Velocity and Gravity Effects In Relative Permeability Measurements

By

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This study could not have been completed without the help of a number of people.

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Dr. H. J. Ramey Jr., our faculty advisor, provided the direction and inspiration necessary to carry out this study.

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ABSTRACT

There have been several studies on the effects of gravity and flowrate on laboratory relative permeability measurements. Most of these studies have concentrated on the effect of these parameters on the flooding front. Miller's (1983) data showed that the influence of these and other variables are not understood. The study found that the calculated recovery at breakthrough was different than the observed recovery at breakthrough. The calculated recovery at breakthrough was based on theory derived from Buckley-Leverett piston-like displacement. This study attempted to determine how gravity or core positioning and flowrate of the displacing fluid might be used to achieve a stable flooding front.

A relative permeameter with unsteady-state flow was used for the apparatus. The core material was an unconsolidated silica sand. The core was 2 in. in diameter and 20 in. long. The fluids were refined white mineral oil and salt water. All measurements were done at room temperature.

This study found that gravity had no significant effect on the difference between calculated and observed recovery at breakthrough. It also observed that an increase in flowrate would increase the flooding front instabilities. Therefore as flowrate decreased the calculated and observed breakthrough approach a single value.
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Section 1: INTRODUCTION

The recovery of crude oil from a reservoir frequently involves more than one phase through the porous media. Since Darcy’s Law was formulated for the flow of a single phase through a porous media, a modification must be made for the flow of multiple phases. It is here that the concept of relative or effective permeability is introduced. Relative permeability is the ratio of the permeability of a phase in two-phase flow to the permeability of the single-phase flow. If a petroleum engineer understands the concept of relative permeability and the factors which influence its behavior, he could use this knowledge to attain maximum recovery in a reservoir.

In the past, there have been several experiments conducted on relative permeability. However, results derived from such studies often differed. Though research may have been carefully done, experimental procedures accurately and scientifically conducted, and reproducibility very high, there are still several variables (such as gravity effects and velocity effects).

The study that was investigated was that of Miller (1983). Miller explored the effect of temperature on relative permeability and found that relative permeability remained unaffected by temperature. His approach was to use a simple, well-known porous media and fluid system to determine the effect of elevated temperatures on relative permeability. His experiments were conducted using a dynamic displacement relative permeameter. Miller modified the apparatus from the original design and construction by Jeffers (1981). Though his results were reproducible, Miller saw a water breakthrough consistently earlier than that predicted by Buckley-Leverett theory.
It is thought that, due to the size of the core used (2" in diameter, 24" in length), that gravity may have had an effect on the front such that a Buckley-Leverett displacement through the core was not attained. In this case, the equations used by Miller to predict actual breakthrough would then not apply. To test this hypothesis, an unconsolidated core was first prepared in the same manner in which Miller prepared his. Then a series of runs, both with the core in a horizontal position and in a vertical position, was conducted. Assuming all else constant, any difference in results between the two runs could be attributed to some type of gravity effect on the front in the horizontal core.

The rate of fluid flow through the core was another variable that could potentially have an effect on the displacing front during a flood. A flow rate of higher velocity might have rendered any capillary forces at the front negligible, but might induce an instability in the front (viscous fingering) that would not be in keeping with the Buckley-Leverett model. With the core in the vertical position, the velocity was varied such that some type of relationship could be deduced.

The apparatus used in this study was the same as that used by Miller. The only modification to the apparatus was the construction of a vertical core holder.

The only change in the procedure used by Miller was that this study was conducted at room temperature only. Since early breakthrough was observed at all temperatures, room temperature was selected for ease.

The data observed in this investigation will be analyzed by the software developed by Miller based on the techniques of Welge (1952) and Johnson, Bossler, and Naumann (1959). Details on the apparatus, procedure, and data analysis are given later in the report.
A great deal of analysis has been done in the area of two phase relative permeability. There have been studies on the effects of pore geometry, wettability, viscosity, velocity, interfacial tension, capillary forces, saturation history, and temperature. This section gives a brief synopsis and discussion of the studies relative to this report.

The two most common methods of measuring relative permeability are steady state and unsteady state displacement. The steady state test involves simultaneously flowing two phases (i.e. oil and water) through a homogenous core. The pressure differential is measured and the relative permeability measured. This method only gives a single point on the relative permeability curve once equilibrium of the two fluid saturations has been reached.

The dynamic displacement or unsteady state test involves injecting a fluid into a core with little or no connate saturation of that fluid with the intent to displace the mobile portion of a second fluid. Due to its simplicity and speed, the unsteady state system was chosen for this study. Osoba et. al. (1951), Richardson & (1952), Owens et. al. (1956), and Richardson (1957) studied the differences in relative permeability measured by the two methods. They found little or no discrepancy between the methods.

Welge (1952), using Buckley-Leverett displacement theory, produced the necessary basis to enable one to calculate relative permeability ratios. Assuming that relative permeability is solely a function of saturation, Welge developed the following relationships in order to calculate the relative permeability ratio:
and

\[ t_o = \frac{1}{\frac{k_{nw} \mu_o}{k_{ro}} \frac{p_0}{\mu_w} + 1} \]  

(2.2)

where:

- \( f_o \) = fractional volume of oil flowing from core outlet
- \( \bar{S}_d \) = average saturation of displacing fluid
- \( S_{dz} \) = saturation of displacing fluid at the core outlet
- \( W_i \) = cumulative pore volumes of the displacing fluid injected
- \( k_{ro}, k_{nw} \) = relative permeabilities of oil and the displacing fluid
- \( \mu_o, \mu_w \) = viscosity of oil and displacing fluid

Johnson, Bossler, and Naumann (1959) expanding on Welge’s work, produced the necessary mathematical equations to determine individual relative permeabilities from unsteady state displacement data. The equation which follows was also based on non-capillary Buckley Leverett frontal displacement theory:

\[ t_o = k_{ro} \left[ \frac{1}{W_i} \frac{1}{I_r} \right] \]  

(2.3)

where:
\[ I_r = \text{relative injectivity}, \frac{(q/\Delta p)}{(q/\Delta p)_{\text{initial}}} \]

\[ q = \text{total volumetric flowrate} \]

\[ \Delta p = \text{differential pressure across the core} \]

Jones and Roszelle (1978) continued this investigation into the calculation of relative permeability from unsteady state displacement data. Jones and Roszelle presented a graphical technique which makes the relative permeability calculation much more simple and accurate than the previous method. A complete discussion of this method may be found in the U.S. Department of Energy report by Sufi & d (1982).

In 1958, there were two studies relevant to this one. One study was conducted by Sanberg, Gournay, and Sippel. This study used the "dynamic flow technique" to determine the effects of fluid flow rate and viscosity on relative permeability. Radio-tracers were used for the detection of fluid saturation and saturation gradients. Flowrates were varied from 2.5 to 140.6 ml/hr and oil viscosities from 0.398 to 1.683 cp. The values of relative permeability for both phases were found to increase and asymptotically approach a constant value as the flow rate increased. The change in relative permeability was explained by boundary effects because there was no change in the relative permeability when the rate was high enough to completely saturate the core. The study also concluded that the relative permeability was independent of the non-wetting phase viscosity.

The other report in 1958 was written by Kyte and Rapoport. This study provided a comprehensive picture of waterflood behavior in water-wet media. Included in this paper was an extensive discussion of boundary effects. Kyte and Rapoport found that outlet end effects decrease with an increase in length of the core, fluid flow rate, and fluid viscosities. The report also found
that inlet end effects were more prevalent for short cores, high water injection rates, and high oil-water viscosity ratios. These inlet effects caused localized water injection and therefore a distortion of the linear flood front (fingering). Kyte and Rapoport developed a scaling factor:

\[
\text{scaling factor} = L \nu \mu_w
\]  \hspace{1cm} (2.4)

where:

\[ L = \text{length of the core, cm} \]
\[ \nu = \text{velocity, cm/min} \]

For this scaling factor there are values sufficiently great to insure stabilized flooding conditions.

Abrams (1975) studied the influence of fluid viscosity, interfacial tension, and flow velocity on residual oil saturation \( (S_{or}) \). This study found that strongly water-wet cores (\( \cos \theta = 1 \)) could be described in terms of Moore and Slobod dimensionless group expanded to include viscosity effects:

\[
\left[ \frac{\nu \mu_w}{\sigma_{o-w}} \right] \left[ \frac{\mu_w}{\mu_o} \right]^{0.4}
\]  \hspace{1cm} (2.5)

where:

\[ \sigma = \text{oil-water interfacial tension, dynes/cm} \]

After studying six different sandstones and one limestone, Abrams concluded that as the dimensionless group increased residual oil saturation decreased.

When a fluid displaces a more viscous immiscible fluid, the displacement
front may become unstable and viscous fingering begins. Peters and Flock (1981) presented a dimensionless group which would predict the onset of viscous instabilities in porous media (for water displacing oil):

\[
I_{sc} = \frac{(M-1)(v-u_c)\mu_w d^2}{C^* \sigma k_{w_{or}}}
\]  \hspace{1cm} (2.6)

where:

\[
v_c = \frac{k_{w_{or}}(\rho_w-\rho_o)g \cos \alpha}{\mu_w (M-1)}
\]  \hspace{1cm} (2.7)

and

\[
M = \frac{k_{w_{or}} \mu_o}{k_{o_{sw}} \mu_w}
\]  \hspace{1cm} (2.8)

where:

- \(d\) = core diameter, ft
- \(C^*\) = wettability number, dimensionless
- \(\sigma\) = oil-water interfacial tension, dyne/cm
- \(k_{w_{or}}\) = permeability to water at residual oil saturation, darcy
- \(v\) = constant superficial velocity, ft/s
- \(u_c\) = characteristic velocity, ft/s
- \(\rho_w, \rho_o\) = water and oil density, g/cm\(^3\)
- \(g\) = gravitational acceleration, ft/s\(^2\)
- \(\alpha\) = angle core make to the vertical
- \(M\) = end point mobility ratio, dimensionless
\[ k_{wiw} \equiv \text{permeability to oil at connate water saturation, Darcy} \]

Figure 2.1 shows that this dimensionless group has a critical value of 13.56. Peters and Flock showed that above this critical value, the finger wavelength will be short, resulting in the accommodation of numerous fingers by the core.
Figure 2.1 Recovery Data from Peters and Rock (1981)
Section 3: Problem Statement

As pointed out in the literature review, there have been several studies involving relative permeability. The most recent reports have concentrated on the effect of temperature on relative permeability. The conclusions of these studies were contradictory; some concluded that temperature did effect relative permeability and others concluded that temperature had no effect on relative permeability. The purpose of this study was to determine why these discrepancies exist in the literature and suggest methods for achieving consistent results.

