	422.7	13.868
15.00	386.7	12.687	15.5	422.9	13.875
17.00	386.6	12.684	18.0	423.3	13.888
20.00	386.4	12.677	20.5	424.0	13.911
23.00	386.3	12.674	23.5	424.2	13.917
32.00	386.1	12.667	32.5	425.6	13.963
40.00	385.8	12.657	40.5	426.5	13.993
52.00	385.5	12.648	52.5	427.5	14.026
67.00	385.3	12.641	68.0	429.3	14.085
84.00	384.9	12.628	85.0	430.5	14.124
96.00	384.8	12.625	96.5	431.5	14.157
210.00	384.4	12.612	210.0	438.6	14.390

Table 3

Free Product Bail-Down Test Field Data for
CR-3B, Located in Carson City, Michigan
(Test Performed on August 8, 1994)

Air/Free Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	376.0	12.336	0	509.8	16.726
1.98	387.7	12.720	2.52	447.0	14.665
3.12	387.8	12.723	3.48	448.3	14.708
4.02	387.5	12.713	4.62	449.4	14.744
4.98	387.5	12.713	5.40	449.9	14.761
6.18	386.8	12.690	6.66	450.7	14.787
7.68	386.5	12.680	8.22	451.5	14.813
9.30	386.3	12.674	9.84	452.4	14.843
11.16	386.1	12.667	11.64	452.8	14.856
13.32	386.0	12.664	13.62	453.0	14.862
15.18	385.8	12.657	15.48	453.5	14.879
17.10	385.7	12.654	17.52	453.8	14.888
20.16	385.5	12.648	20.52	454.5	14.911
26.88	385.3	12.641	27.48	456.3	14.970
33.00	385.0	12.631	33.48	456.8	14.987
41.52	384.8	12.625	42.12	457.9	15.023
52.68	384.5	12.615	53.28	459.0	15.059
68.40	384.2	12.605	69.30	460.5	15.108
84.60	383.9	12.595	85.20	462.0	15.157
210.0	382.3	12.543	210.0	472.4	15.499

CHAPTER IV

DATA ANALYSIS AND RESULT INTERPRETATION

General

The bail-down test data collected as a part of this project were analyzed using each of the bail-down methods discussed in the Literature Review section of this report. The results of the various bail-down test method analysis will be discussed first for the Constantine site then for the Carson City site in the following order: (1) Bouwer and Rice method, (2) Jacob-Lohman method, (3) Yaniga method, (4) Gruszczenski method, and (5) Hughes, Sullivan, and Zinner method.

Constantine Site - Well MW-18

Bouwer and Rice Method

The Bouwer and Rice slug test was developed for ground water applications. Instead of applying this method to a ground water slug test, it has been applied to a free product bail-down test. AQTESOLV v.1.1 was used to analyze the results of the bail-down test using the Bouwer and Rice equations. Time versus drawdown data was entered in spread sheet format within the program. The drawdown values entered into the spread sheet represent the product drawdowns in the well which were calculated from the field data using the following equation. Data collected from time t = 0.37 minutes has been included as an example calculation:

$$y_p = D_{pt} - D_{pi} = 10.46 - 10.10 = 0.36 \text{ ft}$$

where y_p = product drawdown = 0.36 ft

D_{pt} = product depth at time 't' = 10.46 ft

D_{pi} = initial product depth = 10.10 ft

The elapsed time and calculated free product drawdown data for well MW-18 have been included as Table 4.

The potentiometric surface was calculated using the following equation and the initial product and product/water interface depths have been included as a sample calculation:

$$w_e = o_i\,(SGhc) = 1.69\,(0.75) = 1.27 \text{ ft}$$

$$D_{ps} = D_{p/w} - w_e = 11.79 - 1.27 = 10.52 \text{ ft}$$

where: w_e = equivalent water thickness = 1.27 ft

o_i = initial product thickness = 11.79 - 10.10 = 1.69 ft

SGhc = specific gravity of the hydrocarbon = 0.75

D_{ps} = depth to the potentiometric surface = 10.52 ft

$D_{p/w}$ = initial depth to the product/water interface = 11.79 ft

Table 4

Free Product Bail-Down Test Bouwer and Rice Calculated Values
for MW-18 located in Constantine, Michigan
(Test Performed on September 2, 1988)

ELAPSED TIME, minutes	PRODUCT DEPTH, feet	PRODUCT DRAWDOWN, feet (a)
0 (b)	10.51	0.41
0.37	10.46	0.36
0.77	10.44	0.34
1.27	10.43	0.33
1.68	10.41	0.31
2.08	10.40	0.30
2.63	10.36	0.26
3.05	10.37	0.27
3.42	10.33	0.23
3.87	10.30	0.20
4.25	10.30	0.20
4.75	10.29	0.19
5.20	10.28	0.18
5.63	10.27	0.17
6.13	10.25	0.15
6.58	10.23	0.13
7.12	10.22	0.12
7.50	10.22	0.12
8.00	10.20	0.10
8.55	10.20	0.10
9.16	10.19	0.09
9.60	10.19	0.09
10.10	10.17	0.07
10.68	10.17	0.07
12.62	10.15	0.05
15.00	10.13	0.03

(a) Calculated by subtracting the product depth at time ‘t’ from the initial product depth 10.10 ft.
(b) Values estimated from log drawdown (displacement) versus time plot.

The program requires the input of several site specific parameters which include the following: initial drawdown in the well; radius of well casing; radius of well; saturated thickness; screen length; and static height of water in well. The results of the product bail-down test were entered for these site specific parameters so the results should represent the oil characteristics in the subsurface. The y_o intercept value extrapolated at time equaling zero was assumed to be the initial drawdown in the well and was 0.41 feet. The well was constructed using 2-inch diameter PVC casing, so the radius of the well casing was 0.083 feet. The well borehole was approximately 7 1/4-inches in diameter, so the radius of the well was 0.30 feet.

The actual oil saturated thickness is reportedly 0.6 feet in the vicinity of MW-18 (Wagner et al, 1989). Therefore, a value of 0.6 feet was inputted for the saturated thickness. The product saturated length of the well screen was used as the screen length and was inputted as 1.69 feet. The initial oil thickness above the potentiometric surface measured in the well prior to the test was assumed to correlate with the static height of water in well parameter. This value was calculated by subtracting the potentiometric surface depth from the inital product depth and was inputted as 0.42 feet. A summary of the site specific parameters entered into the program has been included as Table 5.

AQTESOLV plotted the log product displacement versus time and calculated a hydrocarbon hydraulic conductivity of 9.57×10^{-5} ft/min. Using the saturated thickness of 0.6 feet, the calculated hydrocarbon transmissivity was 5.74×10^{-5}

ft^2/min. The AQTESOLV plot used for MW-18 has been included as Figure 1.

Table 5

Free Product Bail-Down Test Calculated Bouwer and
Rice Slug Test AQTESOLV Input Values for
MW-18 Located in Constantine, Michigan
(Test Performed on September 2, 1988)

Parameter	Value
Initial Drawdown in Well (@ t = 0)	0.41 feet
Radius of Well Casing	0.083 feet
Radius of Well	0.30 feet
Saturated Thickness	0.6 feet
Screen Length	1.69 feet
Static Height of Water in Well	0.42 feet

Jacob-Lohman Method

Data collected from the product bail-down test were analyzed using the Jacob-Lohman method for constant drawdown, variable rate slug test analysis as applied by Huntley et al (1994). The hydrocarbon transmissivity was calculated using the following equation (based on Lohman, 1979, equation 72):

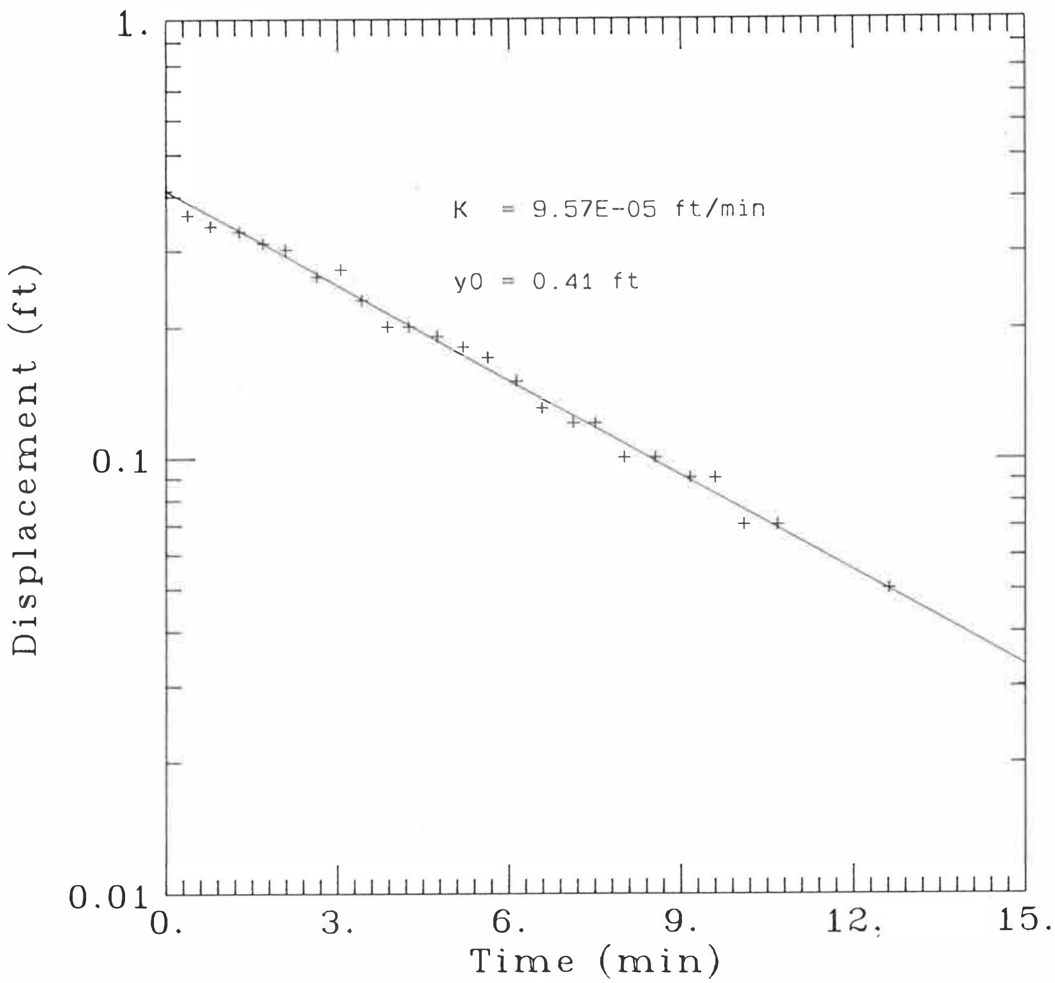

Figure 1. Bouwer & Rice Method for MW-18.

$T = 2.3 / [4 \pi y_p (\Delta 1/Q)/\Delta \log_{10} t] = 2.3 / [4 \pi (0.121)(1800)] = 8.4 \times 10^{-4}$ ft^2/min

where T = transmissivity = 8.4×10^{-4} ft^2/min

y_p = fluid drawdown in discharging well = 0.121 ft

$\Delta 1/Q$ = reciprocal of discharge over one time log cycle = 1800 min/ft^3

The reciprocal of the instantaneous product discharge (1/Q) values were plotted against log elapsed time. A straight line was fitted to the data and used to determine the reciprocal of the variable discharge rate into the well, $\Delta 1/Q$, which was 1800 min/ft^3. An average product drawdown of 0.121 feet was calculated using the product drawdown values determined in the previous Bouwer and Rice method and was used as the constant drawdown, y_p. The hydrocarbon transmissivity value calculated was 8.4×10^{-4} ft^2/min. Using a product saturated thickness of 0.6 feet, the hydrocarbon hydraulic conductivity value calculated was 1.4×10^{-3} ft/min. The calculated reciprocal discharge values used to generate this plot are summarized on Table 6. MW-18 discharge versus log time data plot used to determine these parameters has been included as Figure 2.

The hydrocarbon transmissivity was then calculated using the Jacob-Lohman variable discharge, variable rate straight-line method as follows (based on Lohman, 1979, equation 71):

$T = 2.3 / [4 \pi (\Delta y_p/Q) / \Delta \log_{10} t] = 2.3 / [4 \pi (70.5)] = 2.6 \times 10^{-3}$ ft^2/min

Table 6

Free Product Bail-Down Test Jacob-Lohman Method Calculated Values for MW-18 Located in Constantine, Michigan (Test Performed on September 2, 1988)

ELAPSED TIME, minutes	PRODUCT DRAWDOWN, feet	1/Q, minute/feet^3	y_p/Q, minute/feet^2
0.57	0.36	62.0	22.3
1.17	0.34	172.0	58.5
1.52	0.33	229.0	75.6
1.92	0.31	270.0	83.7
2.40	0.30	218.0	65.4
2.80	0.26	182.0	47.3
3.22	0.27	2100.0	567.0
3.65	0.23	195.0	44.9
4.07	0.20	233.0	46.6
4.52	0.20	300.0	60.0
4.93	0.19	456.0	86.6
5.40	0.18	588.0	106.0
5.93	0.17	408.0	69.4
6.38	0.15	409.0	61.4
6.83	0.13	409.0	53.2
7.33	0.12	455.0	54.6
7.72	0.12	1950.0	234.0
8.40	0.10	523.0	52.3
8.82	0.10	840.0	84.0
9.40	0.09	967.0	87.0
9.87	0.09	940.0	84.6
10.42	0.07	917.0	64.2
10.92	0.07	1000.0	70.0
12.82	0.05	1267.0	63.4
15.17	0.03	2136.0	64.1

where T = transmissivity = 2.6×10^{-3} ft^2/min

$\Delta (y_p/Q)$ = drawdown divided by discharge over one log cycle = 70.5 min/ft^2

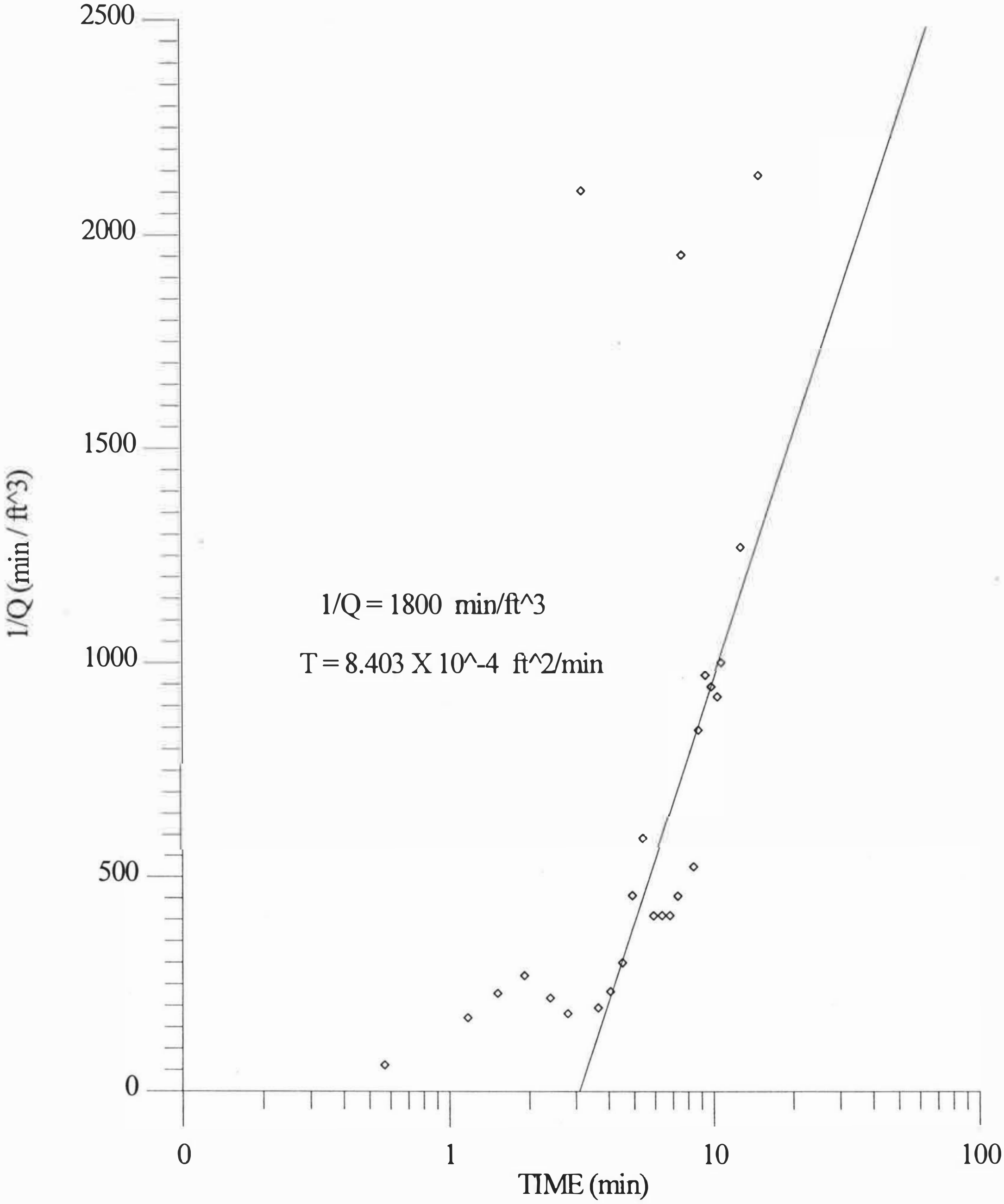

Figure 2. Jacob-Lohman 1/Q Method for MW-18.

The reciprocal of the instantaneous product discharge (1/Q) value was multiplied by the product drawdown at each reading and plotted against log elapsed time. A straight line was fitted to the data and used to determine the time weighted drawdown divided by discharge rate into the well over one log cycle of time, $\Delta(y_p/Q) / \Delta\log_{10}t$, which was 70.5 min/ft^2. The hydrocarbon transmissivity value calculated was 2.6 x 10^{-3} ft^2/min. Using an oil saturated thickness of 0.6 feet, the hydrocarbon hydraulic conductivity value calculated was 4.3 x 10^{-3} ft/min. The calculated drawdown divided by discharge values used to generate the plot are also summarized on Table 6. The MW-18 drawdown divided by discharge versus log time data plot used to determine these parameters has been included as Figure 3.

Yaniga Method

The true product thickness was determined following the Yaniga method of analysis as used by Wagner et al. (1989). Application of this method was very quick and easy. First, the depth to product versus log time and the depth to product/water interface versus log time was plotted. Then, two straight lines were fitted on the product/water interface curve. The vertical distance between the point where the two straight lines intersect on the product/water curve and product curve is reportedly the true product thickness. The true product thickness was determined to be 0.53 feet. MW-18 depth versus log time data plotted for this method has been included as Figure 4.

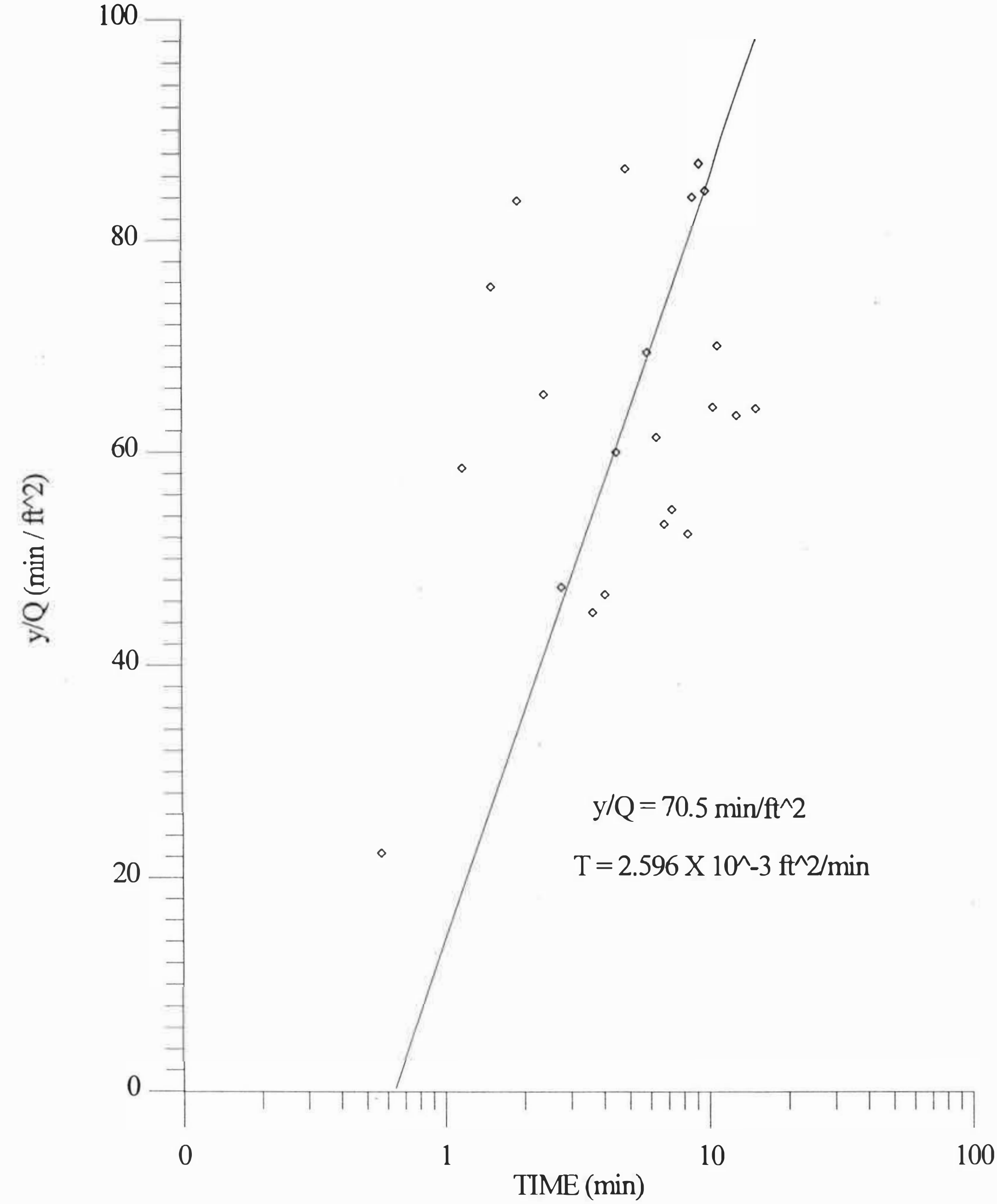

Figure 3. Jacob-Lohman y/Q Method for MW-18.

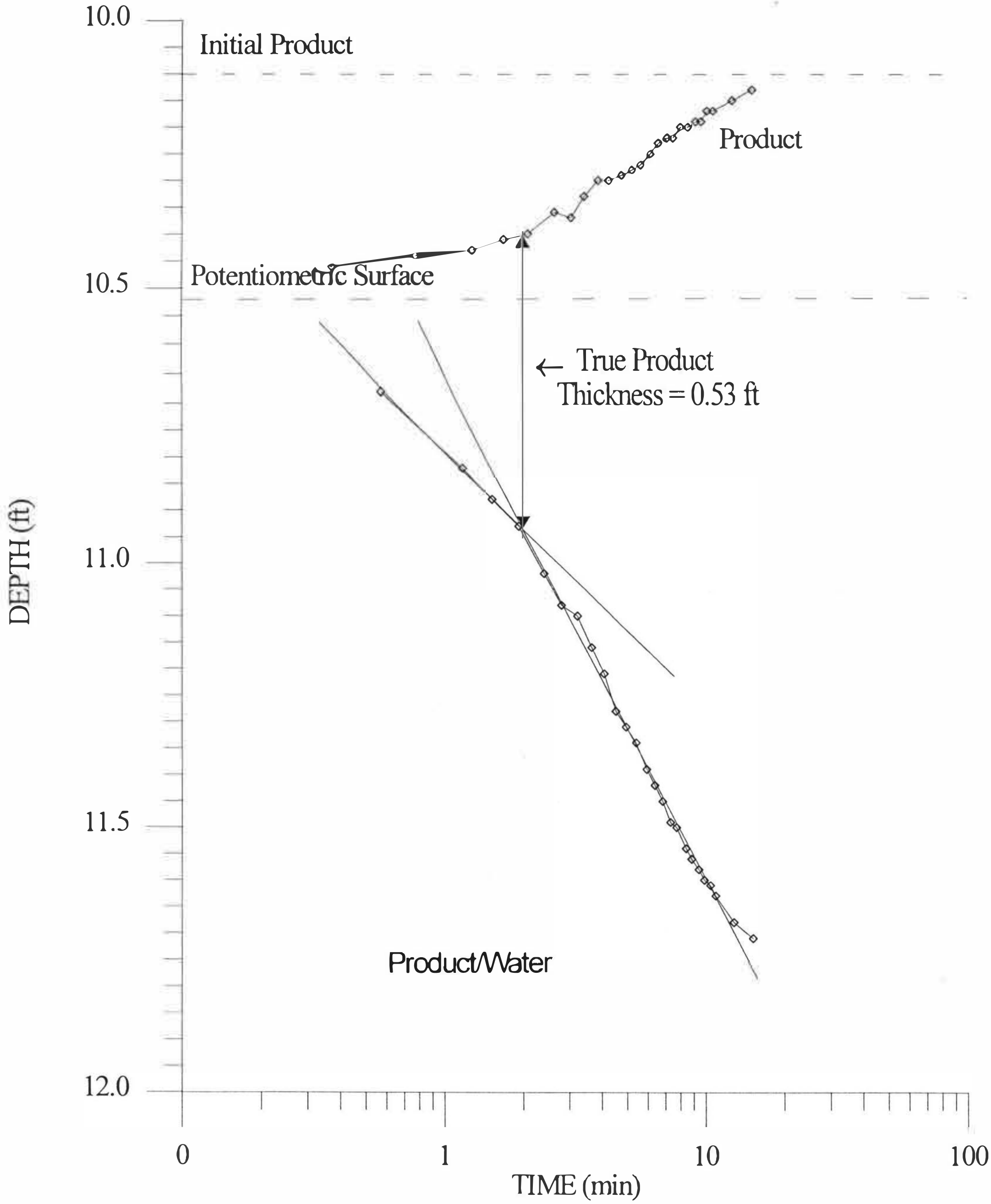

Figure 4. Yaniga Method for MW-18.

Gruszczenski Method

The true product thickness, the capillary fringe thickness and the location of the tops and bottoms associated with these features can be determined using the Gruszczenski method for analyzing bail-down test results. The depth to product versus time and depth to product/water interface versus time values recorded in the field were plotted on cartesian graph paper. The initial product depth measurement recorded during the test was taken as the inflection point on the product/water curve because the slope of this curve was negative from this point to the end. The vertical distance between the inflection point on the product/water interface curve and the product curve is reportedly the true product thickness in the formation and was measured to be 0.23 feet.

The depth to the potentiometric surface calculated in the Bouwer and Rice Section of this paper was determined to be 10.52 feet. This surface was plotted on the graph as a dashed horizontal line. The vertical distance between the potentiometric surface and the initial product level represents the total product and capillary fringe thickness and was 0.42 feet. The thickness of the capillary fringe is calculated by subtracting the product thickness from the total product and capillary fringe thickness. The calculated capillary fringe thickness is 0.19 feet.

The depths to the top and bottom of these features were calculated relative to the average corrected water depth calculated at the inflection point and at static conditions. The corrected depth to water at static conditions, the potentiometric surface previously calculated, is 10.52 feet. The corrected depth to water at the inflection point is 10.51 feet. The average of the two is 10.52 feet. The top of the water table correlates to the bottom of the capillary fringe; therefore, the bottom of the capillary fringe is at a depth of 10.52 feet. The top of the capillary fringe correlates with the bottom of the free product layer and is at a depth of 10.33 feet. The top of product in the formation is at a depth of 10.10 feet. MW-18 depth versus time data plotted for this method have been included as Figure 5.

Hughes, Sullivan, and Zinner Method

One of the criteria to use the Hughes, Sullivan, and Zinner method is that the hydrocarbon/water interface in the formation must be above the potentiometric surface in the formation. The reported saturated thickness of the free product layer was 0.6 feet at the Constantine site. Assuming the top of the free product corresponds to the initial, static product depth in the well, 10.10 feet, the bottom of the free product layer, the product/water interface, would be at a depth of 10.70 feet. The potentiometric surface depth was calculated in the Bouwer and Rice section to be 10.52 feet. Therefore, the product/water interface is reportedly below the potentiometric surface and the first criteria is not met. The Hughes et al. method was still applied to this well for comparison purposes.

The true free product thickness and the depth at which it is encountered in the formation were ascertained using the Hughes, Sullivan, and Zinner (1988) method for

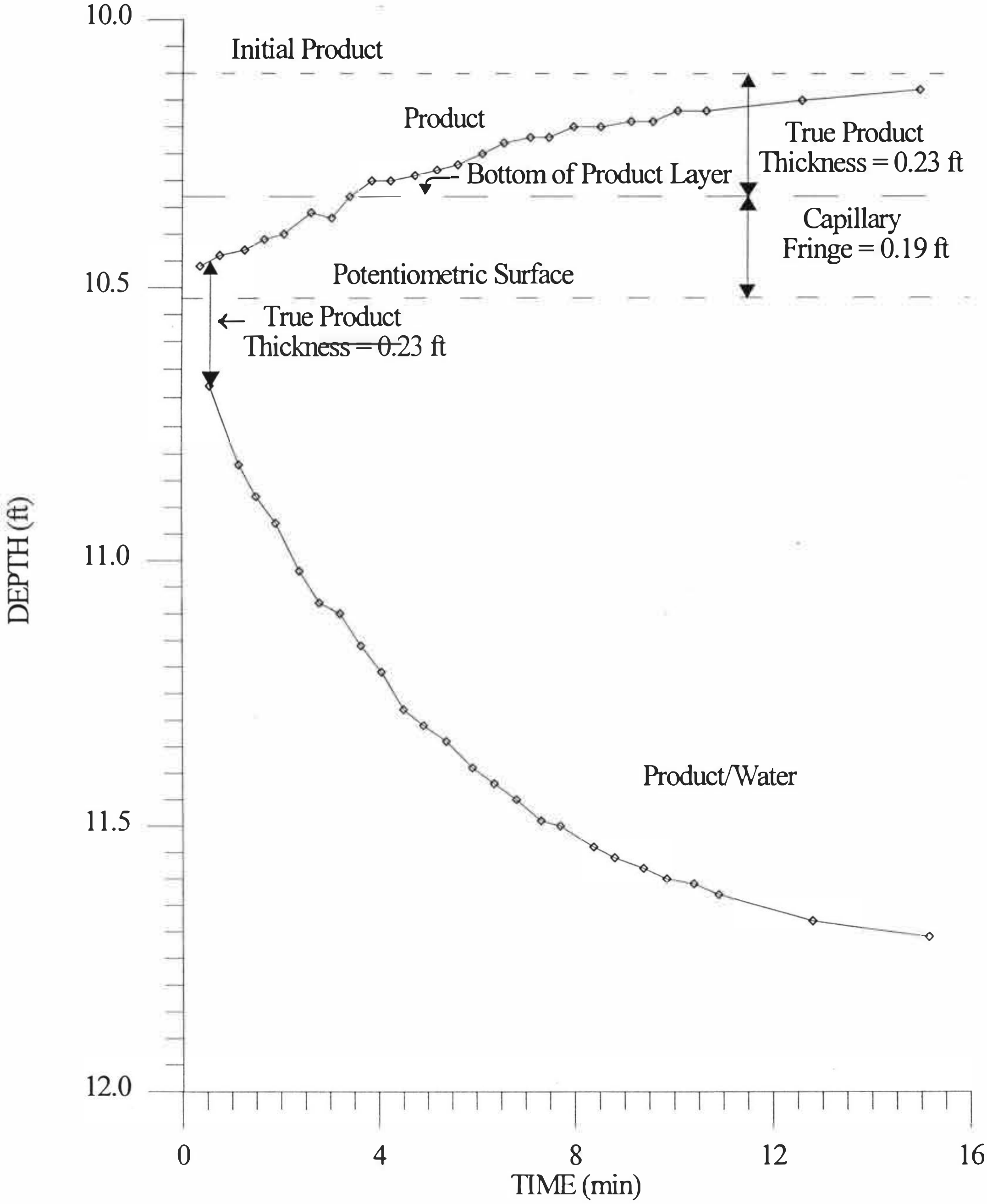

Figure 5. Gruszczenski Method for MW-18.

analyzing free product bail-down test data. The depth to product versus elapsed time was plotted on cartesian graph paper. A straight line was fitted to the readings taken at the beginning of the test which reportedly represent product entering the well at a constant rate during this portion of the recovery. The point at which the curve begins to curve, thus deviating from the straight line, is referred to as the inflection. The inflection was located at a depth of 10.30 feet, which represents the free product base depth. The initial free product depth measured in the well which reportedly correlates with the top of the free product in the formation was at a depth of 10.10 feet. The vertical distance between the inflection point and the initial, static oil depth was 0.20 feet, which is the true free product thickness in the formation.

A capillary fringe overlying the ground water table and underlying the mobile free product layer can be inferred using the above information. The capillary fringe thickness was 0.22 feet and would be encountered from a depth of 10.30 to a depth of 10.52 feet. MW-18 depth to product versus time data plotted for this analysis have been included as Figure 6.

Carson City Site - Well CR-3A

<u>Bouwer and Rice Method</u>

The Bouwer and Rice slug test was developed for ground water applications. Instead of applying this method to a ground water slug test, it has been applied to a free product bail-down test. AQTESOLV v.1.1 was used to analyze the results of the

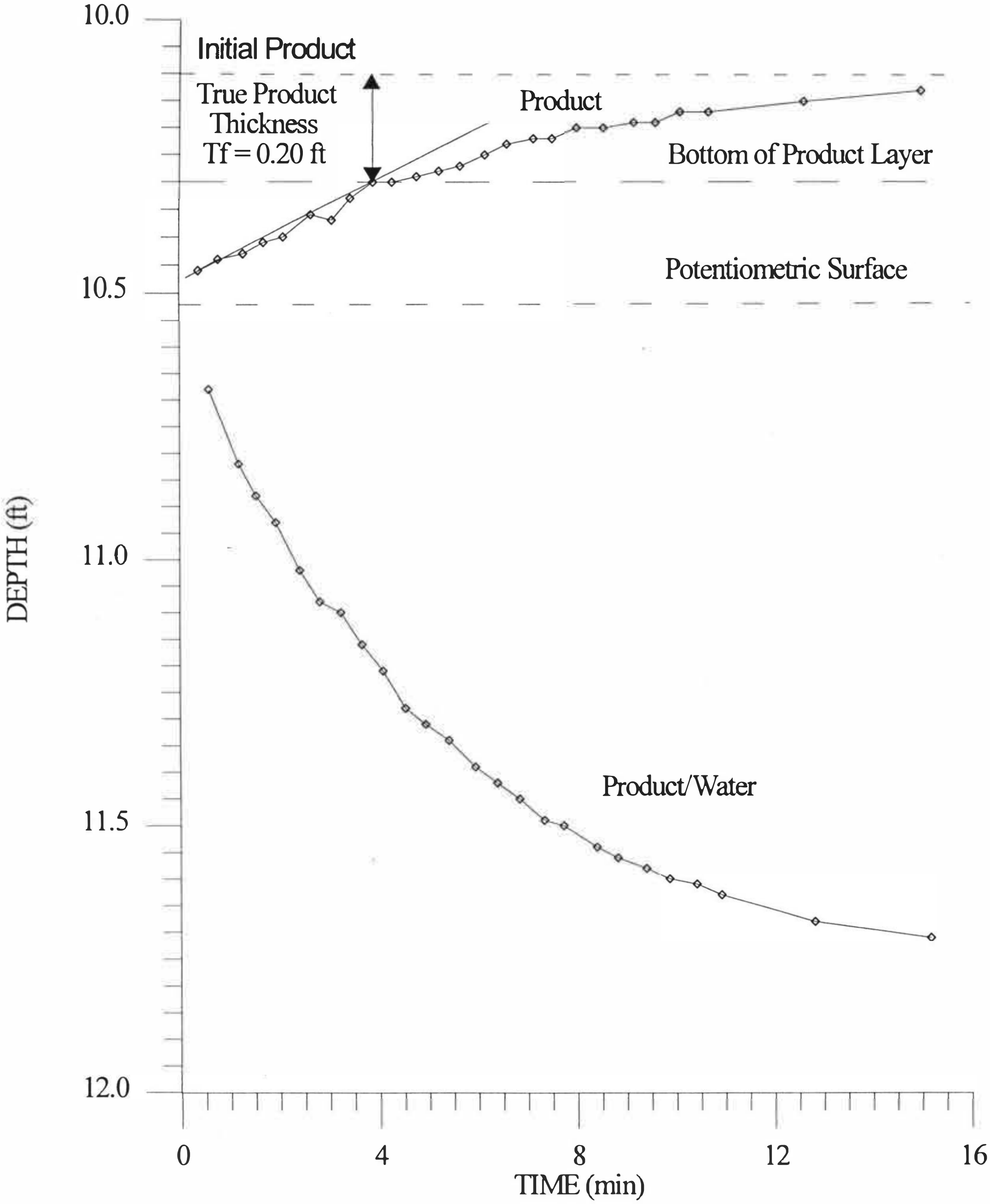

Figure 6. Hughes et al. Method for MW-18.

bail-down test using the Bouwer and Rice equations. Time versus drawdown data were entered in spread sheet format within the program. The drawdown values entered into the spread sheet represent the product drawdowns in the well which were calculated from the field data using the following equation. The data collected from time t = 0.65 minutes has been included as an example calculation:

$$y_p = D_{pt} - D_{pi} = 12.730 - 12.172 = 0.56 \text{ ft}$$

where y_p = product drawdown = 0.56 ft

D_{pt} = product depth at time 't' = 12.730 ft

D_{pi} = initial product depth = 12.172 ft

The elapsed time and calculated oil drawdown data have been included as Table 7.