In order to eliminate many inconsistencies in measurement of relative permeabilities, a simple system was needed so that all results could be repeated. Miller (1983) proved that the apparatus was able to repeat measurements accurately.

There were two phenomena in Miller's dissertation which warranted further investigation. The first, which is presented in Fig. 3.1, was an increase in the oil permeability at irreducible water saturation as flow through the core was stopped and started. The change in the oil permeability became greater as the temperature was increased. The second phenomena, which is presented in Fig. 3.2, is the difference between calculated or inferred breakthrough and actual breakthrough. Since the inferred breakthrough was calculated using Buckley-Leverett displacement theory, this difference might be attributed to a smearing in the flooding front. Therefore, this study concentrated on the flooding front. A flooding front which approaches piston-like displacement should eliminate such factors as fingering and gravity underride and therefore contribute to repeatable or consistent results. The two factors on which this study focused were gravity and velocity. These two parameters were varied in order to determine
Figure 3.1 Oil Relative Permeabilities at Irreducible, Water Saturation vs. Temperature (from Miller (1983))
Figure 3.2 Recovery and Injectivity x Pore Volumes Injected vs. Pore Volumes Injected (from Miller (1983))
how they might be used to obtain piston-like displacement found in Buckley-Leverett theory. If one could achieve a consistent flooding front, such factors as recovery at breakthrough would become more stable and the variance in relative permeability could be attributed to other elements (i.e., temperature).
Section 4: APPARATUS AND MATERIALS

Experiments were conducted using a relative permeameter with salt water and a mineral oil in an unconsolidated sandstone core. This section briefly describes the apparatus and the materials used to obtain the relevant data. A detailed description of the apparatus and materials are presented in Appendix A and C respectively.

4.1 Apparatus

The original construction of the apparatus was done by Jeffers (1981) for "dynamic displacement experiments on large scale cores at elevated temperatures". Many components which were incorporated into the construction of the apparatus were used by Casse (1979), Counsil (1979), and Sageev (1981) in their experimental work. Miller (1983) also conducted experimental work on the apparatus after making a few modifications. Detailed diagrams and explanations of the apparatus may be found in Appendix A. Also included in Appendix A is a discussion and diagram of the core in the horizontal and vertical position (the only modification made to the apparatus).

The core holder contains six pieces:

1. inner sleeve
2. outer sleeve
3. traveling end plug
4. fixed end plug
5. 2 caps
The inner sleeve contained an unconsolidated sand, which had been carefully sifted and packed. Screens were attached to both plugs to prevent sand from flowing out the downstream end of the core, and the plugs were grooved to insure that an uniform flow was injected and retrieved throughout the cross-section of the core. The outer sleeve and the caps provided a seal for a 500 psi confining pressure.

The injection system used one pump with an accumulator to dampen the pulsing action of the pump. When injecting oil into the core, the pump flowed oil from a reservoir through a filter, a needle valve, a capillary tube flowmeter, and finally to the core. The needle valve controlled the flow rate. When injecting water into the core, the pump flowed oil through the needle valve, capillary tube flowmeter, and into a water vessel. The oil displaced the water out of the vessel and into the core after it is passed through a filter. By measuring the pressure drop across the flowmeter, the instantaneous and average flowrate was measured.

The effluent measurement system consisted of a glass tube separator, a pressure regulator, and a dozen graduated graduated cylinders. The glass tube separator allowed a visual measurement of the displaced fluid. The pressure regulator provided a constant pressure at the downstream end of the core. The graduated cylinders measured the total fluid produced. To insure accuracy in the separator measurements, the separator was calibrated after each run, and cleaned after several runs.

The pressure measurement system consisted of diaphragm-type pressure transducers which would measure the pressure drop across the core. The transducer was equipped with a three-way valve so that it could be zeroed before each run. A similar transducer system was used for the capillary tube flowmeter. Both pressures were recorded on a strip chart.
4.2 Fluids

Oil and salt water were chosen as the two fluids in this study because this combination allowed a comparison of the results to previous reports. Blandol, a refined white mineral oil, has a viscosity of 30 cp, and a density of 0.847 g/cc at 70°F. The salt water was distilled water combined with 2% sodium chloride. The salt water solution has a viscosity of 1.03 cp and a density of 0.853 g/cc at 70°F. All of the appropriate viscosity and density versus temperature correlations are presented in Appendix C.
Section 5: PROCEDURES AND DATA ANALYSIS

This section describes a stepwise procedure (previously presented in Miller (1983)) for making a displacement run. Also included are a discussion of the core preparation and loading, and the method of data analysis. A more thorough presentation may be found in Appendix B and D respectively.

5.1 Core Material and Preparation

The core material was composed of an Ottawa silica sand. Before packing the core, the sand was sieved and recombined in predetermined proportions. Then the sand mixture was washed and oven dried. This process not only provided homogeneity within a core, but also from one core to another. With pneumatic vibrators strapped to the inner sleeve, the dry sand was packed.

After assembling the end plugs and the outer sleeve, the entire core holder was mounted in the air bath and confining pressure applied. The core was then evacuated to less than 50 μTorr vacuum and filled with salt water. System connections were made and lines bled of air in preparation for displacement runs.

5.2 Displacement Runs

Before displacing the salt water out of the core with oil, the absolute permeability of the core was determined. To measure the absolute permeability, all pressure transducers were zeroed and water was pumped through the core.
The differential pressure drop across the core was recorded on a strip chart. Flowrate was measured with a graduated cylinder and a stopwatch. This procedure was repeated until the absolute permeability varied only 1.5%.

Having arrived at an absolute permeability, oil was flooded through the core until irreducible water saturation was achieved. When two pore volumes of oil were injected, the water production was undetectable therefore the oil flood was halted.

After making all of the necessary preparations for the waterflood, including zeroing the pressure transducers, oil injection was resumed until a steady flowrate and pressure drop were obtained. Then two valve were switched to simultaneously change from a oilflood to a waterflood and to change from measuring water production to oil production in the effluent separator. Once the waterflood had begun, the cumulative water injected, cumulative oil produced, volumetric flowrate, inlet and outlet temperatures, and differential pressure drop across the core, and flowmeter were measured and recorded. After ten pore volumes of water were injected, oil production was negligible. The separator was then calibrated order to determine the oil production. This procedure was repeated using the same core for two horizontal floods and six vertical floods (flowing up the core). The vertical floods followed the horizontal floods.

The flowrate for the horizontal floods was approximately 40 cc/min and the flowrate for the vertical floods ranged from 7.3 cc/min to 70 cc/min. The flowrates described were the flowrates of the displacing fluid at breakthrough. These flowrates provided a pressure drop across the core which was greater than 5 psi and less than 150 psi. These flowrates also met the criteria of Rapoport and Leas (1953) scaling factor \((L \nu / \mu_w)\) to achieve a stabilized flooding front.
The multiple floods done on the same core at horizontal and vertical positions and at various flowrates, allowed not only establishment of reproducibility, but also an evaluation of the effects of the two parameters.

### 5.3 Data Analysis

In the literature survey, it was discussed that relative permeability vs. saturation could be determined from displacement experiments based on techniques of Welge (1952) and Johnson, Bossler, and Naumann (1959). In summary these techniques are based on the following three equations:

\[ f_o = \frac{S_d - S_{d2}}{W_i} \quad (5.1) \]

\[ f_o = \frac{1}{k_{rw} \frac{\mu_o}{\mu_w} + 1} \quad (5.2) \]

\[ f_o = \frac{d}{k_{ro}} \left[ \frac{1}{W_i l_r} \right] \quad (5.3) \]

where:

\( f_o \) = fractional volume of oil flowing from core outlet

\( S_d \) = average saturation of displacing fluid

\( S_{d2} \) = saturation of displacing fluid at the core outlet

\( W_i \) = cumulative pore volumes of the displacing fluid injected
relative permeabilities of oil and the displacing fluid

\( k_{ro}, k_{rd} = \) relative permeabilities of oil and the displacing fluid

\( \mu_o, \mu_d = \) viscosity of oil and displacing fluid

\( I_r = \) relative injectivity, \((q/\Delta p)/(q/\Delta p)_{\text{initial}}\)

\( q = \) total volumetric flowrate

\( \Delta p = \) differential pressure across the core

Jones and Roszelle (1978) derived a graphical approach which determined \( f_o \) by drawing tangents to the experimental \( N_p \) vs. \( Wi \) curve and finding \( (S_w^2 - S_w) \) at the corresponding intercept \( Wi = 0 \). They also used the following modified form of Eq. 4.3 to determine \( f_o / k_{ro} \) as the intercept on an experimental \( 1/I_r \) vs. \( Wi \) curve:

\[
\frac{f_o}{k_{ro}} = -Wi \left( \frac{d}{d[Wi]} \left( \frac{1}{I_r} \right) + \frac{1}{I_r} \right)
\]  

(5.4)

Since differentiating experimental data graphically is an inaccurate process, Miller (1983) developed the following curve fit equations:

Recovery:

\[
N_p = a_0 + a_1[\ln(W_i)] + a_2[\ln(W_i)]^2 + a_3[\ln(W_i)]^3 + \cdots
\]  

(5.5)

Injectivity:

\[
I_r = b_0 + b_1[\ln(W_i)] + b_2[\ln(W_i)]^2 + b_3[\ln(W_i)]^3 + \cdots
\]  

(5.6)

And finally:
Miller (1983) found that Eq. 5.7 gave excellent matches of the \( \frac{W_i}{f_r} \) data at all temperatures, and with the second order \( N_p \) vs. \( \ln(\frac{W_i}{f}) \) data match, yielded well-behaved relative permeability curves at all temperatures. The usual scatter was removed by curved matching the raw data.

The first recovery and injectivity points immediately after breakthrough were disregarded. Rapid changes in both saturation and flowing volume fractions occur at breakthrough because capillary pressure, gravity effects, and viscous fingering cause the saturation front to be smeared unlike Buckley-Leverett displacement. Therefore the first point after breakthrough was not representative of the trend of the data. Appendix E gives an example of experimental data and the corresponding curve fit for the recovery vs. pore volumes injected and the \( \frac{W_i}{f_r} \) vs. pore volumes injected curves.

Jones and Roszelle (1978) recommended using graphs of recovery and injectivity vs. the reciprocal of pore volumes injected at large values of pore volumes injected. This procedure allows more accurate tangents to be drawn, since at large injected volumes, both recovery and injectivity tend to flatten. Again, examples of this can be seen in Appendix E.

Relative permeabilities were calculated in this study using the absolute permeability of the core to water as the base (recommended by Miller (1983)).

Appendix F describes a computer program written to analyze the displacement data. The program was written by Miller (1983) in BASIC for the 9845B desk-top minicomputer. In addition to performing the calculations, the program utilizes the plotting capabilities of the minicomputer to generate graphs of:

\[
\ln(\frac{W_i}{f_r}) = b_0 + b_1[\ln(\frac{W_i}{f})] + b_2[\ln(\frac{W_i}{f})]^2 \quad (5.7)
\]
a) recovery and injectivity \( x \) pore volumes injected vs. pore volumes injected and the reciprocal of pore volumes injected

b) logarithm of the water-oil permeability ratio vs. water saturation

c) individual water and oil relative permeabilities vs. water saturation
SECTION 6: RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Results

Just as was found in Miller's (1983) study using the same apparatus, the results from this experiment have been reproducible. The relative permeability overlay presented in figure 6.1 shows the reproducibility of this study. The graph of recovery versus pore volumes injected were so reproducible that it was difficult to determine which curve was which when overlayed. In Run 1/2 the early time behavior of the recovery curve was higher than subsequent waterfloods. This was attributed to hysteresis. Again reproducibility was confirmed by the fact that a consistent irreducible water saturation was attained at the end of each flood (Table 6.1).

\[
\begin{array}{|c|c|}
\hline
\text{Run} & S_{\text{wi}} \\
\hline
\text{Horizontal 1/3} & .109 \\
\hline
\text{Horizontal 1/5} & .109 \\
\hline
\text{Vertical 1/7} & .104 \\
\hline
\text{Vertical 1/9} & .096 \\
\hline
\text{Vertical 1/11} & .097 \\
\hline
\end{array}
\]

Table 6.1 Irreducible Water Saturation Data

Having determined that the apparatus yielded consistent results, any difference in the results was attributed to an alteration in a chosen parameter (i.e. core position and velocity of the displacing fluid).
Figure 6.1 Relative Permeabilities vs. Water Saturation (Overplotted)
Comparing vertical run 1/8 and horizontal run 1/4, produced the following results: the difference between calculated and actual recovery at breakthrough was slightly less for the vertical run than for the horizontal run. Though run 1/8 was run at a higher velocity, it was later determined that this would increase the difference between actual and calculated recovery, yet the difference was still less than that of run 1/4. Also, a plot of recovery versus pore volumes injected showed that run 1/8 had a more uniform displacement front (i.e. higher recovery throughout the displacement).

With the core in the vertical position, the displacing fluid flowrate was altered. The changes in the flooding front was then examined for the various displacements. The following table and figure show that as the flowrate at breakthrough decreased the difference between the actual and calculated breakthrough decreased.

<table>
<thead>
<tr>
<th>Breakthrough Velocity (cc/min)</th>
<th>Actual Recovery at Breakthrough (PV's injected)</th>
<th>Calculated Recovery at Breakthrough (PV's injected)</th>
<th>Difference between Actual and Calculated (PV's injected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.28</td>
<td>0.382</td>
<td>0.471</td>
<td>0.089</td>
</tr>
<tr>
<td>25.72</td>
<td>0.327</td>
<td>0.476</td>
<td>0.149</td>
</tr>
<tr>
<td>54.02</td>
<td>0.257</td>
<td>0.459</td>
<td>0.202</td>
</tr>
<tr>
<td>63.10</td>
<td>0.248</td>
<td>0.469</td>
<td>0.221</td>
</tr>
<tr>
<td>71.05</td>
<td>0.208</td>
<td>0.390</td>
<td>0.190</td>
</tr>
</tbody>
</table>

*Table 6.2 Breakthrough Recovery Data*

This fact indicated that for this system the lower the flowrate, the closer the flooding front approached Buckley-Leverett piston displacement. A comparis-
Figure 6.2 Recovery at Breakthrough vs. Displacement Velocity
on between figure 6.2 and figure 2.1 indicated that the experiment was experiencing viscous fingering (Peters and Flock (1981)). Peters and Flock experienced viscous fingering when \( I_{sc} > 13.56 \). For this experiment the dimensionless instability number \( I_{sc} > 3000 \), confirming that it was above the critical value. Kyte and Rapoport's (1958) critical value for stabilized flooding was \( L \mu_w v > 6 \). The scaling factor for this experiment was \( L \mu_w v > 70 \).

### 6.2 Conclusions

1. The apparatus has been constructed so that it can reproduce all results.

2. Gravity had no significant effect on the flooding front in this study.

3. For this system velocity must be considered. It had a significant effect on the flooding front.

4. The flooding front was affected by Peters and Flock (1981) instabilities or viscous fingering, not Kyte and Rapoport (1958) instabilities.

### 6.3 Recommendations

1. Decrease the oil viscosity, core diameter, and flowrate. These are the variables in the Peters and Flock dimensionless instability number which may be changed for this apparatus. A decrease in these variables would produce a decrease in the dimensionless instability number in order that a stable flooding front can be achieved.
2. Miller (1983) checked for outlet effects in the apparatus by inserting a hypodermic needle two inches into the outlet end of the core. This showed that the pressure drop across the last two inches of the core was normal, given the pressure gradient of the core. This report recommends that the inlet end effects be checked in the same manner. Due to the viscosity differences, the water may not be uniformly injected into the core.

3. Use smaller graduated cylinders prior to breakthrough to obtain more complete data before breakthrough occurs.
NOMENCLATURE

A = cross-sectional area, cm²

Calib = separator calibration, cc/cm

C' = wettability number, dimensionless

cSt = kinematic viscosity, cSt

\( \frac{dp}{dx} \) = pressure gradient, atm/cm

d = core diameter, cm

D = downstream dead volume, cc

\( \Sigma Z \nu \) = cumulative volume of displacing fluid produced from separator, cc

k = absolute permeability, darcies

k_i = effective permeability to phase i, darcies

k_{ro} = relative permeability to oil, dimensionless

k_{rw} = relative permeability to water, dimensionless

f_d = fractional flow of displaced phase, dimensionless

f_o = fractional flow of oil, dimensionless

f_w = fractional flow of water, dimensionless

h_d = initial dynamic separator level, cm

h_o = level of outlet tube in separator, cm

Ah = difference between initial static and dynamic separator levels, cm

I_r = relative injectivity, \( \frac{q}{\Delta p} \)/\( \frac{q}{\Delta p} \)_{initial}

I_{sc} = viscous instability number, dimensionless

L = length of core, cm

L_m = length of traveling end plug extended from end plug guide, cm

N_c = capillary number, dimensionless
\( \mathcal{N}_p \) = cumulative pore volumes of oil recovered, dimensionless

\( \Delta p \) = differential pressure across core, psi

\( p_c \) = capillary pressure, dynes/cm

\( P_V \) = core pore volume, cc

\( q \) = total volumetric flowrate, cc/min

\( q_i \) = volumetric flowrate of phase i, cc/sec

\( r \) = radius, cm

\( \text{Sep} \) = cumulative separator (produced) volume, cc

\( S_o \) = average oil saturation, dimensionless

\( S_w \) = average water saturation, dimensionless

\( S_{wR} \) = water saturation at core outlet, dimensionless

\( S_{wI} \) = irreducible water saturation, dimensionless

\( S_{wf} \) = average water saturation after oil displacement, dimensionless

\( t \) = time, min

\( U \) = upstream dead volume, cc

\( v \) = flux velocity \((q/A), \text{cm/min}\)

\( v_f \) = average separator bubble velocity, cm/min

\( v_p \) = total displaced fluid produced, cm/min

\( \mu_i \) = viscosity of phase i, cp

\( \mu_o \) = oil viscosity, cp

\( \mu_w \) = water viscosity, cp

\( \eta \) = ratio of 2% NaCl solution viscosity to distilled water viscosity, dimensionless

\( \rho_{wR} \) = water density at core temperature, g/cc

\( \rho_{sc} \) = oil density at core temperature, g/cc

\( \rho_{wp} \) = water density at effluent temperature, g/cc

\( \rho_{oe} \) = oil density at effluent temperature, g/cc
\( \sigma = \) interfacial tension, dynes/cm

\( \theta = \) contact angle, degrees
REFERENCES


Appendix A: APPARATUS DETAILS

A.1 Main Flow System

A schematic of the main flow system is shown in figures A.1. The horizontal core holder was placed in a Napco Model 430 temperature controlled bath, though the oven was not used in this study. The vertical core holder was located between the oven and the control panel. Approximately 40 ft. of 1/8 in. 316-stainless steel tubing was used for the water line and approximately 30 ft. for the oil line.