The potentiometric surface was calculated using the following equation with the initial product and product/water interface depths included as a sample calculation:

$$w_e = o_i\,(SGhc) = (4.80)\,(0.827) = 3.97 \text{ ft}$$

$$D_{ps} = D_{p/w} - w_e = 16.97 - 3.97 = 13.00 \text{ ft}$$

where: w_e = equivalent water thickness = 3.97 ft

o_i = initial product thickness = 4.80 ft

Table 7

Free Product Bail-Down Test Bouwer and Rice Calculated Values for CR-3A Located in Carson City, Michigan (Test Performed on August 8, 1994)

ELAPSED TIME, minutes	PRODUCT DEPTH, feet	PRODUCT DRAWDOWN, feet (a)
0 (b)	12.172	0.560
0.65	12.730	0.558
4.00	12.713	0.541
5.00	12.710	0.538
6.00	12.707	0.535
7.00	12.703	0.531
8.00	12.700	0.528
9.00	12.697	0.525
11.00	12.694	0.522
13.00	12.690	0.518
15.00	12.687	0.515
17.00	12.684	0.512
20.00	12.677	0.505
23.00	12.674	0.502
32.00	12.667	0.495
40.00	12.657	0.485
52.00	12.648	0.476
67.00	12.641	0.469
84.00	12.628	0.456
96.00	12.625	0.453
210.00	12.612	0.440

(a) Calculated by subtracting the product depth at time ‘t’ from the initial product depth 12.172 ft.
(b) Values estimated from log drawdown (displacement) versus time plot.

SGhc = specific gravity of the hydrocarbon = 0.827

D_{ps} = depth to the potentiometric surface = 13.00 ft

$D_{p/w}$ = initial depth to the product/water interface = 16.97 ft

The program requires the input of several site specific parameters which include the following: initial drawdown in the well; radius of well casing; radius of well; saturated thickness; screen length; and static height of water in well. The details of the product bail-down test were entered for these site specific parameters so the results should represent the oil characteristics in the subsurface. The y_o intercept value extrapolated to time zero was assumed to be the initial drawdown in the well and was inputted as 0.56 feet. The well was constructed using 4-inch diameter PVC casing, so the radius of the well casing was entered as 0.167 feet. The well borehole was approximately 10.5-inches in diameter, so the radius of the well was entered as 0.438 feet. The actual oil saturated thickness is not known; therefore, an estimate of 1.0 foot was inputted for the saturated thickness. The product saturated length of the well screen was used as the screen length and was entered as 4.797 feet. The initial oil thickness above the potentiometric surface measured in the well prior to the test was assumed to correlate with the static height of water in well parameter. This value was calculated by subtracting the potentiometric surface depth from the initial product depth and was inputted as 0.828 feet. A summary of the site specific parameters entered into the program has been included as Table 8.

AQTESOLV plotted the log oil drawdown versus time and calculated a hydrocarbon hydraulic conductivity of 2.29×10^{-6} ft/min. Using the saturated thickness of 1.0 feet, the hydrocarbon transmissivity was calculated to be 2.29 x 10^{-6} ft^2/min. The AQTESOLV plot used for CR-3A has been included as Figure 7.

Table 8

Free Product Bail-Down Test Calculated Bouwer and Rice Slug Test AQTESOLV Input Values for CR-3A Located in Carson City, Michigan (Test Performed on August 8, 1994)

Parameter	Value
Initial Drawdown in Well (@ t = 0)	0.56 feet
Radius of Well Casing	0.167 feet
Radius of Well	0.438 feet
Saturated Thickness	1.0 feet
Screen Length	4.797 feet
Static Height of Water in Well	0.828 feet

Jacob-Lohman Method

Data collected from the product bail-down test were analyzed using the Jacob-Lohman method for constant drawdown, variable rate slug test analysis as applied by Huntley et al. (1994). The transmissivity was calculated using the following equation (based on Lohman, 1979, equation 72):

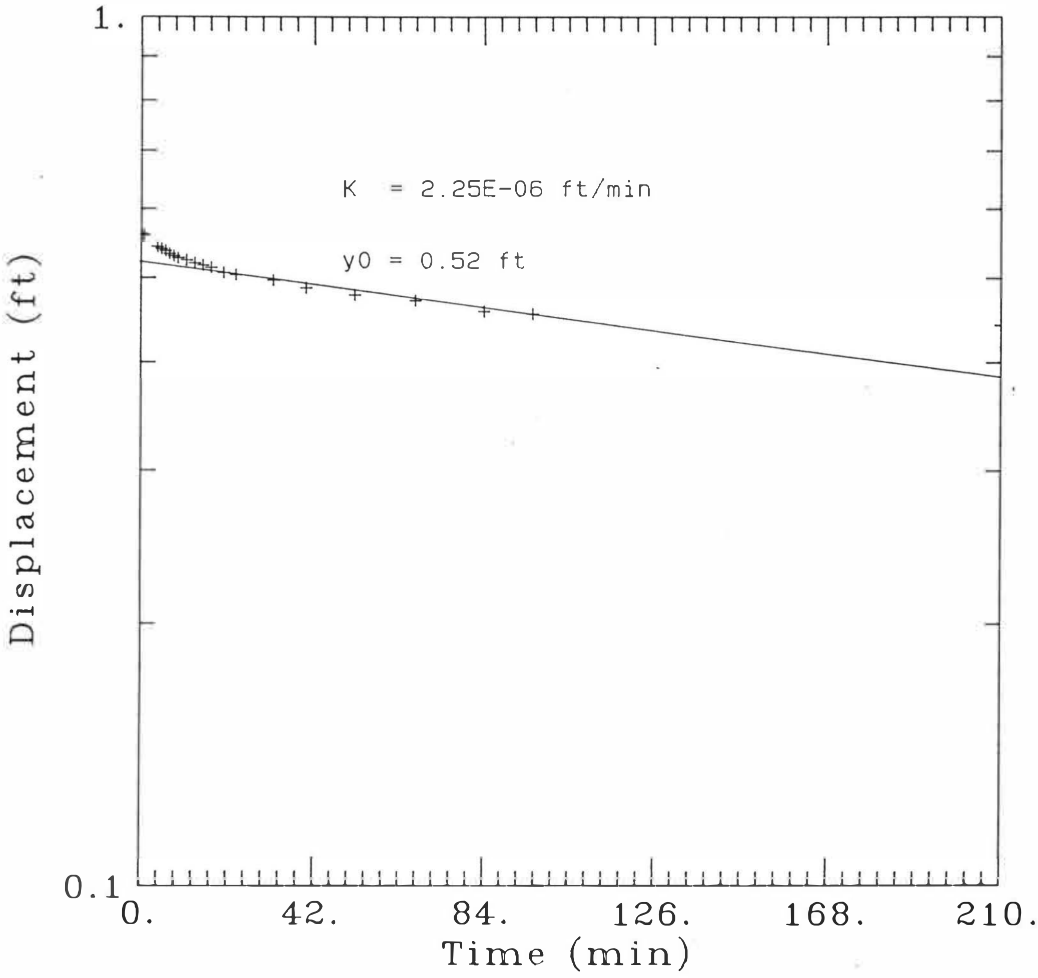

Figure 7. Bouwer & Rice Method for CR-3A.

$T = 2.3 / [4\pi\ y_p\ \Delta(1/Q) / \Delta\log_{10}t] = 2.3 / [\ 4\ \pi\ (0.498)\ (3340)] = 1.1 \times 10^{-4}\ ft^2/min$

where T = transmissivity = $1.1 \times 10^{-4}\ ft^2/min$

y_p = fluid drawdown in discharging well = 0.498 ft

$\Delta 1/Q$ = reciprocal of discharge over one time log cycle = 3340 min/ft^3

The reciprocals of the instantaneous product discharge (1/Q) values were plotted against log elapsed time. A straight line was fitted to the data and used to determine the reciprocal of the variable discharge rate into the well, $\Delta 1/Q$, which was 3340 min/ft^3. An average product drawdown of 0.498 feet was calculated using the product drawdown values determined in the previous Bouwer and Rice method and was used as the constant drawdown, y_p. The hydrocarbon transmissivity value calculated was $1.1 \times 10^{-4}\ ft^2/min$. Using a product saturated thickness of 1.0 feet, the hydrocarbon hydraulic conductivity value calculated was 1.1×10^{-4} ft/min. The calculated reciprocal discharge values used to generate this plot are summarized in Table 9. The CR-3A discharge versus log time data plot used to determine these parameters has been included as Figure 8.

The hydrocarbon transmissivity was then calculated using the Jacob-Lohman variable discharge, variable rate straight-line method as follows (based on Lohman, 1979, equation 71):

$T = 2.3\ /\ [4\ \pi\ \Delta(y_p/Q) / \Delta\log_{10}t] = 2.3 / [\ 4\ \pi\ (1330)] = 1.4 \times 10^{-4}\ ft^2/min$

Table 9

Free Product Bail-Down Test Jacob-Lohman Method Calculated Values
for CR-3A Located in Carson City, Michigan
(Test Performed on August 8, 1994)

ELAPSED TIME, minutes	PRODUCT DRAWDOWN, feet	1/Q, minute/feet^3	y_p/Q, minute/feet^2
1.25	0.558		
4.50	0.541	2660	1439
5.50	0.538	881	474
6.50	0.535	1910	1022
7.50	0.531	477	253
8.50	0.528	3820	2017
9.50	0.525	1910	1003
11.5	0.522	1763	920
13.5	0.518	764	396
15.5	0.515	2292	1180
18.0	0.512	1790	917
20.5	0.505	955	482
23.5	0.502	3820	1917
32.5	0.495	1946	963
40.5	0.485	2292	1112
52.5	0.476	3274	1558
68.0	0.469	2691	1262
85.0	0.456	3746	1708
96.5	0.453	3661	1658
210.0	0.440	5287	2326

where T = transmissivity = 1.4×10^{-4} ft^2/min

$\Delta (y_p/Q)$ = drawdown divided by discharge over one log cycle = 1330 min/ft^2

The reciprocals of the instantaneous product discharge (1/Q) values were multiplied by the product drawdown at each reading and plotted against log elapsed

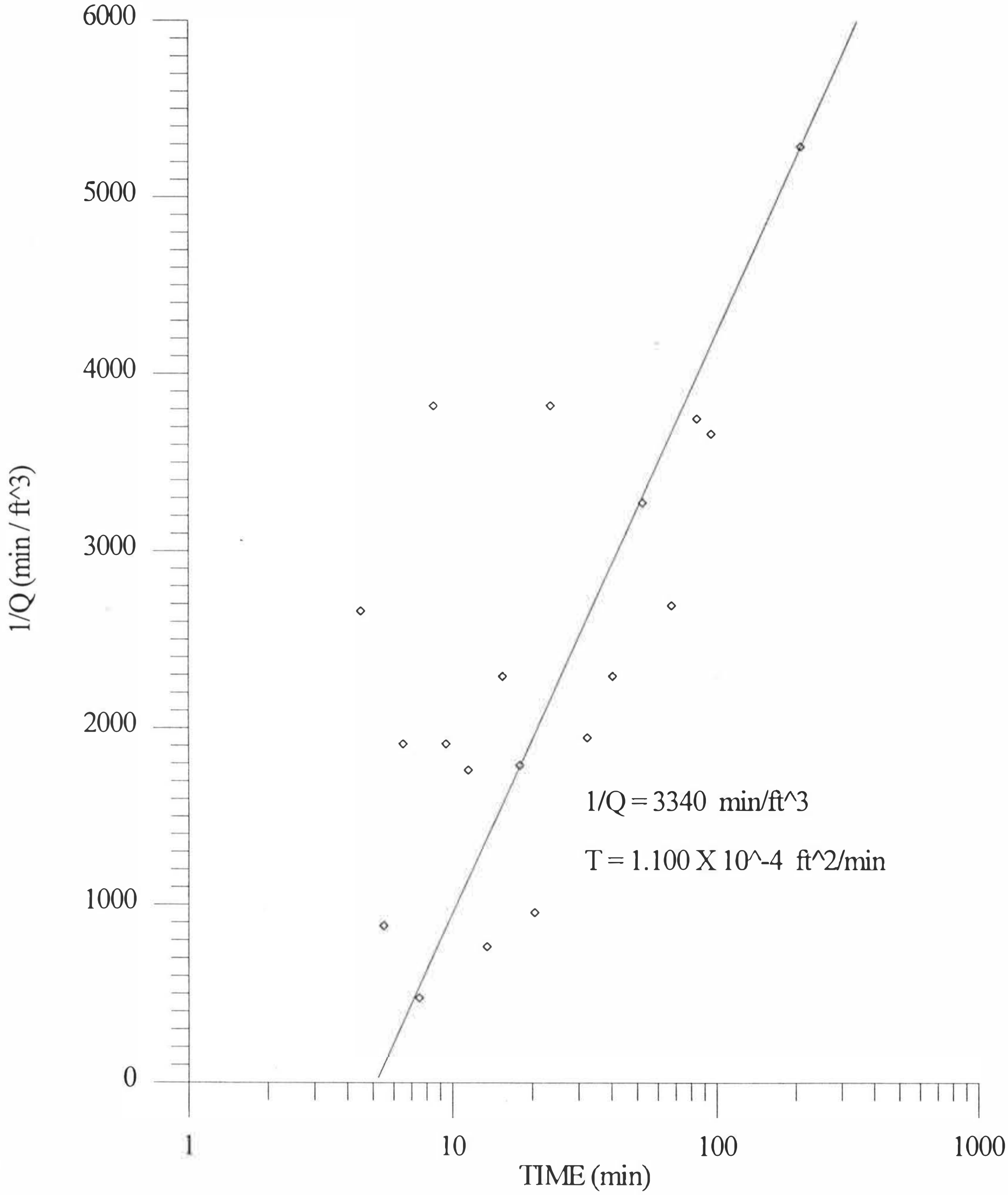

Figure 8. Jacob-Lohman 1/Q Method for CR-3A.

time. A straight line was fitted to the data and used to determine the time weighted drawdown divided by discharge rate into the well over one log cycle of time, $\Delta(y_p/Q) / \Delta\log_{10}t$, which was 1330 min/ft^2. The hydrocarbon transmissivity value calculated was 1.4×10^{-4} ft^2/min. Using an oil saturated thickness of 1.0 feet, the hydrocarbon hydraulic conductivity value calculated was 1.4×10^{-4} ft/min. The calculated drawdown divided by discharge values used to generate the plot are also summarized in Table 8. The CR-3A drawdown divided by discharge versus log time data plot used to determine these parameters has been included as Figure 9.