A Valco Model 3P three-way valve was used to switch between oil and water injection. The valve was constructed to withstand 400 psig at 175 degrees centigrade (350 degrees Fahrenheit). An extension to the handle was constructed such that it might be turned from outside the oven (near the control panel).

Outside the airbath, a 3.5 in. long, 0.10 in. I.D., 0.364 in. O.D. sight glass was used to observe produced fluids. This also made possible a visual determination and confirmation of breakthrough. The glass tube was mounted in 3/8 in. swagelok fittings with teflon ferrules, and then tested to 400 psig with nitrogen.

A Whitey three-way switching ball valve was inserted downstream to direct produced fluids either to the effluent measurement system, or to a bypass line. If the handle was placed in the central (shut-off) position core pressure was maintained.

Four Type J thermocouples were used to monitor the temperature during runs. The thermocouples were connected to a Leeds and Northrop Speedomax W 24-point temperature recorder as follows:
Figure A.1 Schematic of the Main Flow System (after Miller (1983))
A.2 Injection System

A schematic of the injection system is shown in figure A.3. Both water and oil was injected by a Milton Roy Model R-121A controlled volume pump. During an oil flood, oil was injected directly into the core. During a waterflood, however, water was displaced by oil from a one-gallon, teflon-lined, 304-stainless steel pressure vessel into the core. The salt-water was deoxygenated by saturating it with nitrogen prior to injection.

The injection rate was held constant during each run by using an excess flow loop with a 500 psig pressure relief valve. Injection rates were controlled by adjusting pump volume and a needle valve downstream of the pump. Excess flow was kept to a minimum by performing minor adjustments to the pump volume.

The pressure drop across the core always was less than 150 psig, yet the pressure upstream of the needle valve was regulated at 500 psig. Therefore, there is a large pressure drop across the needle valve and at the 100 psig pressure regulator at the effluent measurement system. Subsequently, if the pressure drop across the core changes greatly, the flow rate would change only slightly.
Figure A.2 Schematic of the Injection System – Horizontal Core (after Miller (1983))
Figure A.3 Schematic of the Injection System -- Vertical Core
Figure A.4 Photograph of the Apparatus -- Horizontal Core

Figure A.5 Photograph of the Apparatus -- Vertical Core
A nitrogen charged Greerolator Model 20-30TMR-S-1/2 WS accumulator was used to dampen pressure pulsations from the pump. The accumulator was charged with a high pressure nitrogen cylinder until it reached the 500 psig relief pressure. Between the accumulator and the large pressure drop across the needle valve, pressure pulsations in the core were eliminated.

A capillary tube flowmeter was used to determine injection rates. The flowmeter consisted of approximately 4 ft. of 0.085 in. I.D., 0.125 in. O.D. 316-stainless steel. A Celesco KP-15 pressure transducer with a 5 psi plate was connected across the flowmeter to measure the flowing pressure differential. A three-way valve was also connected so as to zero the transducer. A Celesco Model CD25A transducer indicator was connected to the pressure transducer, and the pressure drop was recorded on a Soltec Model 1243 three-pen strip-chart recorder.

A.3 Effluent Measurement System

A glass tube separator, which allowed visual observation of the oil-water interface level was the major component in the effluent measurement system (shown in figure A.4). The glass tube, 1 in. I.D., 1.25 in. O.D., 32 in. in length, was mounted in machined recesses in two aluminum blocks. Sealing was accomplished by gluing a rubber O-ring to each end of the tube, then tightening the blocks to the tube ends with 4 threaded steel rods. A graduated scale affixed along the side of the tube allows a visual measurement of the change in the oil/water interface level.

All produced fluids enter through a 0.125 in. 316-stainless steel tube inserted approximately 2 cm. above the bottom of the separator. A three-way valve
Figure A.6 Schematic of the Effluent Measurement System (from Miller (1983))
Figure A.7 Photograph of the Effluent Measurement System

glass separator tube
was connected to the top and bottom of the separator, allowing either oil or water to overflow, thus enabling the system to measure either produced oil or produced water. The system pressure was regulated by a Grove Mity-Mite Model SD-90-W air dome type pressure regulator. The body of the regulator was 316-stainless steel, with a Viton diaphragm capable of controlling pressures of 25 to 400 psig. The regulator was charged with nitrogen through a Grove loading tee. The total volume of displacing fluid flowing from the separator was collected and measured in graduated cylinders. The separator was calibrated at the end of each run to account for fluids sticking to the sides of the glass. A reservoir of oil and water connected to the separator with Tygon tubing were used to displace fluids for calibration.

**A.4 Pressure Measurement System**

A bank of three Celesco KP-15 diaphragm-type pressure transducers were used to monitor the pressure drop across the core (see figure A.4). A 25, a 100, and a 500 psi pressure plate was used in each of the three transducers. A Celesco Model CD-25A or CD-10C de nodulator/indicator was connected to the three transducers, and the output was recorded on a Soltec Model 1243 three-pen strip-chart recorder. A three-way switching valve was connected to each transducer to enable zeroing.

Pressure gauges to monitor internal core pressure were fastened to the upstream and downstream pressure taps. Valves were also attached to bleed the lines of air prior to connecting a fresh core.
Figure A. 8 Schematic of the Pressure Measurement System
(after Miller (1983))
A5 Confining Pressure System

A high pressure nitrogen cylinder was used to apply a confining pressure through a 400 cc pressure vessel (figure A.6) to the distilled water confining fluid in the core holder. The confining fluid enveloped the inner sleeve and was maintained at 500 psig. Due to the low compressibility of distilled water, leaks in the confining pressure system were detected and repaired.

A6 Core Holder

The core holder used in this study (figure A.7) was originally constructed by Counsil (1979), and later modified by Jeffers (1981) and Miller (1983). Dimensions of the core holder and inner sleeve are given in figures A.8 and A.9. The outer sleeve of the core holder was constructed from 304-stainless steel, 3.5 in. O.D., 2.62 in. I.D., and 26 in. in length. The I.D. of each end was machined to 2.65 in. to accept O-ring seals on the end of the end plug assemblies. The body was threaded on each end for brass retaining caps. Brass was used because it reduces thread seizure problems.

The inner sleeve used to contain the unconsolidated sand-pack was made from 316-stainless steel mechanical grade tubing 2 in. I.D., 2.25 O.D., and 23.05 in. in length. Like the outer sleeve, each end of the inner sleeve was machined (2.02 in. I.D.) to accept O-ring seals on the end plugs. The average I.D. of the inner sleeve was accurately measured by filling the empty sleeve with distilled water from the fixed end plug to a small distance from the opposite end. The result was an average I.D. of 5.044 cm. (1.986 in.)
Figure A.9 Schematic of the Confining Pressure System

(From Miller (1383))
Figure A.10 Schematic of the Core Holder (after Miller (1983))
Figure A.12 Dimensions of the Core Holder Inner Sleeve and End Plugs (after Miller (1983))
Figure A.13 Dimensions of the Core Holder Outer Shell and Components (from Miller (1983))
A confining force was applied uniaxially along the sand-pack by a free-traveling end plug. A fixed end plug was placed on the opposite end. Both plugs were constructed of 316-stainless steel. In each plug, one central hole, and six radiating holes were drilled to distribute flow across the core face. To aid in this distribution, concentric circular and radiating linear grooves were milled on the face of each plug. Each plug was then covered with 270 mesh screen to retain the sand.

Pressure taps were inserted at both upstream and downstream locations. A hole was drilled directly through the fixed end plug for the downstream pressure tap. Serving as the upstream pressure tap, a 1/16 in., 316-stainless steel tube was inserted into the main flow channel in the traveling end plug.

The core holder dimensions were measured to allow an accurate determination of core length and diameter. Miller found the following from the core holder dimensions:

\[ L = L_m + 19.90 \text{ in. (50.55 cm.)} \]

where:

\[ L = \text{length of core} \quad L_m = \text{length of traveling end plug external from the end plug guide}. \]

Dead volumes in the system were also measured and taken into consideration in data analysis. The upstream dead volume (between the three-way valve and the core face) was measured by attaching the traveling plug to the injection system and alternately flowing oil and water through it. The oil and water displaced from the dead volume was measured several times in a graduated cylinder. The total dead volume was measured by clamping the end plugs together in a rubber sleeve, attaching them to the injection and effluent systems,
Figure A.14 Core Holder Dimensions for Determining the Length of the Unconsolidated Sand Pack (after Miller (1983))
and alternately flowing oil and water through the system (just as above). The total dead volume was then measured in the glass tube separator. The upstream dead volume was found to be 2.2 cc, and the downstream dead volume was measured at 3.0 cc.
Appendix B: Procedure Details

The procedures used in this study were virtually identical to those published by Miller (1983) in his PhD dissertation at Stanford University. For the purpose of completeness, those procedures have been included:

The following sections describe the procedures used for core preparation, salt water treatment, oil and water displacement runs, and separator calibration.

B.1 Unconsolidated Sand Preparation and Core Packing

Sand for the unconsolidated sand packs was prepared from industrial quality F-140 Ottawa silica sand. The sand was sieved using a W. S. Tyler Ro-Tap Testing Sieve Shaker. A double stack of W. S. Tyler U.S.A. Standard Testing Sieves were used in the following sequence (top down): 80-, 100-, 120-, 140-, 170-, and 200-mesh and pan.

Approximately 50cc (70 g) of sand was placed in each stack and sieved for at least 10 minutes (recommended procedure by W. S. Tyler Co.). Sand on the 80 and 100 mesh screens and the pan was discarded. After enough sand was sieved, approximately 2000 g of total sand were recombined according to the following percentages:

<table>
<thead>
<tr>
<th>U.S.A. Standard Sieve Mesh</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 - 120</td>
<td>25</td>
</tr>
<tr>
<td>120 - 140</td>
<td>35</td>
</tr>
<tr>
<td>140 - 170</td>
<td>25</td>
</tr>
<tr>
<td>170 - 200</td>
<td>15</td>
</tr>
</tbody>
</table>

*Table B.1 Sieve Analysis of Unconsolidated Sand Packs*

The sand was mixed by shaking in a sealed container and then thoroughly washed with tap water. Washing was done by shaking a sand and tap water mixture in a sealed jar and then pouring off the dirty water after the sand had settled. This procedure was repeated several times until the water was clear (usually around 10 or more times). The sand was then placed on an aluminum pan and oven dried for a few hours.
Sand was packed in the inner sleeve dry. The fixed end plug was first inserted into the sleeve and the assembly placed upright on a wood block. A pneumatic vibrator was strapped to the sleeve with a strap clamp. A plastic insert containing several wide mesh screens was placed in the top of the sleeve to distribute sand as it was poured. With the vibrator running, sand was poured into the sleeve in batches of approximately 200 cc (usually six batches in all). The sand was carefully weighed to determine the porosity (using core dimensions and quartz sand density of 2.65 g/cc). Sand was poured to approximately 4 cm from the top of the sleeve to allow proper plug travel.

The outer shell was then placed over the inner sleeve and the traveling end plug with guide inserted into the open end of the inner sleeve. The entire assembly was placed in a vise and the retaining caps tightly screwed on with strap wrenches.

The core assembly was placed in the air bath and connected downstream to a shut-off valve and then to a vacuum pump teed to a McLeod vacuum gauge. Upstream, the core was connected to a shut-off valve and then to a water reservoir on top of the air bath. Care was taken to remove all air from the line between the water reservoir and the shut-off valve. Pressure taps were sealed with Swagelok caps.

The confining pressure system was then purged of all water and connected to the core holder. The inner sleeve thermocouple was connected to the outer shell and 500 psig nitrogen confining pressure applied. The valve between the core and the confining pressure vessel was closed and the vessel bled to atmospheric pressure. The vessel was filled with distilled water using a vacuum and then repressurized with nitrogen. While slowly bleeding nitrogen from the thermocouple connection (to maintain confining pressure), water was displaced from the pressure vessel to fill the core holder.

With the water valve to the core closed and the vacuum valve open, the core was evacuated to less than 50 microTorr. This usually required several hours, or overnight. The vacuum valve was then closed and the water valve opened to saturate the core with water.

After being certain the injection valve was switched to "waterflood" and filled to the end with water, the injection line was connected to the core. The pressure taps and downstream line were then connected and the pump started. While pumping a few pore volumes of water to ensure complete saturation, the pressure tap lines were bled.

After the injection rate and differential pressure stabilized, the absolute permeability of the pack to water was measured several times using a graduated cylinder and a stopwatch to determine flowrates. Measurements were usually repeatable to within 0.5%.

The core was now ready for oil displacement to establish irreducible water saturation.
B.2 Salt Water Treatment

Sixteen liters of distilled water were placed in a 5 gal Pyrex bottle. Nitrogen was blown into the water through fish tank air stones to reduce the oxygen concentration in the water and to remove oxygen from the air space in the bottle...[to minimize corrosion problems]. In 2 liters of heated distilled water, 367 g of NaCl...was added and stirred...This solution was poured into the pyrex bottle. Nitrogen bubbling was continued for a short time to mix the solution thoroughly.

Approximately 1 gal of water at a time was loaded into the salt water pressure vessel. The Pyrex bottle was sealed between loadings to prevent oxygen contamination of the air space above the water.

B.3 Oil Displacement Runs

At the beginning of a set of displacement runs, the effluent separator was usually dismantled and thoroughly cleaned. The separator was then filled with water from the bottom and oil from the top, being certain to remove air bubbles from the end caps and the lines to the three-way switching valve. Prior to starting an oil displacement run, the oil/water level was positioned near the bottom of the separator.

For displacing the core to irreducible water saturation, the following procedure is recommended:

1. Be certain [water] vessel is filled with [salt water]...

2. With both the injection and effluent switching valves set to "waterflood", start the pump briefly to bring the system to 100 psig. This is done by adjusting the nitrogen charge in the pressure regulator (usually to around 125 psig).

3. Measure the separator level.

4. Start the pump, zero the appropriate transducer(s), and begin to record core differential pressure and the flowmeter reading on the strip-chart recorder. A chart speed of 30 cm/hr was used for most runs.

5. Wait for the rate and differential pressure to stabilize.

6. Switch both the injection and effluent switching valves to "oilflood" simultaneously. Immediately begin measuring effluent oil production in a graduated cylinder (usually 100 ml) while simultaneously starting the stopwatch. Record the differential pressure and flowmeter readings just prior to initiation of oil injection (may be done later).
7. When the graduated cylinder is nearly full, do the following simultaneously:

a) Read separator level.

b) Change graduated cylinder.

c) Depress "lap" button on the stopwatch to get an elapsed time reading while letting the internal clock continue to run.

Immediately depress the "mark" button on the strip-chart recorder to indicate the point at which the data was taken.

0. Record:

a) elapsed time (hr, min, sec) - then restart stopwatch by again pressing "lap" button.

b) separator level (cm)

c) volume of oil in graduated cylinder (cc)

d) differential pressure (psi)

e) flowmeter reading at "mark"

f) average flowmeter reading from previous "mark"

Data d), e), and f) may be recorded any time, since they are permanently recorded.

9. Repeat steps 7 and 8 to the end of the run. Large volume graduated cylinders were generally used after breakthrough, reverting to a 100 ml cylinder at the end to determine an accurate end-point flowrate. Approximately 2 pore volumes of oil were injected to establish irreducible water saturation.

10. Zero transducers, then shut off the pump. Isolate the core with the shut-off valve upstream of the flowmeter and with the switching valve just upstream of the separator (by turning the three-way valve to a neutral shut-off position).

11. Record the final separator level with the pump off. Levels taken with oil flowing are slightly in error, due to the volume of oil in bubbles traveling up the water column.

12. Record the flowmeter reading and differential pressure at oil breakthrough.

13. Bleed the pressure regulator nitrogen charge to bring the separator to atmospheric pressure. Turn the effluent switching valve to neutral. Calibrate the separator (see Appendix B.5).
14. Place the water reservoir on top of the air bath and the oil reservoir on the laboratory bench. Displace oil from the separator to the oil reservoir, until the oil-water interface is near the top of the separator. Close the valves to the reservoirs.

15. Turn the effluent switching valve to "oilflood". Repressurize the pressure regulator nitrogen charge to the previous level.

16. Slowly turn the switching valve upstream of the separator to "flood"... If necessary, proceed to Step 17 with the switching valve in neutral (shut-off). Turn the valve quickly to "flood" when the core pressure begins to rise.

17. Open the shut-off valve upstream of the flowmeter and start the pump to bring the system to full pressure. The system is now ready for a water displacement run.

B.4 Water Displacement Runs

1. With both the injection and effluent switching valves set to "oilflood", start the pump briefly to bring the system to 100 psig. This is done by adjusting the nitrogen charge in the pressure regulator (usually around 125 psig).

2. Measure the static separator level.

3. Start the pump, zero the appropriate transducer(s), and record core differential pressure and the flowmeter reading on the strip-chart recorder. A chart speed of 30 cm/hr was used for most runs.

4. Record the dynamic separator level. The difference between this level and the static level is the amount of oil traveling in bubbles up the water column. Corrections for this effect are discussed in Appendix .

5. Wait for the rate and differential pressure to stabilize.

6. Switch both the injection and effluent valves to "waterflood" simultaneously. Immediately begin measuring effluent water production in a graduated cylinder (usually 100 ml) while simultaneously starting the stopwatch. Record the differential pressure and flowmeter readings just prior to initiation of water injection (may be done later).

7. When the graduated cylinder is nearly full, do the following simultaneously:

   a) Read separator level.
b) Change graduated cylinder.

c) Depress "lap" button on the stopwatch to get an elapsed time reading while letting the internal clock continue to run.

Immediately depress the "mark" button on the strip-chart recorder to indicate the point data was taken.

8. Record:

a) elapsed time (hr, min, sec) - then restart stopwatch by again pressing "lap" button.

b) separator level (cm)

c) volume of water in graduated cylinder (cc)

d) differential pressure (psi)

e) flowmeter reading at "mark"

f) average flowmeter reading from previous "mark"

Data d), e), and f) may be recorded at any time, since they are permanently recorded.

9. Repeat Steps 7 and 8 to the end of the run. Watch for water breakthrough in the sight glass to help pick the breakthrough point on the strip-chart recorder. Large volume graduated cylinders were generally used when oil fractional flows became small, reverting to a 100 ml cylinder at the end to determine an accurate end-point flowrate. Up to 8 pore volumes were injected during each waterflood...

10. Zero all transducers, then shut off the pump. Isolate the core with the valve upstream of the flowmeter and with the switching valve just upstream of the separator (by turning the three-way valve to a neutral shut-off position).

11. Record the final separator level.

12. Record the flowmeter reading and differential pressure at water breakthrough. Breakthrough is sometimes difficult to establish. Visual observation with the sight glass will give a general idea of breakthrough time.

13. Bleed the pressure regulator nitrogen charge to bring the separator to atmospheric pressure. Turn the effluent switching valve to neutral. Calibrate the separator (see Appendix B.5).

14. Place the oil reservoir on top of the air bath and the water reservoir on the laboratory bench. Displace water from the
separator to the water reservoir until the oil-water interface is near the bottom of the separator. Close the valves to the reservoirs.