Yaniga Method

The true product thickness was determined following the Yaniga method of analysis as used by Wagner et al. (1989). Application of this method was very quick and relatively easy. First, the depth to product versus log time and the depth to product/water interface versus log time were plotted. An attempt was made to fit 2 straight lines to the product/water interface data points. Unfortunately, 3 straight lines could be fitted to this data. The first straight line is assumed to correlate to free product draining out of the gravel pack, and therefore, is not representative of the formation. The intersection of the second and third line was therefore used to determine the vertical distance between this intersection point on the product/water curve and the top of product curve, which reportedly represents the true product thickness. The true product thickness was determined to be 1.37 feet. CR-3A depth

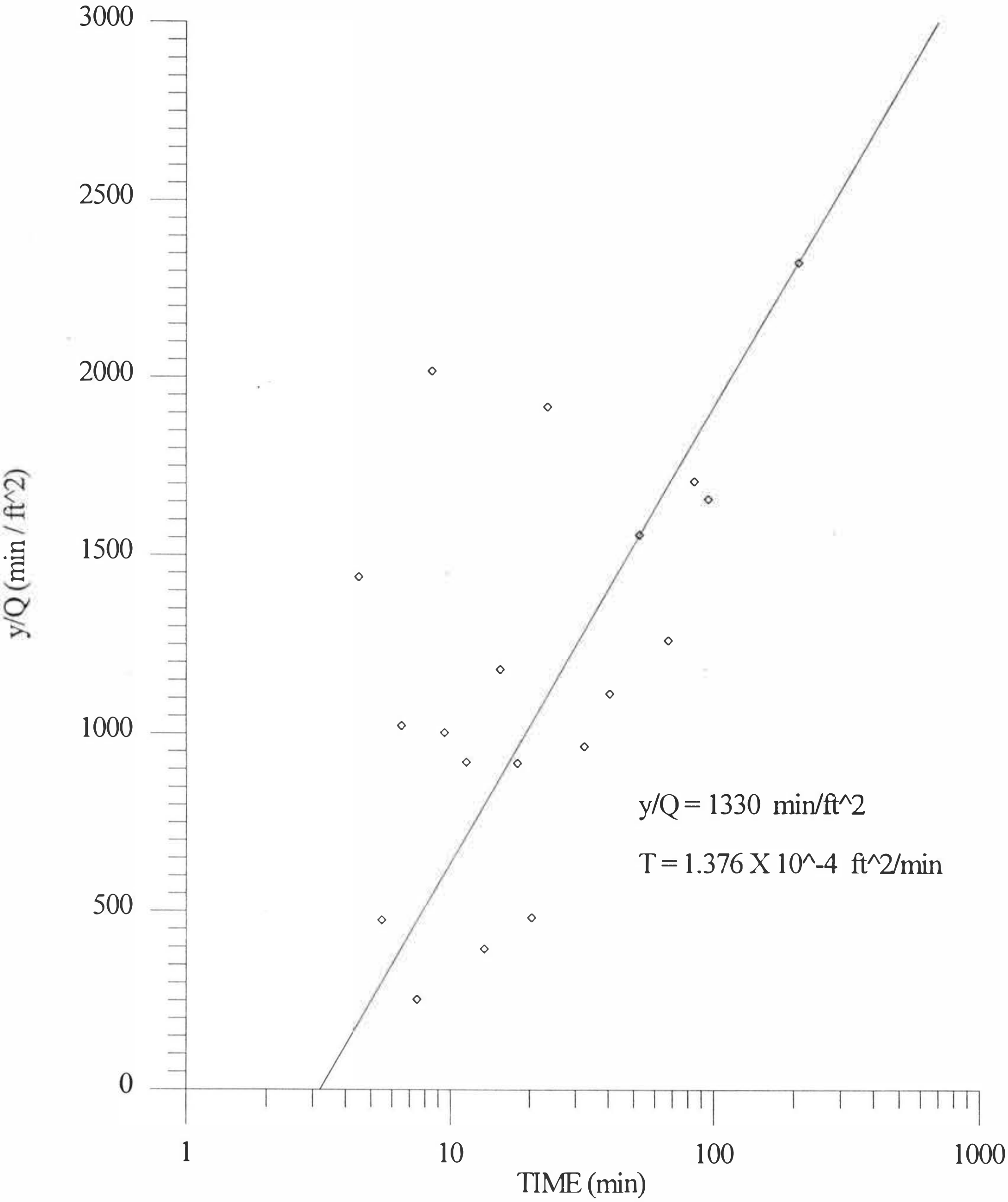

Figure 9. Jacob-Lohman y/Q Method for CR-3A.

versus log time data plotted for this method has been included as Figure 10.

Gruszczenski Method

The true product thickness, the capillary fringe thickness and the location of the tops and bottoms associated with these features can be determined using the Gruszczenski method for analyzing bail-down test results. The depth to product versus time and depth to product/water interface versus time values recorded in the field were plotted on cartesian graph paper. The inflection point on the product/water curve was determined where the slope of this curve was negative. The vertical distance between this point and the product curve, which reportedly represents the true product thickness in the formation, was measured to be 1.09 feet.

The depth to the potentiometric surface calculated in the Bouwer and Rice Section of this paper was determined to be 13.00 feet. This surface was plotted on the graph as a dashed horizontal line. The vertical distance between the potentiometric surface and the initial product level reportedly represents the total product and capillary fringe thickness and was 0.828 feet. Since this thickness is less than the true product thickness determined from the graph, there is apparently no capillary fringe in this area.

The depths to the top and bottom of the free product layer were calculated relative to the average corrected water depth calculated at the inflection point and at static conditions. The corrected depth to water at static conditions, the potentiometric

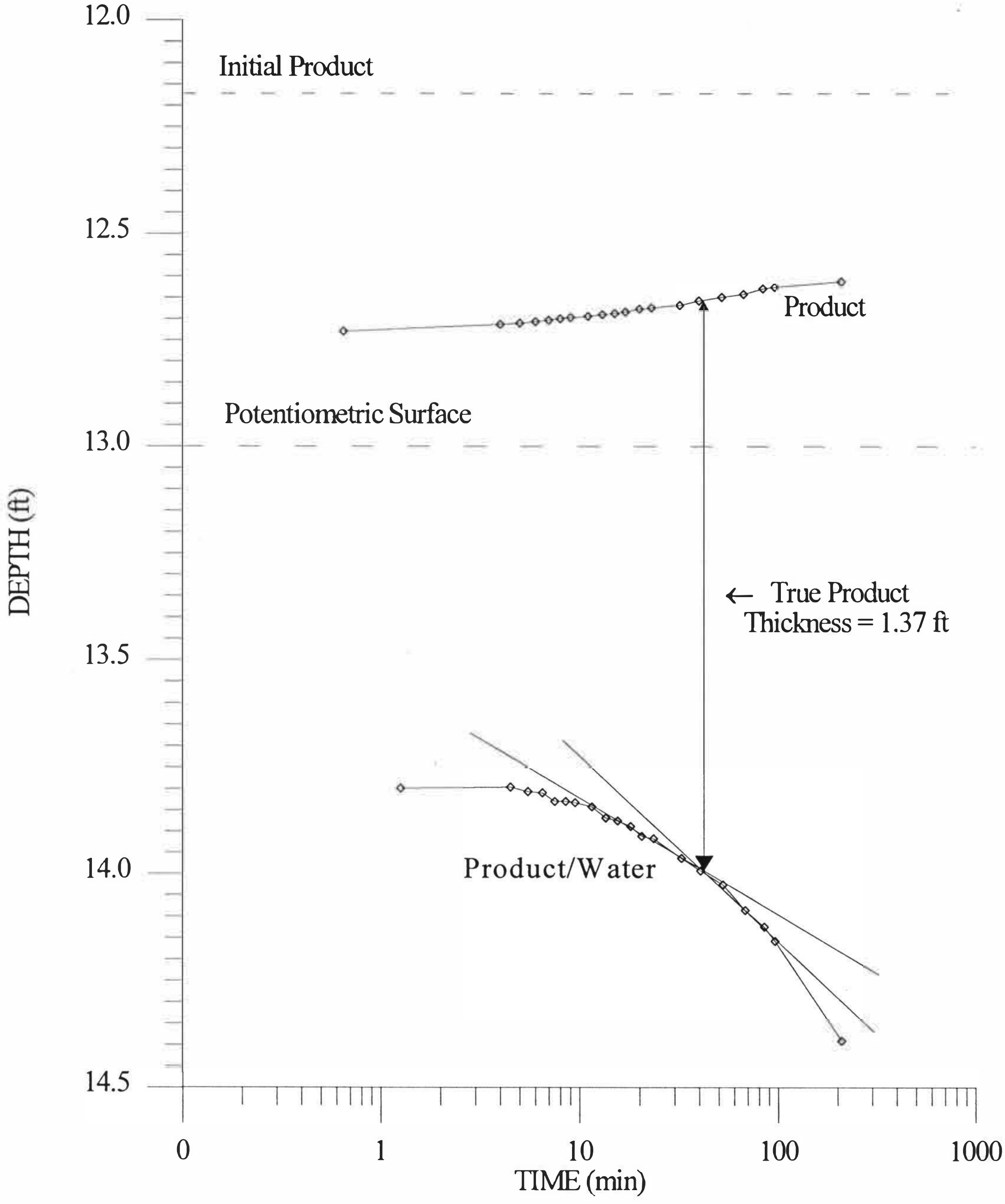

Figure 10. Yaniga Method for CR-3A.

surface previously calculated and the corrected depth to water at the inflection point were both 13.00 feet. The top of the product in the formation is at a depth of 12.172 feet and the bottom of this layer is at a depth of 13.262 feet. It should be noted that the bottom of the product layer determined using this method is below the potentiometric surface in the formation. Well CR-3A depth versus time data plotted for this method has been included as Figure 11.

Hughes, Sullivan, and Zinner Method

One of the criteria to use the Hughes, Sullivan, and Zinner method is that the hydrocarbon/water interface in the formation must be above the potentiometric surface in the formation. The previous method indicated that this may not be the situation at the Carson City site. The Hughes et al. method was still applied to this well even though the actual free product thickness was not known.

The true free product thickness, and the depth at which it is encountered in the formation were ascertained using the Hughes, Sullivan, and Zinner (1988) method for analyzing free product bail-down test data. The depth to product versus elapsed time was plotted on cartesian graph paper. A straight line was fitted to the readings taken at the beginning of the test which reportedly represent product entering the well at a constant rate during this portion of the recovery. The point at which the data trace begins to curve, thus deviating from a straight line, is referred to as the inflection point, which represents the point where the product enters the well from the

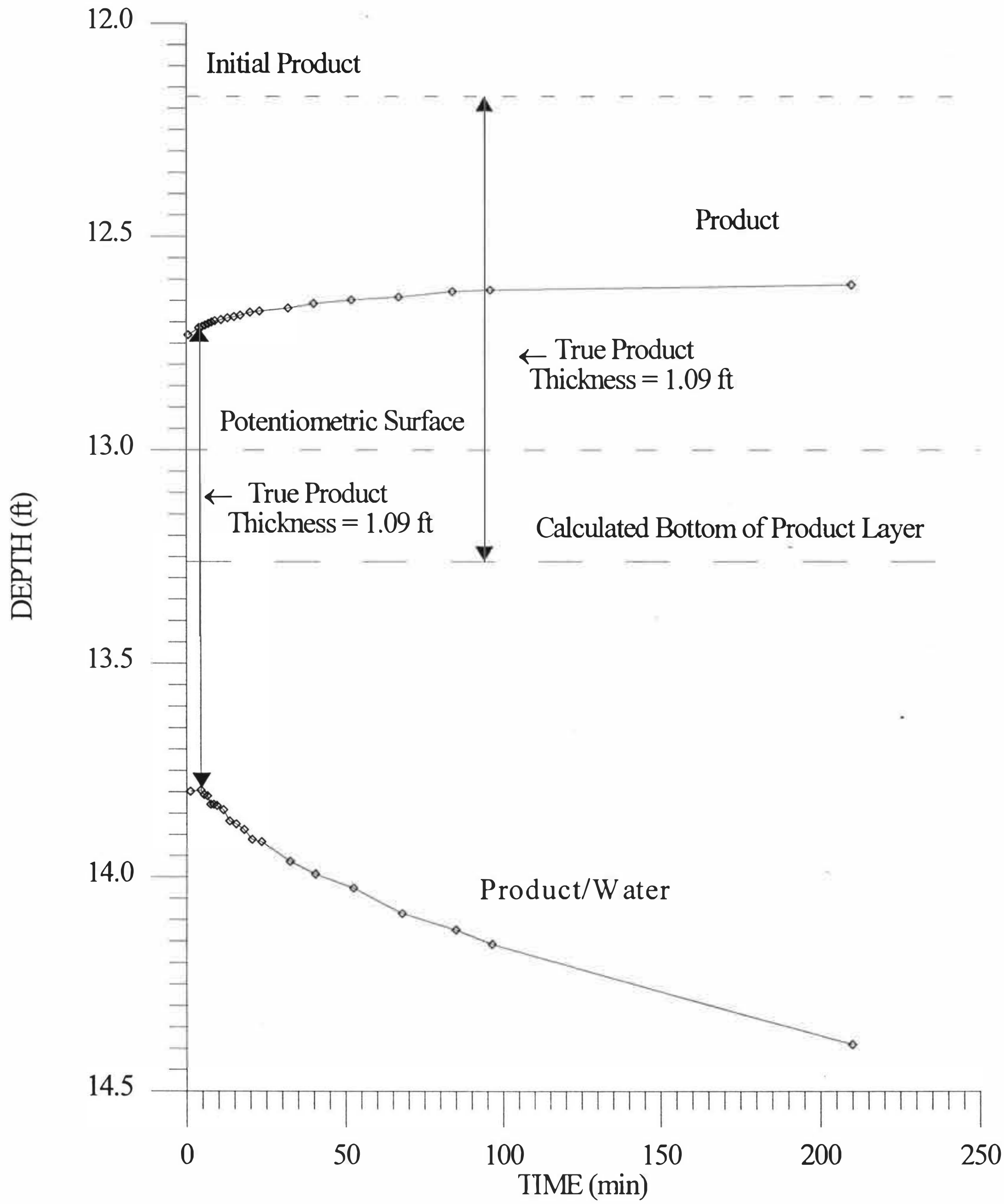

Figure 11. Gruszczenski Method for CR-3A.

formation. The inflection point was located at a depth of 12.70 feet, which represents the mobile free product base depth. The vertical distance between the inflection point and the initial, static product depth of 12.17 feet was 0.53 feet, which represents the total product thickness in the formation.

A capillary fringe overlying the ground water table and underlying the mobile free product layer can be inferred using the above information. The capillary fringe thickness would be 0.30 feet and would be encountered from a depth of 12.70 to a depth of 13.00 feet. Well CR-3A depth to product versus time data plotted for this analysis has been included as Figure 12.

Carson City Site - Well CR-3B

Bouwer and Rice Method

The Bouwer and Rice slug test was developed for ground water applications. Instead of applying this method to a ground water slug test, it has been applied it to a free product bail-down test. AQTESOLV v.1.1 was used to analyze the results of the bail-down test using the Bouwer and Rice equations. Time versus drawdown data was inputted in spread sheet format within the program. The drawdown values entered into the spread sheet represent the product drawdowns in the well which were calculated from the field data using the following equation. The data collected from time t = 1.98 minutes has been included as an example calculation:

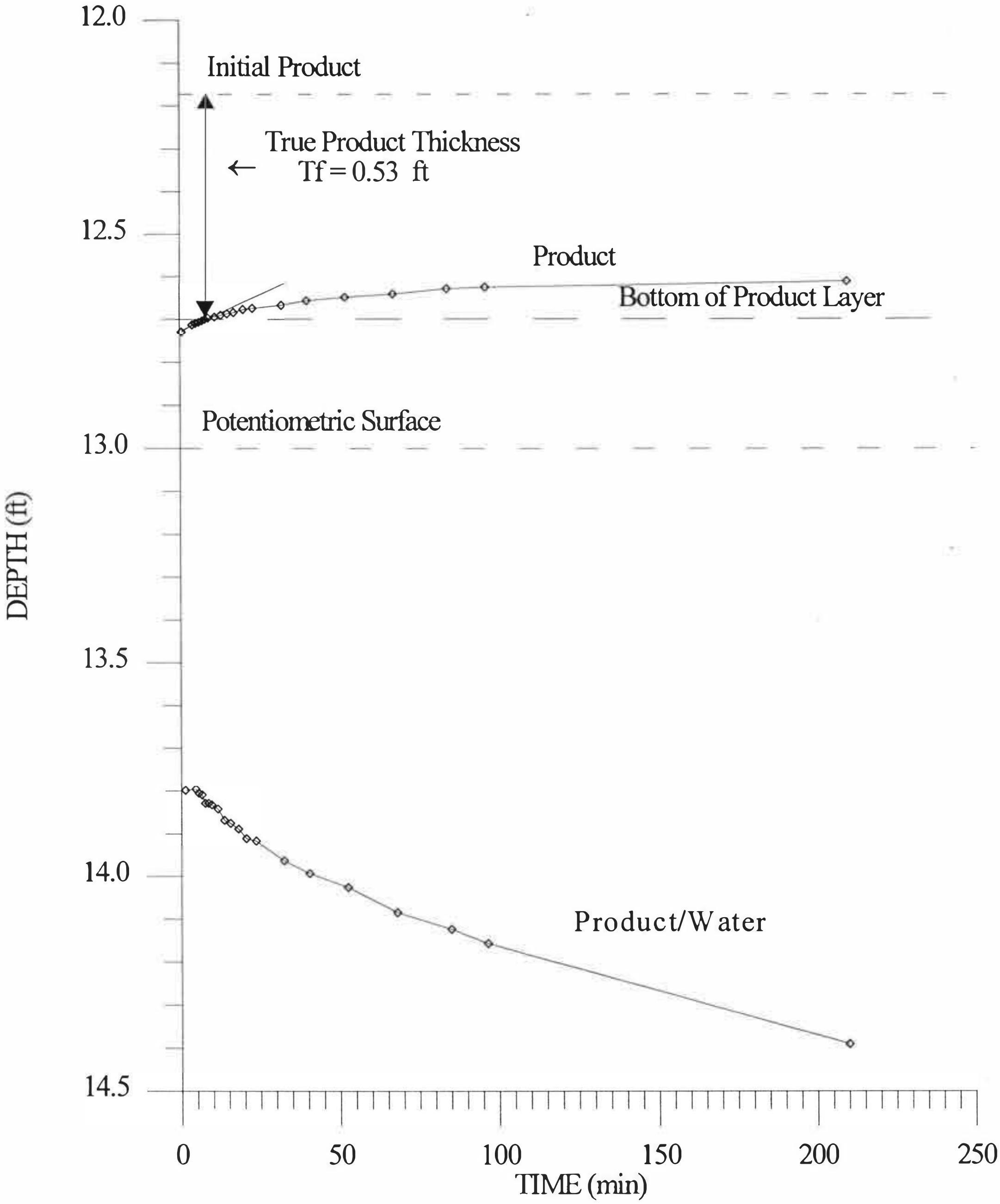

Figure 12. Hughes et al. Method for CR-3A.

$$y_p = D_{pt} - D_{pi} = 12.720 - 12.336 = 0.38 \text{ ft}$$

where y_p = product drawdown = 0.38 ft

D_{pt} = product depth at time 't' = 12.72 ft

D_{pi} = initial product depth = 12.34 ft

The elapsed time and calculated product drawdown data has been included as Table 10.

The potentiometric surface was calculated using the following equation, with the initial product and product/water interface depths included as a representative calculation.

$$w_e = o_i \, (SGhc) = (4.390)\,(0.827) = 3.62 \text{ ft}$$

$$D_{ps} = D_{p/w} - w_e = 16.726 - 3.631 = 13.095 \text{ ft}$$

where: w_e = equivalent water thickness = 3.631 ft

o_i = initial product thickness = 4.390 ft

SGhc = specific gravity of the hydrocarbon = 0.827

D_{ps} = depth to the potentiometric surface = 13.095 ft

$D_{p/w}$ = initial depth to the product/water interface = 16.726 ft

The details of the product bail-down test were entered for these site specific parameters so the results should represent the oil characteristics in the subsurface. The y_o intercept value extrapolated to time zero was assumed to be the initial drawdown in the well, and was 0.39 feet. The well was constructed using 4-inch diameter PVC casing, so the radius of the well casing was 0.167 feet. The well

Table 10

Free Product Bail-Down Test Bouwer and Rice Calculated Values
for CR-3B Located in Carson City, Michigan
(Test Performed on August 8, 1994)

ELAPSED TIME, minutes	PRODUCT DEPTH, feet	PRODUCT DRAWDOWN, feet (a)
1.98	12.720	0.384
3.12	12.723	0.387
4.02	12.713	0.377
4.98	12.713	0.377
6.18	12.690	0.354
7.68	12.680	0.344
9.30	12.674	0.338
11.16	12.667	0.331
13.32	12.664	0.328
15.16	12.654	0.322
17.10	12.654	0.318
20.16	12.648	0.312
26.88	12.641	0.305
33.00	12.631	0.295
41.52	12.625	0.289
52.68	12.615	0.279
68.40	12.605	0.269
84.60	12.595	0.259
210.0	12.543	0.207

(a) Calculated by subtracting the product depth at time ‘t’ from the initial product depth 12.336 ft.
(b) Values estimated from log drawdown (displacement) versus time plot.

borehole was approximately 10.5-inches in diameter, so the radius of the well was 0.438 feet. The actual oil saturated thickness is not known, therefore a value of 1.0 foot was assumed for the saturated thickness. The product saturated length of the well screen was used as the screen length and was 4.39 feet. The initial product thickness above the potentiometric surface measured in the well prior to the test was assumed to correlate with the static height of water in well parameter. This value was calculated by subtracting the potentiometric surface depth from the initial product depth and was 0.759 feet. A summary of the site specific parameters entered into the program has been included as Table 11.

Table 11

Free Product Bail-Down Test Calculated Bouwer and Rice Slug Test AQTESOLV Input Values for CR-3B Located in Carson City, Michigan (Test Performed on August 8, 1994)

Parameter	Value
Initial Drawdown in Well (@ t = 0)	0.39 feet
Radius of Well Casing	0.167 feet
Radius of Well	0.438 feet
Saturated Thickness	1.0 feet
Screen Length	4.39 feet
Static Height of Water in Well	0.759 feet

AQTESOLV plotted the log oil drawdown versus time and calculated a hydrocarbon hydraulic conductivity of 4.35×10^{-6} ft/min. Using the saturated thickness of 1.0 feet, the hydrocarbon transmissivity was calculated to be 4.35×10^{-6} ft^2/min. The AQTESOLV plot used for CR-3B has been included as Figure 13.

Jacob-Lohman Method

Data collected from the product bail-down test were analyzed using the Jacob-Lohman method for constant drawdown, variable rate slug test analysis as applied by Huntley et al. (1994). The transmissivity was calculated using the following equation (based on Lohman, 1979, equation 72):

$$T = 2.3 / [4\pi\, y_p\, \Delta(1/Q) / \Delta\log_{10}t] = 2.3 / [4\,\pi\,(0.430)\,(2880)] = 1.5 \times 10^{-4}\ ft^2/min$$

where T = transmissivity = 1.5×10^{-4} ft^2/min

y_p = fluid drawdown in discharging well = 0.43 ft

$\Delta 1/Q$ = reciprocal of discharge over one time log cycle = 2880 min/ft^3

The reciprocals of the instantaneous product discharge (1/Q) values were plotted against log elapsed time. A straight line was fitted to the data and used to determine the reciprocal of the variable discharge rate into the well, $\Delta 1/Q$, which was 2880 min/ft^3. An average product drawdown of 0.43 feet was calculated using the product drawdown values determined in the previous Bouwer and Rice method, and was used as the constant drawdown, y_p. The hydrocarbon transmissivity value

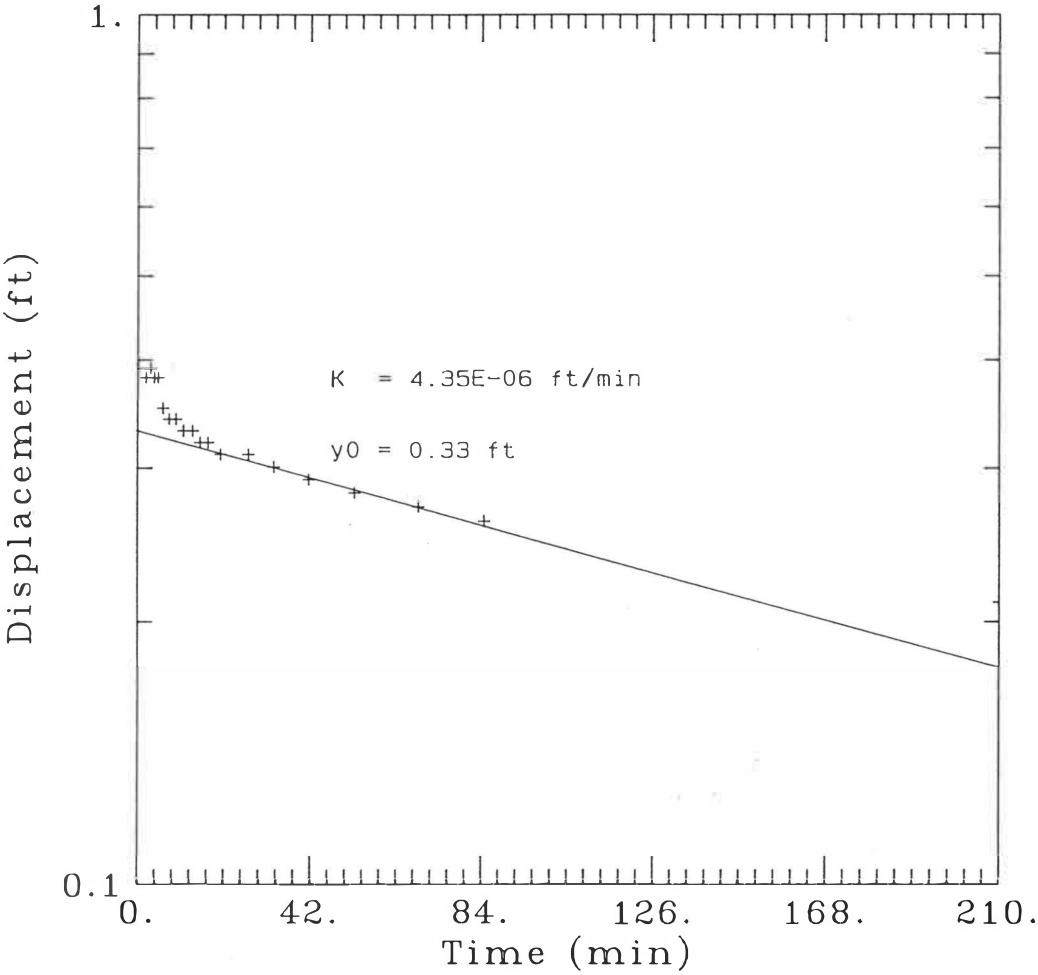

Figure 13. Bouwer & Rice Method for CR-3B.

calculated was 1.5 x 10^{-4} ft^2/min. Using a product saturated thickness of 1.0 feet, the hydrocarbon hydraulic conductivity value calculated was 1.5 x 10^{-4} ft/min. The calculated reciprocal discharge values used to generate this plot are summarized in Table 12. The CR-3B discharge versus log time data plot used to determine these parameters has been included as Figure 14.

Table 12

Free Product Bail-Down Test Jacob-Lohman Method Calculated Values
for CR-3B Located in Carson City, Michigan
(Test Performed on August 8, 1994)

ELAPSED TIME, minutes	PRODUCT DRAWDOWN, feet	1/Q, minute/feet^3	y_p/Q, minute/feet^2
3.48	0.387	279	108
4.62	0.377	284	107
5.40	0.377	545	206
6.66	0.354	293	104
8.22	0.344	495	171
9.84	0.338	514	174
11.64	0.331	1048	347
13.62	0.328	2305	756
15.48	0.322	928	298
17.52	0.318	1781	567
20.52	0.312	1164	363
27.48	0.305	1215	371
33.48	0.295	2619	773
42.12	0.289	2321	670
53.28	0.279	2784	776
69.30	0.269	3108	836
85.20	0.259	3085	800
210.0	0.207	3632	751

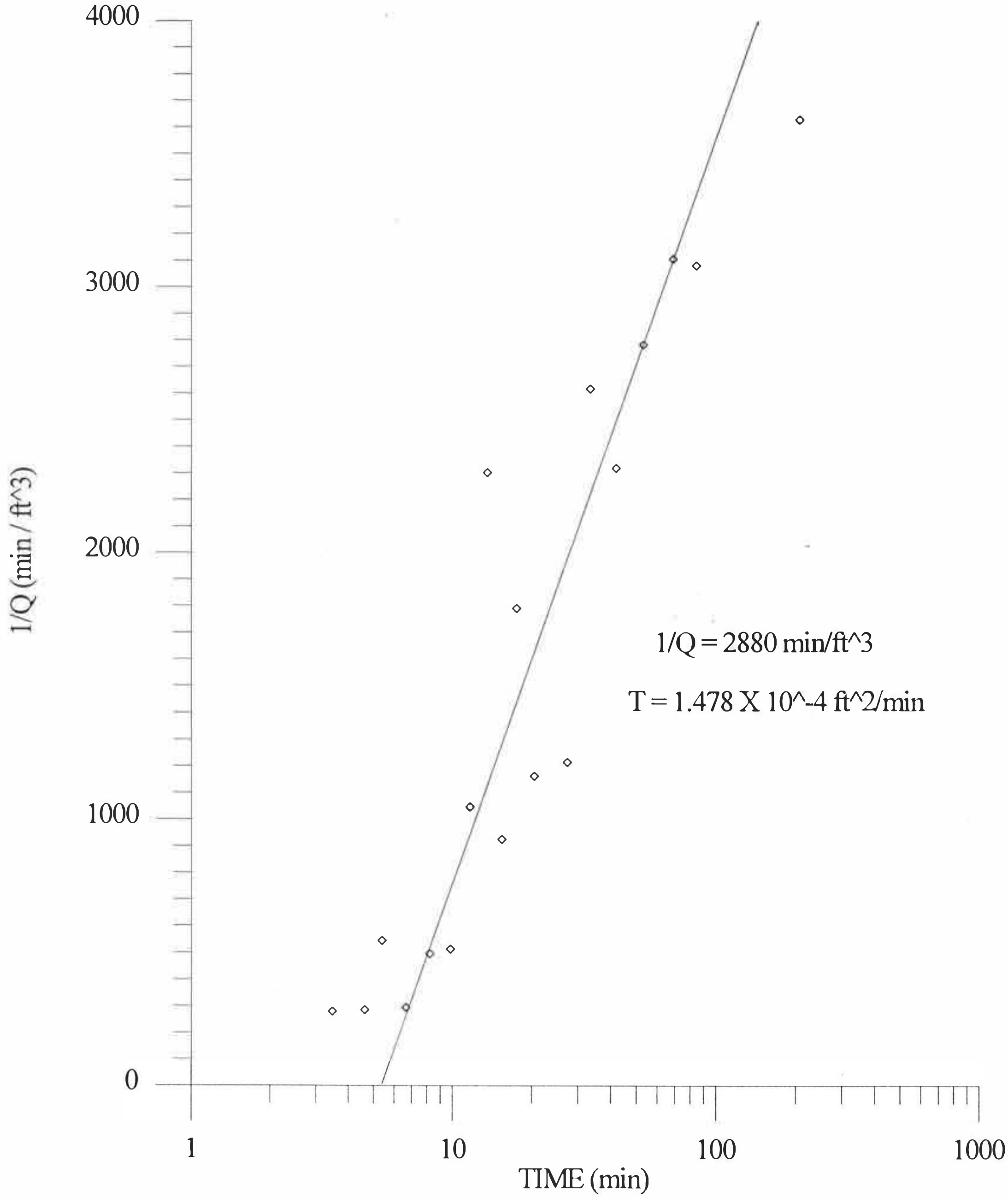

Figure 14. Jacob-Lohman 1/Q Method for CR-3B.

The hydrocarbon transmissivity was then calculated using the Jacob-Lohman variable discharge, variable rate straight-line method as follows (based on Lohman, 1979, equation 71):

$$T = 2.3 \ / \ [4 \pi \ \Delta(y_p/Q) \ / \ \Delta\log_{10}t] = 2.3 \ / \ [4 \pi \ (710)] = 2.6 \times 10^{-4} \ ft^2/min$$

where T = transmissivity = 2.6×10^{-4} ft^2/min

$\Delta y_p / Q$ = time weighted drawdown devided by discharge over one log cycle

= 710 min/ft^2

The reciprocals of the instantaneous product discharge (1/Q) value was multiplied by the product drawdown at each reading, and plotted against log elapsed time. A straight line was fitted to the data and used to determine the time weighted drawdown divided by discharge rate into the well over one log cycle of time, $\Delta(y_p/Q) / \Delta\log_{10}t$, which was 710 min/$ft^2$. The hydrocarbon transmissivity value calculated was 2.6×10^{-4} ft^2/min. Using an oil saturated thickness of 1.0 feet, the hydrocarbon hydraulic conductivity value calculated was 2.6×10^{-4} ft/min. The calculated drawdown divided by discharge values used to generate the plot are also summarized in Table 12. The CR-3B drawdown divided by discharge versus log time data plot used to determine these parameters has been included as Figure 15.

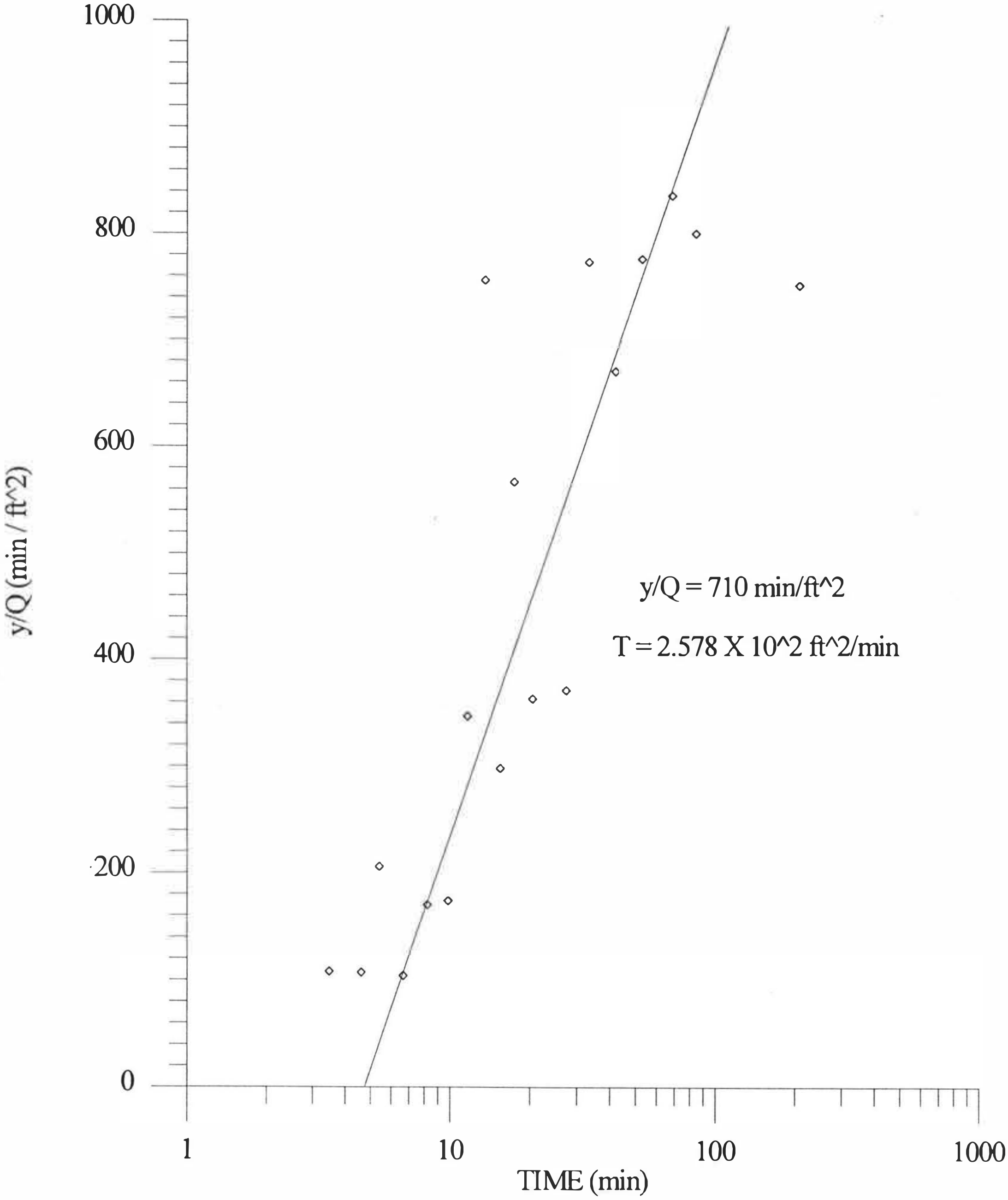

Figure 15. Jacob-Lohman y/Q Method for CR-3B.

Yaniga Method

The true product thickness was determined following the Yaniga method of analysis as used by Wagner et al. (1989). Application of this method was very quick and relatively easy. The depth to product versus log time and the depth to product/water interface versus log time were plotted. Two straight lines were fitted to the product/water interface data points. Like CR-3A, 3 straight line segments could be fitted to the data. The first straight line was assumed to correlate to free product draining out of the gravel pack and therefore is not representative of the formation. The intersection of the second and third line was used to determine the vertical distance between the product/water curve and the top of product curve, which reportedly represents the true product thickness. The true product thickness was determined to be 2.22 feet. The CR-3B depth versus log time data plotted for this method has been included as Figure 16.