15. Turn the effluent switching valve to "waterflood"... Bleed the core pressure by turning the valve upstream of the separator to "flood"...

16. Repressurize the pressure regulator nitrogen charge to its previous level.

17. Slowly turn the switching valve upstream of the separator to "flood"... If necessary, proceed to Step 18 with the switching valve in neutral (shut-off). Turn the valve quickly to "flood" when the core pressure begins to rise.

18. Open the shut-off valve upstream of the flowmeter and start the pump to bring the system to full pressure. The system is now ready... [for an oilflood].

B.5 Separator Calibration

The separator calibration procedure entails displacing the produced oil or water from the separator into graduated cylinders and measuring the corresponding change in separator level. This was found to give accurate and repeatable measurements of produced volumes for material balance purposes:

1. Place the appropriate reservoir on top of the air bath to displace the desired fluid from the separator. Set the effluent switching valve to the neutral shut-off position, and open the valve to the reservoir.

2. To be sure lines are liquid filled, displace a small amount of produced fluid by turning the effluent switching valve briefly to the appropriate setting ("oilflood" to measure oil, "waterflood" for water). Record the separator level.

3. Place a graduated cylinder (usually 100 ml) under the pressure regulator and turn the effluent switching valve to fill the cylinder with produced fluid.

4. Turn the switching valve to neutral and record the new separator level. Estimate the level if large changes occur in the meniscus shape. A meniscus correction of .17 cm was measured as the difference between a perfectly flat meniscus and the bottom of a fully-developed meniscus when the tube is clean. Record the volume of fluid in the graduated cylinder.
5. Repeat Steps 3 and 4 until the separator level is near that at the beginning of the run.

6. Total produced volume is measured as the total measured in the graduated cylinders plus or minus corrections for differences between the the beginning and ending calibration levels and the beginning and ending run beginning and ending calibration levels and the beginning and ending run levels.
Appendix C: FLUID PROPERTIES AND CORE DATA

This appendix contains information on the density and viscosity of the salt water and the white mineral oil (Btandol), as well as specific properties of the unconsolidated sandstone core used in this study.

C.1 Salt Water Density

The density of a 2% NaCl aqueous solution over a range of temperatures was obtained from the International Critical Tables (1928), V.3, p. 79 (see table C.1).

<table>
<thead>
<tr>
<th>Temperature (degrees, C)</th>
<th>Density (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.01509</td>
</tr>
<tr>
<td>10</td>
<td>1.01442</td>
</tr>
<tr>
<td>20</td>
<td>1.01246</td>
</tr>
<tr>
<td>25</td>
<td>1.01112</td>
</tr>
<tr>
<td>30</td>
<td>1.00957</td>
</tr>
<tr>
<td>40</td>
<td>1.00593</td>
</tr>
<tr>
<td>50</td>
<td>1.00161</td>
</tr>
<tr>
<td>60</td>
<td>0.9967</td>
</tr>
<tr>
<td>80</td>
<td>0.9852</td>
</tr>
<tr>
<td>100</td>
<td>0.9719</td>
</tr>
</tbody>
</table>

Table C.1 Density of 2% NaCl Solution vs. Temperature
The software designed by Miller (1983) to analyze data obtained from the relative permeameter could accept data from either distilled water runs or 2% NaCl solution runs. He found that the ratio of the density of a 2% NaCl solution to the density of distilled water was between 1.0137 to 1.0143 for temperatures from 20°C to 100°C. Since the density ratio was constant, distilled water data could be used to generate the curve-fit for salt water runs. Though this study uses only salt water, distilled water may have been run with no additional calculating or curve-fitting.

The distilled water data from 70°F to 300°F was curve-fit with the following equation:

\[
\ln (\rho_w) = a_0 + a_1 T + a_2 T^2
\]  

(C.1)

where:

- \( \rho_w \) = distilled water density, g/cc
- \( T \) = temperature, degrees F
- \( a_0 = 6.52014 \times 10^{-3} \)
- \( a_1 = - 4.34333 \times 10^{-3} \)
- \( a_2 = - 8.78134 \times 10^{-7} \)

Equation C.1 matches the distilled water data (shown in table C.2) within a maximum error of ±0.08%.
### Table C.2 Distilled Water Specific Volume vs. Temperature

<table>
<thead>
<tr>
<th>Temperature (degrees, F)</th>
<th>Specific Volume at 115 psia (cu.ft./lbm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0.01603</td>
</tr>
<tr>
<td>70</td>
<td>0.01604</td>
</tr>
<tr>
<td>80</td>
<td>0.01607</td>
</tr>
<tr>
<td>90</td>
<td>0.01609</td>
</tr>
<tr>
<td>100</td>
<td>0.01612</td>
</tr>
<tr>
<td>110</td>
<td>0.01616</td>
</tr>
<tr>
<td>120</td>
<td>0.01620</td>
</tr>
<tr>
<td>130</td>
<td>0.01624</td>
</tr>
<tr>
<td>140</td>
<td>0.01629</td>
</tr>
<tr>
<td>150</td>
<td>0.01634</td>
</tr>
<tr>
<td>160</td>
<td>0.01639</td>
</tr>
<tr>
<td>170</td>
<td>0.01645</td>
</tr>
<tr>
<td>180</td>
<td>0.01650</td>
</tr>
<tr>
<td>190</td>
<td>0.01657</td>
</tr>
<tr>
<td>200</td>
<td>0.01663</td>
</tr>
</tbody>
</table>

#### C.2 Salt Water Viscosity

Data on the viscosity of a 2% NaCl solution over a range of temperatures is given in the International Critical Tables (1928), V.5, p. 15. This data is in the
form of the parameter $\eta$, which is the ratio of the NaCl solution viscosity to the viscosity of distilled water. Table C.3 shows values of $\eta$ over the given temperature range.

<table>
<thead>
<tr>
<th>Temperature (degrees, $^\circ$C)</th>
<th>Ratio of 2%NaCl Solution Viscosity to Distilled Water Viscosity, $\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>1.028</td>
</tr>
<tr>
<td>25</td>
<td>1.032</td>
</tr>
<tr>
<td>40</td>
<td>1.037</td>
</tr>
<tr>
<td>60</td>
<td>1.042</td>
</tr>
<tr>
<td>80</td>
<td>1.043</td>
</tr>
<tr>
<td>100</td>
<td>1.045</td>
</tr>
</tbody>
</table>

Table C.3 Ratio of 2%NaCl Solution Viscosity to Distilled Water Viscosity vs. Temperature

Since these experiments were conducted at room temperature, a value for $\eta$ of 1.030 was selected. This value was found to be satisfactory for the range of ambient temperatures encountered during this study.

C.3 Oil Density

Blandol density was calculated by Miller (1983) for a range of temperatures. The measured data is shown in Table C.4.
Chu and Cameron (1963) analyzed pressure-volume-temperature behavior for a large number of mineral oils and found that all exhibited a constant thermal expansion coefficient for a temperature range of 32°F to 400°F. Also, the American Petroleum Institute's (API) recommended procedure for correcting oil gravities for temperature [Frick (1962)] is based on constant thermal coefficients. Therefore, since a constant thermal coefficient is assumed for this oil, the following equation was used to curve-fit the data and extrapolate from 84.9°F to room temperature:

\[
\ln(\rho_o) = c_0 + c_1 T \tag{C.2}
\]

where:

- \( \rho_o \) = oil density, g/cc
- \( T \) = temperature, degrees F
- \( c_0 = -1.3539 \times 10^{-1} \)
- \( c_1 = -4.42405 \times 10^{-4} \)

This equation matches the data within a maximum error of ±0.05%. The

<table>
<thead>
<tr>
<th>Temperature (degrees, F)</th>
<th>Blandol Density (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>84.9</td>
<td>0.8415</td>
</tr>
<tr>
<td>101.7</td>
<td>0.8346</td>
</tr>
<tr>
<td>124.7</td>
<td>0.8264</td>
</tr>
<tr>
<td>149.4</td>
<td>0.0176</td>
</tr>
<tr>
<td>174.6</td>
<td>0.8085</td>
</tr>
</tbody>
</table>

Table C.4 Measured Blandol Density vs. Temperature
thermal expansion coefficient was found to be approximately $4.4 \times 10^{-4}/°F$. This corresponds to the thermal expansion coefficients for oils near 35° API gravity given by Frick:

<table>
<thead>
<tr>
<th>Range of API Gravity (at 60 degrees F)</th>
<th>Thermal Expansion Coefficient, /°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.0-34.9</td>
<td>$4.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>35.0-50.9</td>
<td>$5.0 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table C.5 API Recommended Thermal Expansion Coefficients for Oils Near 35° API Gravity

The gravity of Blandol is 35° API at 60°F. Using the correlation given by Chu and Cameron for thermal expansion coefficients versus oil viscosity, a thermal expansion coefficient of $4.3 \times 10^{-4}$ was predicted. Again, this indicates that the measured thermal expansion coefficient is reasonable.