Gruszczenski Method

The true product thickness, the capillary fringe thickness and the location of the tops and bottoms associated with these features can be determined using the Gruszczenski method for analyzing bail-down test results. The depth to product versus time and depth to product/water interface versus time values recorded in the field were plotted on cartesian graph paper. The inflection point on the product/water

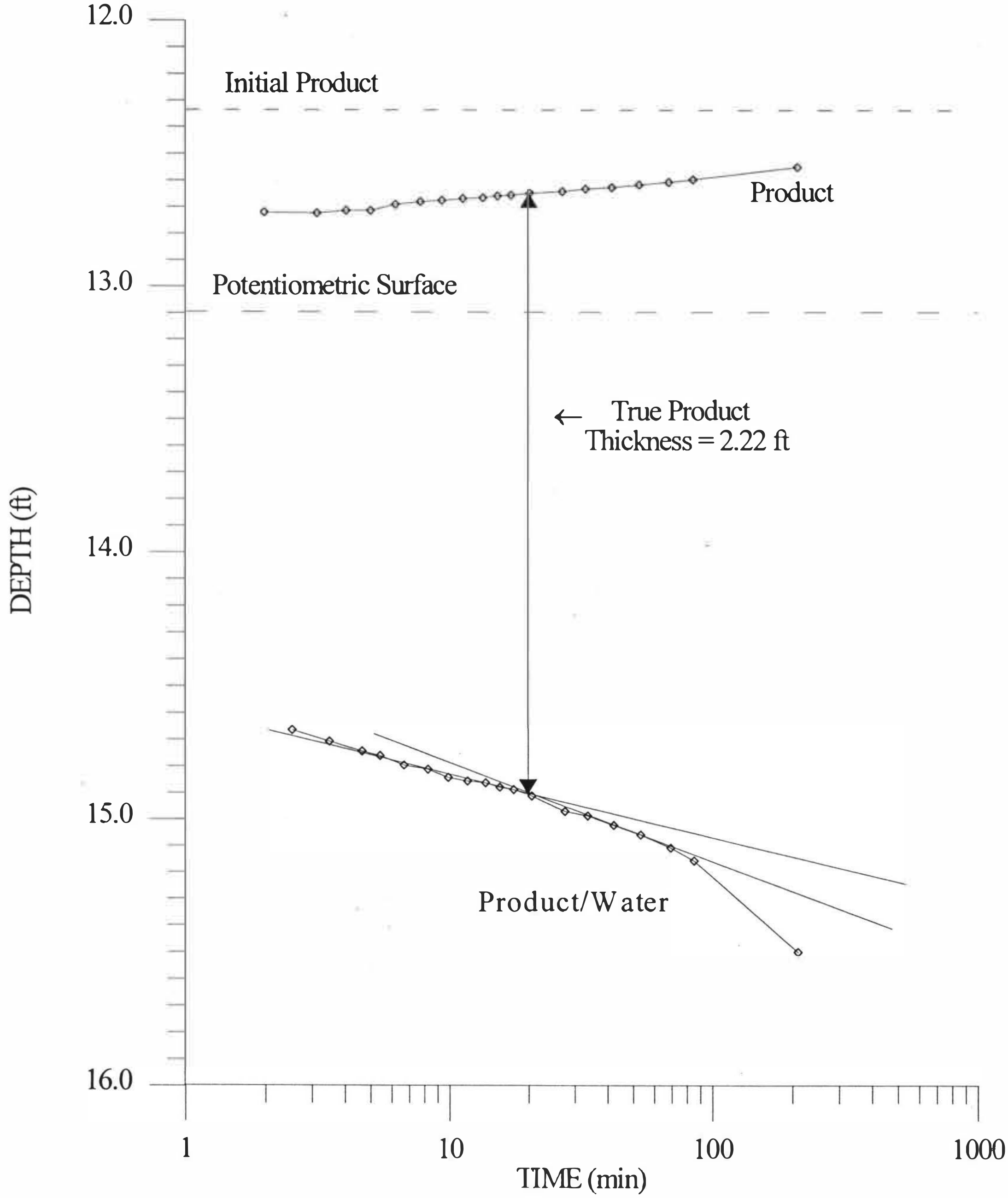

Figure 16. Yaniga Method for CR-3B.

curve was determined where the slope of this curve was negative. The vertical distance between this point and the product curve reportedly represents the true product thickness in the formation. Since the slope of the curve was negative from the first reading, the thickness was measured at the first reading as 1.90 feet.

The depth to the potentiometric surface calculated in the Bouwer and Rice section of this paper was determined to be 13.095 feet. This surface was plotted on the graph as a dashed horizontal line. The vertical distance between the potentiometric surface and the initial product level, which reportedly represents the total product and capillary fringe thickness, was 0.759 feet. Since this thickness is less than the true product thickness determined from the graph, there is apparently no capillary fringe in this area.

The depths to the top and bottom of the free product layer were calculated relative to the average corrected water depth calculated at the inflection point and at static conditions. The corrected depth to water at static conditions, the potentiometric surface previously calculated and the corrected depth to water at the inflection point were all 13.095 feet. The top of the product in the formation is at a depth of 12.336 feet and the bottom of this layer is at a depth of 14.236 feet. It should be noted that the bottom of the product layer determined using this method is below the potentiometric surface in the formation. The CR-3B depth versus time data plotted for this method has been included as Figure 17.

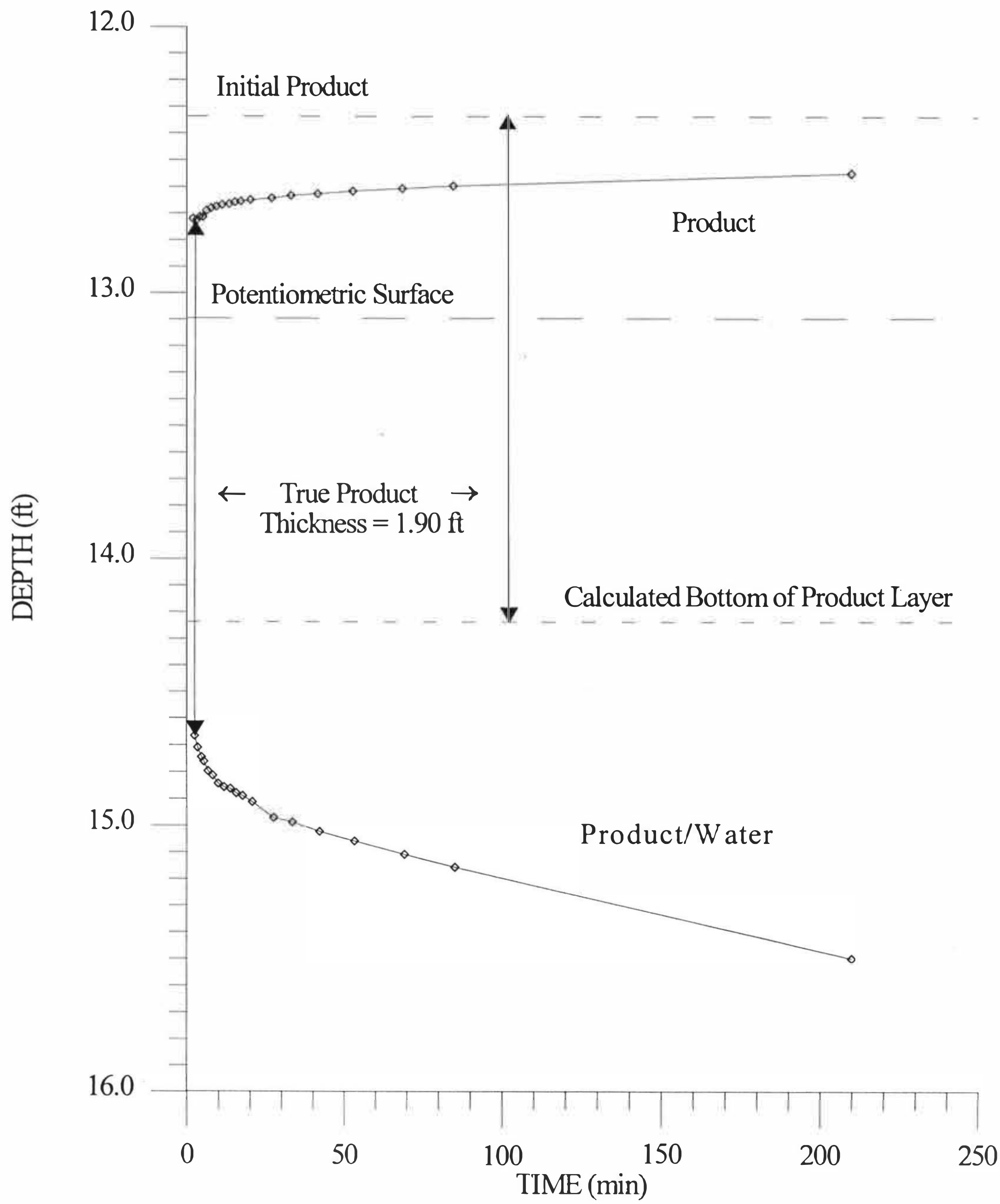

Figure 17. Gruszczenski Method for CR-3B.

Hughes, Sullivan, and Zinner Method

One of the criteria to use the Hughes, Sullivan, and Zinner method is that the hydrocarbon/water interface in the formation must be above the potentiometric surface in the formation. The previous method indicated that this may not be the situation at the Carson City site. The Hughes et al. method was still applied to this well, since the actual free product thickness was not known.

The true free product thickness, and the depth at which it is encountered in the formation were ascertained using the Hughes, Sullivan, and Zinner (1988) method for analyzing free product bail-down test data. The depth to product versus elapsed time was plotted on cartesian graph paper. A straight line was fitted to the readings taken at the beginning of the test which reportedly represent product entering the well at a constant rate during this portion of the recovery. The point at which the data trace begins to curve, thus deviating from a straight line, is referred to as the inflection point which represents the point where the product enters the well from the formation. The inflection point was located at a depth of 12.67 feet, which represents the mobile free product base depth. The vertical distance between the inflection point and the initial, static product depth of 12.34 feet was 0.33 feet, which represents the total product thickness in the formation.

A capillary fringe overlying the ground water table and underlying the mobile free product layer can be inferred using the above information. The capillary fringe thickness would be 0.43 feet and would be encountered from a depth of 12.67 to a depth of 13.095 feet. Well CR-3B depth to product versus time data plotted for this analysis has been included as Figure 18.

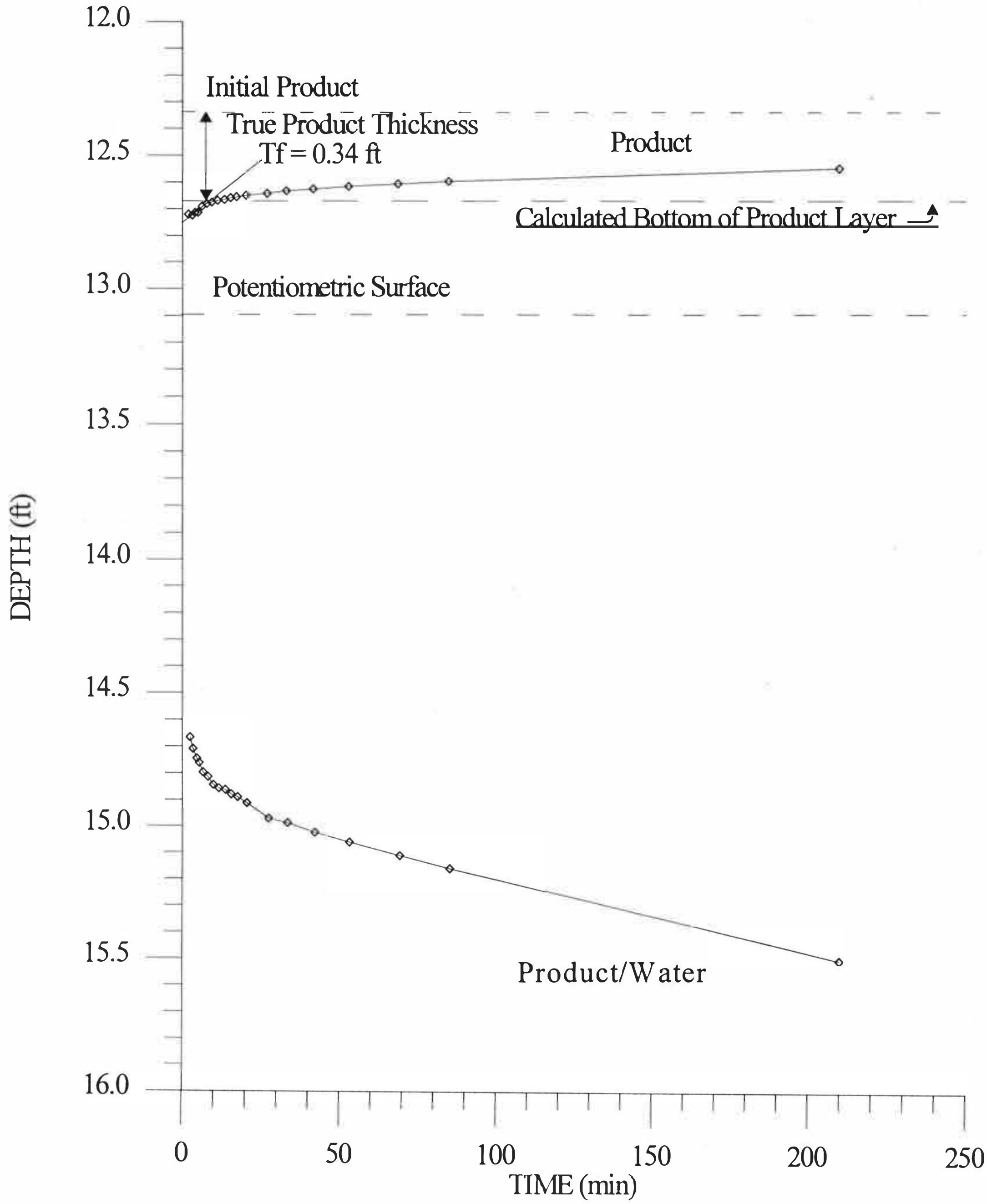

Figure 18. Hughes et al. Method for CR-3B.

CHAPTER V

DISCUSSION

General

The actual free product bail-down test procedures performed in the field were the same for all of the methods reviewed in this study. The field data was analyzed using the different methods presented. The following is a summary of the various free product characteristics determined using each method. Similar parameters will then be compared in attempts to determine the validity, applicability, and/or accuracy of each method.

Constantine Site

The parameters determined using the Bouwer and Rice method as applied by AQTESOLV are hydrocarbon hydraulic conductivity of 9.57×10^{-5} ft/min and the hydrocarbon transmissivity of 5.74×10^{-5} ft^2/min. The depth to the potentiometric surface was 10.52 feet.

The parameters determined using the Jacob-Lohman 1/Q method as applied by Huntley, Hawk and Corley were a hydrocarbon hydraulic conductivity of 1.4×10^{-3} ft/min and the hydrocarbon transmissivity of 8.4×10^{-4} ft^2/min. The parameters determined using the Jacob-Lohman y_p/Q method as suggested by Huntley were hydrocarbon hydraulic conductivity of 4.3 x 10^{-3} ft/min and the hydrocarbon transmissivity of 2.6 x 10^{-3} ft^2/min.

The parameter determined using the Yaniga method as proposed by Wagner et al. is the true formation product thickness of 0.53 feet.

The parameters determined using the Gruszczenski method were the true formation product thickness of 0.23 feet; the true formation capillary fringe thickness of 0.19 feet; the depth to the top of the product of 10.10 feet; depth to the bottom of the product/top of the capillary fringe of 10.33 feet; and the depth to the bottom of the capillary fringe and the potentiometric surface of 10.52 feet.

The parameters determined using the Hughes et al. method were the true formation product thickness of 0.20 feet; the depth to the top of product of 10.10 feet; depth to the bottom of product of 10.30 feet; and, the depth to the potentiometric surface of 10.52 feet. The inferred capillary fringe thickness was 0.22 feet; the depth to the top of the capillay fringe/bottom of the product was 10.30 feet; and, the depth to the bottom of the capillary fringe/corrected water or potentiometric surface was 10.52 feet.

A summary of the calculated parameters for MW-18 has been included as Table 13.

The hydrocarbon hydraulic conductivity values determined using the Bouwer and Rice method and Jacob-Lohman methods vary by two orders of magnitude. The hydrocarbon hydraulic conductivity values determined using the different Jacob-

Table 13

Summary of Calculated Parameters for MW-18

Bail-Down Test Method	Hydraulic Conductivity, ft/min	Transmissivity, ft^2/min	True Product Thickness, ft	True Capillary Fringe Thickness, ft
Bouwer and Rice	9.57×10^{-5}	5.74×10^{-5}	NA	NA
Jacob-Lohman 1/Q	1.4×10^{-3}	8.4×10^{-4}	NA	NA
Jacob-Lohman y_p/Q	4.3×10^{-3}	2.6×10^{-3}	NA	NA
Yaniga	NA	NA	0.53	NA
Gruszczenski	NA	NA	0.23	0.19
Hughes et al	NA	NA	0.20	NA

NA: Not Applicable

Lohman methods vary by a factor of 7, but are of the same magnitude. The calculated hydrocarbon transmissivity values follow the same pattern as the hydrocarbon hydraulic conductivity values. Overall, the hydrocarbon hydraulic conductivity and transmissivity values calculated using these methods appear to vary by more than one order of magnitude and are not very comparable for this location.

The true product thickness in the formation was calculated using the remaining three method of analysis. The Gruszczenski and Hughes et al. methods calculated product thickness values were essentially the same at 0.23 and 0.20 feet, respectively. Surfically, these methods appear to be comparable for the analysis of free product thickness.

The true product thickness calculated using the Yaniga method of 0.53 feet is much higher than the thickness determined using the other two methods. Therefore, this method does not appear to be comparable to the other methods for the analysis of free product thickness. However, if the actual free product thickness is 0.6 feet in the formation, the Yaniga method result appears to be closer to this value than the other two methods.

The calculated potentiometric surface of the formation was determined using the same equation for each method and was 10.52 feet. The depth to the top of the mobile free product in the formation was delineated in the Gruszczenzski and Hughes et al. methods as the initial, static product depth measured in the well of 10.10 feet. The depth to the bottom of the oil was essentially the same using these methods, since the true product thickness calculated using these two methods were essentially the same.

The capillary fringe thickness of 0.19 feet, and depth calculated using the Gruszczenski method can be compared with the inferred capillary fringe thickness of 0.22 feet, and depth calculated using the Hughes et al. values. Based on this limited amount of information, the Gruszczenski and Hughes et al. methods may be comparable for this location.

Carson City Site - Well-CR-3A

The parameters determined using the Bouwer and Rice method as applied by AQTESOLV were hydrocarbon hydraulic conductivity of 2.29 x 10^{-6} ft/min and the hydrocarbon transmissivity of 2.29 x 10^{-6} ft^2/min. The depth to the potentiometric surface was 13.00 feet.

The parameters determined using the Jacob-Lohman 1/Q method as applied by Huntley, Hawk and Corley for hydrocarbon hydraulic conductivity of 1.1 x 10^{-4} ft/min and the hydrocarbon transmissivity of 1.1 x 10^{-4} ft^2/min. The parameters determined using the Jacob-Lohman y_p/Q method as suggested by Huntley for hydrocarbon hydraulic conductivity of 1.4 x 10^{-4} ft/min and the hydrocarbon transmissivity of 1.4 x 10^{-4} ft^2/min.

The parameter determined using the Yaniga method as proposed by Wagner et al. is the true formation product thickness of 1.37 feet.

The parameters determined using the Gruszczenski method were the true formation product thickness of 1.09 feet; the true formation capillary fringe thickness of 0 feet; the depth to the top of the free product of 12.172 feet; depth to the bottom of the free product of 13.262 feet. The potentiometric surface of 13.00 feet. It should be noted that the bottom of the free product layer is deeper than the potentiometric surface which suggests that the free product in this area of the formation is actually depressing the water table surface.

The parameters determined using the Hughes et al. method were the true formation product thickness of 0.53 feet; the depth to the top of product of 12.17 feet; depth to the bottom of product of 12.70 feet; and, the depth to the potentiometric surface of 13.00 feet. The inferred capillary fringe thickness was 0.30 feet; the depth to the top of the capillay fringe/bottom of the product was 12.70 feet; and, the depth to the bottom of the capillary fringe/corrected water or potentiometric surface was 13.00 feet. Using this method, the bottom of the free product layer is not deeper than the potentiometric surface thus the free product does not appear to be depressing the water table surface in this area.

A summary of the calculated parameters for CR-3A has been included in Table 14.

Table 14

Summary of Calculated Parameters for CR-3A

Bail-Down Test Method	Hydraulic Conductivity, ft/min	Transmissivity, ft^2/min	True Product Thickness, ft	True Capillary Fringe Thickness, ft
Bouwer and Rice	2.29×10^{-6}	2.29×10^{-6}	NA	NA
Jacob-Lohman 1/Q	1.1×10^{-4}	1.1×10^{-4}	NA	NA
Jacob-Lohman y_p/Q	1.4×10^{-4}	1.4×10^{-4}	NA	NA
Yaniga	NA	NA	1.37	NA
Gruszczenski	NA	NA	1.09	0
Hughes et al	NA	NA	0.53	0.30

NA = Not Applicable

The hydrocarbon hydraulic conductivity values determined using the Bouwer and Rice method and Jacob-Lohman methods vary by two orders of magnitude and do not appear to be very comparable. The hydrocarbon hydraulic conductivity values determined using the different Jacob-Lohman methods vary only by 20 percent and are of the same magnitude. The Jacob-Lohman calculations seem to be comparable for this location. The calculated hydrocarbon transmissivity values follow the same pattern since a free product thickness of 1 foot was used in these calculations.

The true product thickness in the formation was calculated using the remaining three methods of analysis. The Yaniga and Gruszczenski calculated oil thickness values of 1.37 and 1.09 feet, respectively, varied by 20 percent. Therefore, these methods appear to be somewhat comparable for this location. The oil thickness calculated using the Hughes et al. method of 0.53 feet is much lower than the thicknesses determined using the other two methods. Use of this method for this location was questionable because the criteria requiring the hydrocarbon/water interface in the formation to be above the potentiometric surface in the formation may not have been met. Therefore, this method does not appear to be suitable for the analysis of free product thickness at this site.

The calculated potentiometric surface of the formation was determined the same way for each method and was 13.00 feet. The depth to the top of the oil was delineated in the Gruszczenzski and Hughes et al. methods and was represented as the initial, static oil depth in the well of 12.17 feet. The depth to the bottom of the oil was also calculated using these methods; however, these depths are not the same because the calculated true product thicknesses are not the same. The Gruszczenski method appears to indicate that the free product layer lies directly on top of the water table with no capillary fringe in between. The Hughes et al. method suggests a capillary fringe of 0.30 feet is present above the potentiometric surface. Since the true mobile free product thickness and location are not known at this location, it is difficult to determine the validity or accuracy of any of these methods.

Carson City Site - Well-CR-3B

The parameters determined using the Bouwer and Rice method as applied by AQTESOLV were hydrocarbon hydraulic conductivity of 4.35×10^{-6} ft/min and the hydrocarbon transmissivity of 4.35×10^{-6} ft^2/min. The depth to the potentiometric surface was 13.095 feet.

The parameters determined using the Jacob-Lohman 1/Q method as applied by Huntley, Hawk and Corley were hydrocarbon hydraulic conductivity of 1.5×10^{-4} ft/min and the hydrocarbon transmissivity of 1.5×10^{-4} ft^2/min. The parameters determined using the Jacob-Lohman y_p/Q method as suggested by Huntley for hydrocarbon hydraulic conductivity of 2.6×10^{-4} ft/min and the hydrocarbon transmissivity of 2.6×10^{-4} ft^2/min.

The parameter determined using the Yaniga method as proposed by Wagner et al. is the true formation product thickness of 2.22 feet.

The parameters determined using the Gruszczenski method were the true formation product thickness of 1.90 feet; the true formation capillary fringe thickness of 0 feet; the depth to the top of the free product of 12.34 feet; depth to the bottom of the free product of 14.24 feet. The potentiometric surface of 13.095 feet. It should be noted that the bottom of the free product layer is deeper than the potentiometric surface which implies that the free product in this area of the formation is actually depressing the water table surface.

The parameters determined using the Hughes et al. method were the true formation product thickness of 0.34 feet; the depth to the top of the oil of 12.34 feet; depth to the bottom of the oil of 12.68 feet; and, the depth to the potentiometric surface of 13.095 feet. The inferred capillary fringe thickness was 0.42 feet; the depth to the top of the capillay fringe/bottom of the product was 12.68 feet; and, the depth to the bottom of the capillary fringe/corrected water or potentiometric surface was 13.095 feet. Using this method, the bottom of the free product layer is not deeper than the potentiometric surface. Thus, the free product does not appear to be depressing the water table surface in this area.

A summary of the calculated parameters for CR-3B has been included in Table 15.

The hydrocarbon hydraulic conductivity values determined using the Bouwer and Rice method and Jacob-Lohman methods vary by two orders of magnitude and do not appear to be very comparable. The hydrocarbon hydraulic conductivity values

Table 15

Summary of Calculated Parameters for CR-3B

Bail-Down Test Method	Hydraulic Conductivity, ft/min	Transmissivity, ft^2/min	True Product Thickness, ft	True Capillary Fringe Thickness, ft
Bouwer and Rice	4.35×10^{-6}	4.35×10^{-6}	NA	NA
Jacob-Lohman 1/Q	1.5×10^{-4}	1.5×10^{-4}	NA	NA
Jacob-Lohman y_p/Q	2.6×10^{-4}	2.6×10^{-4}	NA	NA
Yaniga	NA	NA	2.22	NA
Gruszczenski	NA	NA	1.90	0
Hughes et al	NA	NA	0.34	0.42

NA = Not Applicable

determined using the different Jacob-Lohman methods vary only by 25 percent and are of the same magnitude. The Jacob-Lohman calculations seem to be comparable for this location. The calculated hydrocarbon transmissivity values follow the same pattern since a free product thickness estimate of 1.0 feet was used in these calculations.

The true product thickness in the formation was calculated using the remaining three methods of analysis. The Yaniga and Gruszczenski methods calculated product thickness values of 2.22 and 1.90 feet, respectively, varying by 15 percent. Therefore, these methods appear to be somewhat comparable for this location. The product thickness calculated using the Hughes et al. method of 0.34

feet is approximately 85 percent lower than the thickness determined using the other two methods. Use of this method for this location was questionable because the criteria requiring the hydrocarbon/water interface in the formation to be above the potentiometric surface in the formation may not have been met. Therefore, this method does not appear to be comparable for the analysis of free product thickness at this site.

The calculated potentiometric surface of the formation was determined the same way for each method and is 13.095 feet. The depth to the top of product was delineated in the Gruszczenzski and Hughes et al. methods and was represented as the initial, static oil depth in the well of 12.34 feet. The depth to the bottom of the oil was also calculated using these methods; however, these depths are not the same because the calculated true product thicknesses are not the same. The Gruszczenski method appears to indicate that the free product layer lies directly on top of the water table with no capillary fringe in between. The Hughes et al. method suggests a capillary fringe of 0.42 feet is present above the potentiometric surface. Since the true mobile free product thickness and location are not known at this location, it is difficult to determine the validity or accuracy of any of these methods.

CHAPTER VI

CONCLUSIONS

The hydrocarbon hydraulic conductivity and transmissivity values calculated using the Bouwer and Rice and Jacob-Lohman methods vary by over one order of magnitude for both sites. Based on this limited information, these free product bail-down test methods do not appear to be directly comparable. The hydrocarbon hydraulic conductivities and transmissivities calculated for both wells at the Carson City site using the different Jacob-Lohman methods were somewhat comparable.

The mobile free product thickness values calculated using the Gruszczenski and Hughes et al. methods were essentially the same at the Constantine site, but proved not to be comparable in the Carson City site wells. The Gruszczenski method produced a comparable free product thickness to the Yaniga method in both of the Carson City site wells.

It should be noted that the values determined using the Hughes et al. method are probably not reflective of conditions beneath either of these sites. The bottom of the hydrocarbon layer is reportedly below the potentiometric surface at the Constantine site. Based on the product thickness values calculated using the other two methods, the base of the hydrocarbon layer is probably below the potentiometric surface at the Carson City site.

A consistent trend was noted in the calculated values from all three wells. In general, the calculated Bouwer and Rice hydrocarbon hydraulic conductivity values were consistently over one magnitude lower than the calculated Jacob-Lohman hydrocarbon hydraulic conductivity values. The calculated Jacob-Lohman 1/Q hydrocarbon hydraulic conductivity values were consistently higher than the calculated Jacob-Lohman y/Q hydrocarbon hydraulic conductivity values. The product thickness calculated using the Yaniga method was the largest value, the Gruszczenski method value being next and the Hughes et al. method providing the smallest true product thickness value.

Further comparison of these methods using the remaining data collected from Carson City site may produce more favorable and conclusive results. Therefore, further application of these methods for analysis may be warranted.

If one sets aside the differing methods of analyzing bail-down tests, and simply compares the rates of recovery of different wells, much of qualitative value can be gained. For example, MW-18 reached equilibrium in about 15 minutes in 1988. One year later, the well recovered more slowly, suggesting either a decrease in the free product nearby or a change in the well screen permeability. The two Carson City wells were screened in a sandy aquifer comparable in grain size to Constantine, but the wells took one week to recover. This could be due to the different free product in Carson City (a 50-year old crude oil spill) or to biofouling of the aquifer. In either case, a remediation system that might work at the Constantine site may be inappropriate and unsuccessful at the Carson City site. The rates of recovery noted in these bail-down tests are valuable information, even if the methods of analysis tested here did not inspire trust and confidence.

Appendix A

Dual Well Free Product Bail-Down Test Results From
Carson City, Michigan, Wells, Performed in 1994

CR-1B, Dual Well Free Product Bail-Down Test Performed on CR-1B & CR-3B on 7/1/94 at Crystal Refinery, Carson City, Michigan.

Air/Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	373.8	12.264	0	506.8	16.627
0.72	394.0	12.927	0.72	401.0	13.156
1.98	393.7	12.917	1.98	402.0	13.189
2.52	393.6	12.913	2.88	401.0	13.156
3.36	393.6	12.913	3.78	400.9	13.153
4.32	393.5	12.910	4.86	400.9	13.153
5.52	393.4	12.907	6.00	401.4	13.169
6.54	393.4	12.907	7.02	401.5	13.173
7.50	393.4	12.907	7.98	401.5	13.173
8.52	393.3	12.904	9.00	401.6	13.176
9.48	393.3	12.904	10.02	401.6	13.176
10.50	393.3	12.904	10.98	401.7	13.179
11.52	393.2	12.900	12.00	401.7	13.179
13.50	393.2	12.900	13.98	401.8	13.182
14.52	393.1	12.897	15.00	401.9	13.186
15.48	393.1	12.897	16.02	401.9	13.186
18.00	393.0	12.894	18.48	402.0	13.189
19.02	393.0	12.894	19.50	402.2	13.196
21.00	393.0	12.894	21.48	402.6	13.209
22.02	393.0	12.894	22.50	402.6	13.209
22.98	392.9	12.890	23.52	402.7	13.212
24.00	392.9	12.890	24.48	402.7	13.212
25.02	392.9	12.890	26.52	403.0	13.222
28.50	392.8	12.887	31.50	403.4	13.235
33.00	392.8	12.887	36.00	403.8	13.248
38.52	392.7	12.884	42.00	404.2	13.261
51.00	392.5	12.877	52.02	405.8	13.314
58.50	392.3	12.871	60.00	405.8	13.314
67.80	392.2	12.867	69.00	406.8	13.346
73.20	392.0	12.861	73.80	407.5	13.369
7080.00	369.5	12.123	7080.00	490.4	16.089
8490.00	373.4	12.251	8490.00	521.6	17.113

CR-3B, Dual Well Free Product Bail Down Test Performed on CR-1B & CR-3B on 7/1/94 at Crystal Refinery, Carson City, Michigan.

Air/Product Interface			Free Product/Water Interface		
TIME. minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	377.3	12.379	0	502.5	16.486
1.14	390.0	12.795	1.14	434.0	14.239
1.98	390.3	12.805	3.00	436.0	14.304
4.02	389.0	12.762	4.86	438.0	14.370
5.82	388.6	12.749	6.48	439.1	14.406
7.26	388.6	12.749	7.98	440.1	14.439
8.52	388.4	12.743	9.12	440.7	14.459
9.48	388.3	12.740	10.14	441.5	14.485
10.74	388.1	12.733	11.34	442.7	14.524
12.00	387.9	12.726	12.48	442.8	14.528
13.02	387.8	12.723	13.50	443.3	14.544
13.98	387.9	12.726	14.58	443.8	14.560
15.12	387.8	12.723	15.66	444.3	14.577
16.32	387.8	12.723	17.22	444.8	14.593
17.58	387.5	12.713	18.42	445.1	14.603
19.14	387.6	12.717	20.28	445.5	14.616
21.00	387.4	12.710	21.60	445.8	14.626
22.62	387.2	12.703	23.22	446.0	14.633
26.52	387.0	12.697	27.18	447.0	14.665
31.38	386.8	12.690	31.98	447.8	14.692
37.50	386.6	12.684	37.98	448.5	14.715
44.76	386.4	12.677	45.30	449.5	14.747
52.32	386.2	12.671	52.98	450.2	14.770
60.60	386.1	12.667	61.80	451.2	14.803
70.20	386.0	12.664	70.80	452.1	14.833
7080.00	372.1	12.208	7080.00	487.3	15.988
8490.00	377.1	12.372	8490.00	511.5	16.782

CR-1A, Dual Well Free Product Bail-Down Test Performed on CR-1A & CR-2B on 7/7/94 at Crystal Refinery, Carson City, Michigan.

Air/Free Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	381.3	12.510	00	524.6	17.211
1.68	402.5	13.205	1.98	406.5	13.337
2.52	402.5	13.205	3.00	406.4	13.333
4.74	402.4	13.202	5.40	406.3	13.330
6.00	402.4	13.202	6.48	406.1	13.323
7.02	402.3	13.199	7.50	406.1	13.323
8.52	402.2	13.196	9.00	406.1	13.323
10.02	402.2	13.196	10.98	406.0	13.320
12.00	402.2	13.196	13.98	406.0	13.320
13.98	402.1	13.192	16.02	406.0	13.320
18.00	402.1	13.192	19.98	406.0	13.320
24.00	402.1	13.192	28.98	406.3	13.330
34.02	402.1	13.192	40.50	406.6	13.340
61.20	402.0	13.189	61.80	407.0	13.353
91.20	401.6	13.176	91.80	407.3	13.363
115.20	401.5	13.173	115.80	408.0	13.386
1080.00	378.6	12.421	1080.00	481.6	15.801
4530.00	380.1	12.470	4530.00	483.2	15.853
5400.00	380.4	12.480	5400.00	483.7	15.869
7290.00	377.9	12.398	7290.00	503.7	16.526
10290.00	378.5	12.418	10290.00	504.8	16.562
11700.00	377.5	12.385	11700.00	513.7	16.854
15990.00	378.8	12.428	15990.00	516.5	16.946

CR-2B, Dual Well Free Product Bail-Down Test Performed on CR-1A & CR-2B on 7/7/94 at Crystal Refinery, Carson City, Michigan

Air/Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	373.2	12.244	0	514.7	16.886
1.68	394.0	12.927	2.34	398.6	13.077
3.00	393.8	12.920	3.78	398.5	13.074
4.86	393.6	12.913	5.34	398.2	13.064
6.24	393.5	12.910	6.24	398.5	13.074
8.34	393.7	12.917	8.76	398.8	13.084
10.02	393.5	12.910	10.38	399.0	13.091
12.00	393.5	12.910	12.36	399.2	13.097
15.48	393.4	12.907	16.02	399.5	13.107
18.90	393.2	12.900	19.32	400.0	13.123
22.92	393.1	12.897	23.88	400.5	13.140
28.02	393.1	12.897	28.50	401.0	13.156
33.00	393.1	12.897	33.48	401.7	13.179
43.02	392.8	12.887	43.98	403.0	13.222
58.50	392.6	12.881	59.52	404.5	13.271
91.80	391.7	12.851	93.00	407.5	13.369
114.60	391.3	12.838	115.80	409.6	13.438
1080.00	366.7	12.030	1080.00	487.7	16.001
4530.00	368.7	12.096	4530.00	489.7	16.066
5400.00	368.7	12.096	5400.00	489.4	16.056
7290.00	368.0	12.073	7290.00	498.7	16.362
10290.00	368.8	12.100	10290.00	499.8	16.398
11700.00	368.7	12.096	11700.00	502.8	16.496
15990.00	370.0	12.139	15990.00	506.8	16.627
25920.00	371.8	12.198	25920.00	509.7	16.722

CR-2A, Dual Well Free Product Bail-Down Test Performed on CR-2A & CR-3A on 7/18/94 at Crystal Refinery, Carson City, Michigan.