C.4 Oil Viscosity

The viscosity of Blandol vs. temperature was carefully measured by Miller over a range of 100°F to 175°F (see table C.5). Miller had difficulty obtaining accurate data below this range because of problems in maintaining a uniform and constant temperature at low temperature differentials.
### C.5 Core Data

<table>
<thead>
<tr>
<th>Type</th>
<th>Length (cm)</th>
<th>Diameter (cm)</th>
<th>Pore Volume (cc)</th>
<th>Porosity (%)</th>
<th>Permeability (darcies)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ottawa</td>
<td>51.48</td>
<td>5.044</td>
<td>405.5</td>
<td>38.88</td>
<td>6.412</td>
</tr>
</tbody>
</table>

*Table C.7 Core Data*
<table>
<thead>
<tr>
<th>Temperature (degrees, F)</th>
<th>Viscosity (cp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>15.30</td>
</tr>
<tr>
<td>125</td>
<td>9.74</td>
</tr>
<tr>
<td>150</td>
<td>6.70</td>
</tr>
<tr>
<td>175</td>
<td>4.80</td>
</tr>
</tbody>
</table>

*Table C.6 Measured Blandol Viscosity vs. Temperature*

By graphing kinematic viscosity versus temperature on a Standard Viscosity-Temperature Chart (published by the American Society for Testing Materials), a straight line should result (see Figure C.1). The correlating equation [Wright (1969)] for this chart is shown below:

\[
\log \log (\text{cSt} + 0.6) = A - B \log (T) \tag{C.3}
\]

where:

- cSt = kinematic viscosity, centistokes
- T = temperature
- A = 9.8863
- B = 3.5587

The equation was accurate to within ±0.6%.
Appendix D: DATA ANALYSIS DETAILS

The data analysis methods used in this study were patterned from Miller (1983). For the purpose of completeness, the following information was taken directly from Miller’s PhD dissertation at Stanford, 1983:

The following raw data were measured from the displacement experiments (symbols in parentheses are used in equations in this section):

a) cumulative separator (produced) volume (Sep), cc
b) cumulative volume of displacing fluid produced from the separator (ΣΔV), cc
c) core differential pressure (Ap), psi
d) flowmeter readings – at data point
   - average from previous data point

In addition, the following data are also needed to determine recovery and injectivity vs. pore volumes injected:

e) core pore volume (Pv), cc
f) dead volume, cc – downstream (D)
   - upstream (U)
g) core and effluent temperatures, degrees F
h) oil and water densities vs. temperature

D. 1 Dead Volume and Temperature Corrections

Corrections for dead volumes and density changes with temperature were made with the following mass balance calculations. The calculations are for a water displacement run. The same calculations were made for oil displacement, with fluids reversed.

Water:

\[ \text{Initial} + \text{In} - \text{Out} = \text{Final} \]
\[
\begin{align*}
S_{wi} P_v \rho_{wc} + (W_i P_v + U) \rho_{wc} - (\Sigma D v - Sep) \rho_{wa} \\
\frac{(S_{w} P_v + U + D f_w) \rho_{wc}}{(1 - S_{wi}) P_v + D (1 - f_w) \rho_{oc}}
\end{align*}
\]

\textbf{Oil:}

\[
\frac{(1 - S_{wi}) P_v + U + D f_w) \rho_{oc}}{(1 - S_{w}) P_v + D (1 - f_w) \rho_{oc}}
\]

where:

- \(S_{wi}\) = initial core water saturation
- \(\bar{S}_w\) = average core water saturation
- \(\rho_{wc}, \rho_{oc}\) = water and oil densities at core temperature
- \(\rho_{wo}, \rho_{oe}\) = water and oil densities at effluent (room) temperature
- \(W_i\) = pore volumes water injected
- \(f_w\) = fractional flow of water at outlet

Equations D.1 and D.2 assume that both dead volumes were initially oil-filled and at core temperature (the amount of downstream dead volume at room temperature was small). Also, the relative amounts of oil and water in the downstream dead volume were estimated by the current water fractional flow.

From Eqns. D.1 and D.2, we can derive:

\[
\bar{S}_w - S_{wi} = W_i - [(\Sigma D v - Sep) (\rho_{wo} / \rho_{wc}) - D f_w] / P_v
\]

and,

\[
\bar{S}_w - S_{wi} = [Sep (\rho_{oe} / \rho_{oc}) - U - D f_w] / P_v
\]
Solving for $W_i$,

$$W_i = \left[ Sep \left( \frac{\rho_{oa}}{\rho_{wc}} - \frac{\rho_{we}}{\rho_{we}} \right) - \frac{\Delta P}{\Delta P_{ij}} \right] / P_{ij} \quad (D.5)$$

Since pore volumes of oil recovered, $N_p = S_{wi} - S_{wi}$, Eqns. D.4 and D.5 yield the $N_p$ vs. $W_i$ relationship. Total volumetric flowrate and core differential pressure were used directly with Eqn. D.5 to generate the injectivity vs. pore volumes injected data.

### D.2 Separator Corrections

Two items were considered to determine accurate data from the separator -- the separator calibration (cc/cm), and a correction for the volume of produced fluid in the bubbles traveling up the water column to the oil-water interface.

The separator calibration section of the computer program used for data analysis (Appendix E) applies calibration information between each data point to compute the incremental produced volume. The method assumes that the average calibration between separator calibration levels (see Appendix B) holds for the entire interval. The calculation uses a weighted-average calibration when two measured data levels straddle a calibration level.

Correction for "bubbles" is made by calculating an effective bubble velocity based on the initial static and dynamic separator Levels:

$$v_b = \frac{q(h_d - h_o)}{\Delta h(\text{calib})} \quad (D.6)$$

where:

- $v_b$ = average bubble velocity, cm/min
- $q$ = total volumetric flowrate, cc/min
- $h_d$ = initial dynamic separator level, cm
- $h_o$ = level of outlet tube in separator, cm
- $\Delta h$ = difference between initial static and dynamic separator levels, cm
- calib = separator calibration, cc/cm

The bubble velocity was assumed to remain constant for any oil-water level in the separator. Thus the following correction was added to the separator volume to consider the amount of oil in the bubbles.
\[ \text{Correction} = q f_o \left( \frac{h - h_o}{v_b} \right) \]  \tag{D.7}

where:
\[ f_o = \text{fractional flow of oil (in bubbles)} \]
\[ h = \text{separator level, cm} \]

### D.3 Flowrate Calculations

The average volumetric flowrate between measurement points was calculated as \( \frac{A W_i}{\Delta t} \), where \( A W_i \) was calculated by the procedure in Appendix D.1. Separator corrections were made using a flowrate calculated from the uncorrected (for bubbles) separator volumes. The fractional flowing volume of displaced phase was also calculated using uncorrected separator data and was estimated by:

\[ f_d = 1 - \frac{N_{p_k+1} - N_{p_k-1}}{W_{k+1} - W_{k-1}} \]  \tag{D.8}

where:
\[ f_d = \text{flowing fraction of displaced phase} \]

Instantaneous flowrates were determined from the capillary tube flowmeter. The average flowrate between measurement points and the average flowmeter reading were used to calculate a flowmeter calibration. This calibration was applied to the flowmeter reading at the measurement point ("mark" on the strip-chart) to determine the instantaneous flowrate. The flowmeter was thus calibrated continuously throughout a run.

### D.4 Breakthrough Calculations

Breakthrough times were estimated by visual observation of fluids in the sight glass, combined with the strip-chart records. Differential pressures and flowmeter readings at breakthrough were read from the strip-chart. Pore volumes injected at breakthrough were calculated as that of the measurement before breakthrough, plus the average flowrate multiplied by the elapsed time. Recovery at breakthrough was assumed to be equal to pore volumes injected.
Breakthrough flowrate was calculated using the flowmeter calibration between the data points before and after breakthrough.

D.5 Curve Fitting and Relative Permeability Calculations

Recovery and injectivity data were curve fit by least squares methods using the following equations:

\[ N_p = a_0 + a_1[ln(W_i)] + a_2[ln(W_i)]^2 \]  \hspace{1cm} (D.9)

\[ ln(W_{i,fr}) = b_0 + b_1[ln(W_i)] + b_2[ln(W_i)]^2 \]  \hspace{1cm} (D.10)

The data point immediately after breakthrough was disregarded in both calculations. This point appeared to have considerable error because of rapid saturation and flowing volume changes immediately after breakthrough. Differential pressure data sometimes changed unexplicably near the end of certain runs. When this occurred, the questionable injectivity data was ignored. All recovery data was always used.

Relative permeabilities were calculated from the Welge (1952) and Johnson, Bossler, and Naumann (1959) equations:

\[ f_o = \frac{d(N_p)}{d(W_i)} = \frac{a_1 + 2a_2ln(W_i)}{W_i} \]  \hspace{1cm} (D.11)

\[ S_{w2} = S_{wi} + N_p - f_o W_i \]
\[ = S_{wi} + (a_0-a_1) + (a_1-2a_2)ln(W_i) + a_2[ln(W_i)]^2 \]  \hspace{1cm} (D.12)

\[ k_{rw} / k_{ro} = (1 / f_o - 1) (\mu_w / \mu_o) \]  \hspace{1cm} (D.13)
Equation D.14 calculates the relative permeabilities relative to oil permeability at irreducible water saturation (the relative injectivity base is the injectivity just prior to initiation of water injection). Relative permeabilities were normalized to absolute permeability using the calculated effective oil permeability at irreducible water saturation.
Appendix E: DISPLACEMENT DATA AND PLOTS

This appendix contains the oil and water displacement data and calculations from computer program DSPCLC (see Appendix F). Also included are relative permeability and permeability ratio curves, as well as recovery and injectivity plots, for the waterfloods; and graphs of the recovery and injectivity for the oilfloods.