Air/Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	369.9	12.136	0	512.0	16.798
1.02	384.3	12.608	1.98	434.8	14.265
2.52	384.5	12.615	3.00	435.3	14.281
4.02	383.8	12.592	4.32	436.0	14.304
5.34	383.6	12.585	6.00	436.6	14.324
7.32	383.5	12.582	8.34	498.6	16.358
9.36	383.2	12.572	10.02	438.3	14.380
11.76	383.1	12.569	12.48	439.1	14.406
13.08	383.1	12.569	13.80	439.4	14.416
15.00	383.0	12.566	15.48	445.6	14.619
16.80	382.9	12.562	17.58	440.3	14.446
19.62	382.7	12.556	20.52	441.4	14.482
21.48	382.6	12.552	22.08	441.9	14.498
24.00	382.6	12.552	24.78	442.5	14.518
34.92	382.3	12.543	35.76	443.7	14.557
44.76	382.2	12.539	45.42	444.2	14.573
1260.00	367.8	12.067	1260.00	496.6	16.293
2400.00	369.0	12.106	2400.00	499.7	16.394
4560.00	371.5	12.188	4560.00	502.8	16.496
7200.00	371.0	12.172	7200.00	502.3	16.480
9960.00	372.2	12.211	9960.00	510.5	16.749

CR-3A, Dual Well Free Product Bail-Down Test Performed on CR-2A & CR-3A on 7/18/94 at Crystal Refinery, Carson City, Michigan.

Air/Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	369.0	12.106	0	517.4	16.975
0.48	384.1	12.602	0.48	428.5	14.058
0.96	384.0	12.598	1.26	425.7	13.967
1.74	384.2	12.605	2.16	428.5	14.058
2.64	384.5	12.615	3.06	428.5	14.058
3.90	384.5	12.615	4.50	429.2	14.081
5.46	383.5	12.582	5.94	429.2	14.081
6.78	383.5	12.582	7.08	429.8	14.101
7.92	383.5	12.582	8.28	430.0	14.108
8.76	383.4	12.579	9.18	430.5	14.124
9.66	383.4	12.579	10.08	430.6	14.127
10.86	383.4	12.579	11.16	431.0	14.140
11.88	383.4	12.579	12.18	431.3	14.150
13.26	383.3	12.575	13.56	431.3	14.150
14.46	383.3	12.575	14.82	431.6	14.160
16.32	383.3	12.575	16.68	432.0	14.173
18.12	383.0	12.566	18.66	432.5	14.190
19.86	383.0	12.566	20.40	433.5	14.222
21.90	383.0	12.566	22.38	433.5	14.222
24.18	382.9	12.562	24.60	433.7	14.229
25.98	382.9	12.562	26.34	433.8	14.232
35.82	382.9	12.562	36.36	435.4	14.285
41.46	382.7	12.556	41.94	436.0	14.304
44.16	382.7	12.556	44.58	436.0	14.304
1260.00	370.0	12.139	1260.00	498.4	16.352
2400.00	370.1	12.142	2400.00	501.0	16.437
4560.00	370.5	12.156	4560.00	513.0	16.831
7200.00	371.2	12.178	7200.00	512.8	16.824
9960.00	371.7	12.195	9960.00	516.0	16.929

CR-2B, Dual Well Free Product Bail-Down Test Performed on CR-2B & CR-3A on 7/25/94 at Crystal Refinery, Carson City, Michigan.

Air/Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	371.8	12.198	0	509.7	16.722
1.32	391.6	12.848	1.98	397.9	13.054
2.58	391.8	12.854	3.00	398.2	13.064
9.48	390.6	12.815	10.20	398.7	13.081
10.80	390.9	12.825	11.52	399.0	13.091
13.02	390.6	12.815	13.50	399.1	13.094
14.88	390.4	12.808	15.66	399.3	13.100
18.36	390.4	12.808	18.90	399.4	13.104
21.48	390.1	12.799	22.02	399.6	13.110
23.34	390.0	12.795	23.88	399.6	13.110
31.98	389.8	12.789	32.82	400.4	13.136
43.38	389.8	12.789	43.98	401.4	13.169
63.60	389.4	12.776	64.92	403.3	13.232
77.40	389.2	12.769	78.00	404.3	13.264
1380.00	381.3	12.510	1380.00	471.3	15.463
2940.00	380.7	12.490	2940.00	470.9	15.449
5820.00	376.0	12.336	5820.00	510.4	16.745
8880.00	375.0	12.303	8880.00	509.9	16.729
11700.00	375.4	12.316	11700.00	510.2	16.739
13980.00	375.4	12.316	13980.00	510.8	16.759
17460.00	375.9	12.333	17460.00	510.9	16.762
20160.00	371.7	12.195	20160.00	507.2	16.640

CR-3A, Dual Well Free Product Bail-Down Test Performed on CR-2B & CR-3A on 7/25/94 at Crystal Refinery, Carson City, Michigan.

Air/Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	371.0	12.172	0	514.1	16.867
0.90	387.0	12.697	1.50	419.8	13.773
1.98	386.8	12.690	2.76	420.5	13.796
3.24	386.8	12.690	3.48	421.0	13.812
4.50	386.6	12.684	5.52	421.5	13.829
7.50	386.3	12.674	8.52	422.0	13.845
9.48	386.1	12.667	10.50	422.5	13.862
11.52	386.0	12.664	12.48	422.5	13.862
13.50	385.9	12.661	14.52	422.5	13.862
19.98	385.5	12.648	21.00	423.8	13.904
30.48	385.0	12.631	31.50	426.0	13.976
44.52	384.5	12.615	45.48	428.8	14.068
63.60	384.1	12.602	64.80	430.0	14.108
77.40	383.8	12.592	78.00	430.5	14.124
1380.00	377.7	12.392	1380.00	490.2	16.083
2940.00	377.5	12.385	2940.00	490.7	16.099
5820.00	375.5	12.320	5820.00	513.7	16.854
8880.00	375.5	12.320	8880.00	513.4	16.844
11700.00	375.7	12.326	11700.00	513.5	16.847
13980.00	375.3	12.313	13980.00	514.0	16.864
17460.00	375.5	12.320	17460.00	513.7	16.854
20160.00	370.9	12.169	20160.00	516.7	16.952

CR-3A, Dual Well Free Product Bail-Down Test Performed on CR-3A & CR-3B on 8/8/94 at Crystal Refinery, Carson City, Michigan.

Air/Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	371.0	12.172	0	517.2	16.969
0.66	388.0	12.730	1.26	420.6	13.799
4.02	387.5	12.713	4.50	420.5	13.796
4.98	387.4	12.710	5.52	420.8	13.806
6.00	387.3	12.707	6.48	420.9	13.809
7.02	387.2	12.703	7.50	421.5	13.829
7.98	387.1	12.700	8.52	421.5	13.829
9.00	387.0	12.697	9.48	421.6	13.832
10.98	386.9	12.694	11.52	421.9	13.842
13.02	386.8	12.690	13.50	422.7	13.868
15.00	386.7	12.687	15.48	422.9	13.875
16.98	386.6	12.684	18.00	423.3	13.888
19.98	386.4	12.677	20.52	424.0	13.911
22.98	386.3	12.674	23.52	424.2	13.917
31.98	386.1	12.667	32.52	425.6	13.963
40.02	385.8	12.657	40.50	426.5	13.993
52.02	385.5	12.648	52.50	427.5	14.026
67.20	385.3	12.641	67.80	429.3	14.085
84.00	384.9	12.628	85.20	430.5	14.124
96.00	384.8	12.625	96.60	431.5	14.157
210.00	384.4	12.612	210.00	438.6	14.390
930.00	384.0	12.598	930.00	445.6	14.619
2850.00	382.4	12.546	2850.00	459.6	15.079
5970.00	382.9	12.562	5970.00	465.7	15.279
8700.00	380.1	12.470	8700.00	490.5	16.093
11670.00	376.0	12.336	11670.00	514.5	16.880
13950.00	376.3	12.346	13950.00	515.4	16.909
17430.00	376.1	12.339	17430.00	516.6	16.949
20310.00	376.9	12.365	20310.00	518.8	17.021

CR-3B, Dual Well Free Product Bail-Down Test Performed on CR-3A & CR-3B on 8/8/94 at Crystal Refinery, Carson City, Michigan.

Air/Product Interface			Free Product/Water Interface		
TIME. minutes	DEPTH, cm	DEPTH, feet	TIME. minutes	DEPTH, cm	DEPTH, feet
0	376.0	12.336	0	509.8	16.726
1.98	387.7	12.720	2.52	447.0	14.665
3.12	387.8	12.723	3.48	448.3	14.708
4.02	387.5	12.713	4.62	449.4	14.744
4.98	387.5	12.713	5.40	449.9	14.761
6.18	386.8	12.690	6.66	450.7	14.787
7.68	386.5	12.680	8.22	451.5	14.813
9.30	386.3	12.674	9.84	452.4	14.843
11.16	386.1	12.667	11.64	452.8	14.856
13.32	386.0	12.664	13.62	453.0	14.862
15.18	385.8	12.657	15.48	453.5	14.879
17.10	385.7	12.654	17.52	453.8	14.888
20.16	385.5	12.648	20.52	454.5	14.911
26.88	385.3	12.641	27.48	456.3	14.970
33.00	385.0	12.631	33.48	456.8	14.987
41.52	384.8	12.625	42.12	457.9	15.023
52.68	384.5	12.615	53.28	459.0	15.059
68.40	384.2	12.605	69.30	460.5	15.108
84.60	383.9	12.595	85.20	462.0	15.157
210.00	382.3	12.543	210.00	472.4	15.499
930.00	382.3	12.543	930.00	474.9	15.581
2850.00	381.4	12.513	2850.00	479.8	15.741
5970.00	380.6	12.487	5970.00	490.6	16.096
8700.00	380.1	12.470	8700.00	499.9	16.401
11670.00	379.0	12.434	11670.00	514.5	16.880
13950.00	379.5	12.451	13950.00	516.0	16.929
17430.00	379.5	12.451	17430.00	516.4	16.942
20310.00	379.5	12.451	20310.00	518.0	16.995

CR-1B, Dual Well Free Product Bail-Down Test Performed on CR-1B & CR-3B on 8/29/94 at Crystal Refinery, Carson City, Michigan.

Air/Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	380.5	12.484	0	524.0	17.192
0.78	401.5	13.173	1.26	411.5	13.501
1.62	401.4	13.169	1.98	411.7	13.507
2.34	401.3	13.166	2.70	411.7	13.507
3.00	401.2	13.163	3.48	411.8	13.511
4.02	401.2	13.163	4.50	411.9	13.514
4.98	401.1	13.159	5.52	412.0	13.517
6.00	401.0	13.156	6.48	412.2	13.524
7.02	401.1	13.159	7.50	412.4	13.530
7.98	401.1	13.159	8.52	412.4	13.530
9.00	401.1	13.159	9.48	412.5	13.533
10.02	401.0	13.156	10.50	412.7	13.540
18.24	400.8	13.150	18.78	412.7	13.540
26.28	400.7	13.146	27.00	413.3	13.560
35.52	400.6	13.143	36.24	413.7	13.573
47.28	400.4	13.136	47.52	414.1	13.586
103.20	399.4	13.104	103.80	417.8	13.707
360.00	397.8	13.051	360.00	429.6	14.094
1500.00	380.7	12.490	1500.00	521.6	17.113
3030.00	381.3	12.510	3030.00	521.6	17.113
4230.00	383.4	12.579	4230.00	514.9	16.893

CR-3B, Dual Well Free Product Bail-Down Test Performed on CR-1B & CR-3B on 8/29/94 at Crystal Refinery, Carson City, Michigan.

Air/Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	382.5	12.549	0	525.0	17.224
0.78	394.0	12.927	1.14	466.0	15.289
1.86	393.2	12.900	2.40	466.3	15.299
2.82	393.2	12.900	3.42	467.5	15.338
3.78	393.1	12.897	4.44	468.1	15.358
4.80	393.0	12.894	5.22	468.2	15.361
5.58	392.7	12.884	6.12	468.8	15.381
9.42	391.9	12.858	10.08	470.5	15.436
10.86	392.0	12.861	11.46	470.8	15.446
16.74	391.5	12.844	17.52	472.5	15.502
18.84	391.5	12.844	19.38	472.8	15.512
22.02	391.3	12.838	23.10	473.7	15.541
33.48	390.9	12.825	34.20	475.8	15.610
47.22	390.3	12.805	48.00	477.7	15.673
103.20	389.0	12.762	103.20	482.3	15.823
360.00	387.0	12.697	360.00	493.7	16.198
1500.00	382.4	12.546	1500.00	522.0	17.126
3030.00	383.6	12.585	3030.00	522.4	17.139
4230.00	384.6	12.618	4230.00	516.3	16.939

CR-1B, Dual Well Free Product Bail-Down Test Performed on CR-1B & CR-2A on 9/2/94 at Crystal Refinery, Carson City, Michigan.

Air/Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	383.6	12.585	0	516.1	16.932
1.02	403.2	13.228	1.62	411.3	13.494
2.16	403.3	13.232	2.58	411.0	13.484
3.06	403.1	13.225	3.42	411.1	13.488
4.26	403.0	13.222	4.50	411.0	13.484
5.82	402.9	13.219	6.48	411.5	13.501
9.48	402.7	13.212	10.02	411.9	13.514
16.74	402.5	13.205	17.70	412.7	13.540
19.98	402.5	13.205	20.52	412.9	13.547
27.36	402.3	13.199	28.02	413.8	13.576
42.42	402.0	13.189	43.20	415.2	13.622
56.88	401.5	13.173	57.90	416.3	13.658
82.80	401.2	13.163	83.40	418.1	13.717
1080.00	387.1	12.700	1080.00	521.4	17.106
4620.00	387.9	12.726	4620.00	522.1	17.129
7260.00	388.0	12.730	7260.00	522.1	17.129
9780.00	388.0	12.730	9780.00	522.3	17.136
10050.00	387.5	12.713	10050.00	523.6	17.178

CR-2A, Dual Well Free Product Bail-Down Test Performed on CR-1B & CR-2A on 9/2/94 at Crystal Refinery, Carson City, Michigan.

Alir/Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	380.6	12.487	0	519.3	17.037
0.48	394.8	12.953	1.50	442.0	14.501
1.86	394.5	12.943	2.34	442.5	14.518
2.52	394.3	12.936	3.00	443.5	14.551
3.24	394.1	12.930	3.48	444.3	14.577
4.02	393.9	12.923	4.44	444.5	14.583
4.68	393.8	12.920	5.28	445.5	14.616
5.76	393.6	12.913	6.00	445.9	14.630
7.02	393.4	12.907	7.26	446.8	14.659
7.98	393.3	12.904	8.52	447.3	14.675
9.00	393.2	12.900	9.24	447.3	14.675
10.26	393.0	12.894	10.74	447.3	14.675
14.76	392.7	12.884	15.24	449.4	14.744
21.78	392.5	12.877	22.26	449.7	14.754
26.52	392.4	12.874	27.00	450.5	14.780
43.02	392.1	12.864	43.74	452.0	14.829
59.52	391.8	12.854	60.00	452.5	14.846
81.60	391.5	12.844	82.80	453.5	14.879
1080.00	385.6	12.651	1080.00	518.6	17.014
4620.00	385.7	12.654	4620.00	519.0	17.028
7260.00	386.0	12.664	7260.00	519.5	17.044
9780.00	386.2	12.671	9780.00	519.7	17.051
10050.00	385.7	12.654	10050.00	520.5	17.077

CR-1B, Dual Well Free Product Bail-Down Test Performed on CR-1B & CR-2B on 9/9/94 at Crystal Refinery, Carson City, Michigan.

Air/Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	387.3	12.707	0	521.6	17.113
0.75	407.1	13.356	1.26	418.5	13.730
1.50	406.8	13.346	1.98	418.3	13.724
2.40	406.9	13.350	2.28	418.5	13.730
3.00	406.8	13.346	3.18	417.9	13.711
4.02	406.6	13.340	4.20	418.4	13.727
4.62	406.5	13.337	4.92	418.5	13.730
5.52	406.4	13.333	5.76	418.8	13.740
6.36	406.4	13.333	6.60	418.9	13.743
7.50	406.3	13.330	7.68	418.9	13.743
8.52	406.3	13.330	8.82	418.8	13.740
9.54	406.4	13.333	9.72	418.8	13.740
10.50	406.3	13.330	10.8	419.0	13.747
15.00	406.3	13.330	15.42	419.3	13.757
20.10	406.4	13.333	20.52	418.3	13.724
25.50	406.3	13.330	25.74	419.9	13.776
30.84	405.5	13.304	31.62	420.4	13.793
35.28	405.5	13.304	35.70	420.1	13.783
41.22	405.6	13.307	41.76	420.5	13.796
47.34	405.5	13.304	48.12	421.8	13.839
53.58	405.4	13.301	53.88	421.5	13.829
61.38	405.1	13.291	62.04	421.8	13.839
71.70	405.0	13.287	72.84	422.3	13.855
91.74	404.6	13.274	92.76	423.4	13.891

CR-2B, Dual Well Free Product Bail-Down Test Performed on CR-1B & CR-2B on 9/9/94 at Crystal Refinery, Carson City, Michigan.

Air/Product Interface			Free Product/Water Interface		
TIME, minutes	DEPTH, cm	DEPTH, feet	TIME, minutes	DEPTH, cm	DEPTH, feet
0	385.6	12.651	0	520.3	17.070
0.60	406.5	13.337	1.14	407.6	13.373
1.50	406.5	13.337	1.86	407.8	13.379
2.10	406.4	13.333	2.40	407.9	13.383
3.00	406.3	13.330	3.24	407.9	13.383
4.02	406.2	13.327	4.32	408.1	13.389
5.52	406.0	13.320	6.06	408.4	13.399
7.02	406.1	13.323	7.50	408.7	13.409
7.98	406.0	13.320	8.28	408.9	13.415
9.00	406.0	13.320	9.24	409.1	13.422
10.02	406.0	13.320	10.26	409.3	13.428
19.74	405.5	13.304	19.98	410.6	13.471
27.06	405.2	13.294	27.42	411.7	13.507
34.98	405.0	13.287	35.52	412.8	13.543
47.52	404.7	13.278	47.82	414.0	13.583
70.20	404.0	13.255	70.80	416.6	13.668
93.00	403.3	13.232	93.60	418.7	13.737

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