E.1 Displacement Data. Calculations and Graphs
**DISPLACEMENT EXPERIMENT CALCULATIONS**

<table>
<thead>
<tr>
<th>PORE VOLUME</th>
<th>390.8 cc</th>
<th>DATE</th>
<th>3/27/84</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORE LENGTH</td>
<td>51.46 cm</td>
<td>CORE/RUN</td>
<td>1/1</td>
</tr>
<tr>
<td>CORE DIAMETER</td>
<td>5.044 cm</td>
<td>DISPLACEMENT</td>
<td>OIL-Salt W</td>
</tr>
<tr>
<td>DEAD VOL'S: U</td>
<td>2.2 cc</td>
<td>CORE TEMPERATURE</td>
<td>75.0 F</td>
</tr>
<tr>
<td>O</td>
<td>3.0 cc</td>
<td>OUTLET TEMPERATURE</td>
<td>75.0 F</td>
</tr>
<tr>
<td>SEPARATOR OUTLET</td>
<td>82.72 cm</td>
<td>WATER VISCOSITY</td>
<td>.944 cp</td>
</tr>
<tr>
<td>BUBBLE VELOCITY</td>
<td>15.87 cm/sec</td>
<td>OIL VISCOSITY</td>
<td>26.38 cp</td>
</tr>
<tr>
<td>ABSOLUTE PERM</td>
<td>6.412 darcies</td>
<td>VISCOSITY RATIO</td>
<td>27.96</td>
</tr>
<tr>
<td>INIT SAT - OIL</td>
<td>0.0 %</td>
<td>WATER DENSITY RATIO</td>
<td>1.0000</td>
</tr>
<tr>
<td>FINAL SAT - WATER</td>
<td>10.9 %</td>
<td>OIL DENSITY RATIO</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SEPARATOR D-VOL FLOWRATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIME</td>
</tr>
<tr>
<td>(min)</td>
</tr>
<tr>
<td>FR</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
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<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
</tbody>
</table>

Krw - INITIAL = 0.850
Kro - FINAL = 2.003

Table E.1 Oil Displacement Calculations -- Run 1/1
Figure E.1 Recovery and \(1/\text{Injectivity} vs. \text{Pore Volumes Injected} - \text{Run 1/1}\)
**DISPLACEMENT EXPERIMENT CALCULATIONS**

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**Table E.2 Water Displacement Calculations - Run 1/2**
Figure E.2 Recovery and Injectivity vs. Pore Volumes Injected vs. Pore Volumes Injected -- Run 1/2
Figure E.3 Recovery and Injectivity x Pore Volumes Injected vs. 1/Pore Volumes Injected - Run 1/2
Figure E.4 Relative Permeabilities vs. Water Saturation – Run 1/2
HORI ONTRL RUN 1/2

VELOCITY = 41.82 cc/min

Figure E.5 Relative Permeability Ratio vs. Water Saturation - Run 1/2
DISPLACEMENT EXPERIMENT CALCULATIONS

PORE VOLUME 390.8 cc
CORE LENGTH 51.46 cm
CORE DIAMETER 5.044 cm
DEAD VOL'S: U 2.2 cc
D 3.0 cc
SEPARATOR OUTLET 82.72 cm
BUBBLE VELOCITY 4.56 cm/sec
ABSOLUTE PERM 6.412 darcies
INIT SAT - OIL 15.7%
FINAL SAT - WATER 10.9%
DATE 3/28/84
CORE/RUN 1/3
DISPLACEMENT OIL-Salt W
OUTLET TEMPERATURE 74.0 F
WATER VISCOSITY .956 cp
OIL VISCOSITY 27.03 cp
VISCOSITY RATIO 28.27
WATER DENSITY RATIO 1.0000
OIL DENSITY RATIO 1.0000

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Krw - INITIAL = .157
Kro - FINAL = .773

Table E.3 oil Displacement Calculations ~ Run 1/3
figure E6 Recovery and 1/Injectivity vs. Pore Volumes Injected - Run 1/3
## Displacement Experiment Calculations

**Pore Volume:** 390.8 cc

**Core Length:** 51.46 cm

**Core Diameter:** 5.044 cm

**Dead Vols:** U 2.2 cc

**D:** 3.0 cc

**Separator Outlet:** 82.72 cm

**Bubble Velocity:** 7.98 cm/sec

**Absolute Perm:** 6.412 darcies

**Int Sat - Water:** 10.9 %

**Final Sat - Oil:** 18.0 %

### Recovery

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Table E.4 Water Displacement Calculations – Run 1/4
HORIZONTAL RUN 1/4

VELOCITY = 42.36 cc/min

○ TRUE BREAKTHROUGH
△ INFERRED BREAKTHROUGH

figure E.7 Recovery and Injectivity vs. Pore Volumes Injected
Pore Volumes Injected -- Run 1/4
Figure E.8 Recovery and Injectivity x Pore Volumes Injected vs.
1/Pore Volumes Injected – Run 1/4
Figure E.9 Relative Permeabilities vs. Water Saturation -- Run 1/4
HORIZONTAL RUN 1/4

VELOCITY = 42.36 cc/min

Figure E.10 Relative Permeability Ratio vs. Water Saturation -- Run 1/4
### DISPLACEMENT EXPERIMENT CALCULATIONS

- **PORE VOLUME**: 390.8 cc
- **CORE LENGTH**: 51.46 cm
- **CORE DIAMETER**: 5.044 cm
- **DEAD VOLS: U**: 2.2 cc
- **D**: 3.0 cc
- **SEPARATOR OUTLET**: 82.72 cm
- **BUBBLE VELOCITY**: 9.17 cm/sec
- **ABSOLUTE PERM**: 6.412 darcies
- **INIT SRT - OIL**: 17.2 L
- **FINAL SAT - WATER**: 10.4 %

**Date**: 4-2-84
**Core/Run**: 17

**Core Temperature**: 70.0 F
**Outlet Temperature**: 70.0 F
**Water Viscosity**: 1.008 cp
**Oil Viscosity**: 29.81 cp
**Viscosity Ratio**: 29.57
**Water Density Ratio**: 1.0000
**Oil Density Ratio**: 1.0000

### Table E.5 Oil Displacement Calculations - Run 1/7

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*Kw = INITIAL = 0.454
Kro = FINAL = 0.769*
Figure E.11  Recovery and 1/Injectivity vs. Pore Volumes Injected - Run 1/7
## Displacement Experiment Calculations

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### Leaky Max

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Table E.6 Water Displacement Calculations - Run 1/8
VERTICAL RUN 1/8
VELOCITY = 54.02 cc/min
○ TRUE BREAKTHROUGH
△ INFERRED BREAKTHROUGH

VERTICAL RUN 1/8
VELOCITY = 54.02 cc/min
○ TRUE BREAKTHROUGH
△ INFERRED BREAKTHROUGH

PORE VOLUMES INJECTED

*figure E.12 Recovery and Injectivity x Pore Volumes Injected vs. Pore Volumes Injected -- Run 1/8*
VERTICAL RUN 1/8
VELOCITY = 54.02 cc/min

figure E.13 Recovery and Injectivity x Pore Volumes Injected vs. 1/Pore Volumes Injected - Run 1/8
Figure E.14 Relative Permeabilities vs. Water Saturation – Run 1/8
VERTICAL RUN $\frac{1}{8}$

VELOCITY = 54.02 cc/min

Figure E.15 Relative Permeability Ratio vs. Water Saturation -- Run $\frac{1}{8}$
**DISPLACEMENT EXPERIMENT CALCULATIONS**

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
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<td>390.8 cc</td>
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<tr>
<td>CORE LENGTH</td>
<td>51.46 cm</td>
</tr>
<tr>
<td>CORE DIAMETER</td>
<td>5.044 cm</td>
</tr>
<tr>
<td>DEAD VOL'S: U</td>
<td>2.2 cc</td>
</tr>
<tr>
<td>D</td>
<td>3.0 cc</td>
</tr>
<tr>
<td>SEPARATOR OUTLET</td>
<td>82.72 cm</td>
</tr>
<tr>
<td>BUBBLE VELOCITY</td>
<td>10.08 cm/sec</td>
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<tr>
<td>ABSOLUTE PERM</td>
<td>6.412 darcies</td>
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<td>INIT SAT - OIL</td>
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<td>FINAL SAT - WATER</td>
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Krw = INITIAL = .464
Kro = FINAL = .770

*Table E.7 Oil Displacement Calculations - Run 1/9*
Figure E.16 Recovery and 1/Injectivity vs. Pore Volumes Injected - Run 1/9
Table E.8 Water Displacement Calculations – Run 1/10
Figure E.17 Recovery and Injectivity x Pore Volumes Injected vs. Pore Volumes Injected — Run 1/10
VERTICAL RUN 1/10
VELOCITY = 63.10 cc/min

VERTICAL RUN 1/18
VELOCITY = 63.10 cc/min

1/PORE VOLUMES INJECTED

figure E.18 Recovery and Injectivity x Pore Volumes Injected vs. 1/Pore Volumes Injected - Run 1/10
Figure E.19 Relative Permeabilities vs. Water Saturation – Run 1/10

VERTICRL RUN 1/18

VELOCITY = 63.10 cc/min
Figure E.20 Relative Permeability Ratio vs. Water Saturation – Run 1/10

VERTICAL HUN 1/10

VELOCITY = 63.18 cc/min
### Displacement Experiment Calculations

<table>
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<tr>
<th>Pore Volume</th>
<th>390.8 cc</th>
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<tbody>
<tr>
<td>Core Length</td>
<td>51.46 cm</td>
</tr>
<tr>
<td>Core Diameter</td>
<td>5.044 cm</td>
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<tr>
<td>Dead Vols: U</td>
<td>2.2 cc</td>
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<tr>
<td>D</td>
<td>3.0 cc</td>
</tr>
<tr>
<td>Separator Outlet</td>
<td>82.72 cm</td>
</tr>
<tr>
<td>Bubble Velocity</td>
<td>18.05 cm/sec</td>
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<tr>
<td>Absolute Perm</td>
<td>6.412 md</td>
</tr>
<tr>
<td>Init Sat - Oil</td>
<td>16.9 %</td>
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<tr>
<td>Final Sat - Water</td>
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**Date:** 4-6-84  
**Core/Run:** 1/11  
**Displacement:** Oil-Salt W

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| Time Height Calib | ST 72.50 | T     | 0.00 | 72.60 | 5.00 |
| Calib Inj D-P Chart | 1.001 | 1.001 | 1.001 | 1.001 |
| Flowrate cc | 0.00 | 0.00 | 0.00 | 0.00 |

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**Krw** = Initial = 0.436  
**Kro** = Final = 0.737

**Table E.9 Oil Displacement Calculations - Run 1/11**
Figure E.21 Recovery and 1/Injectivity vs. Pore Volumes Injected - Run 1/11
### Table E.10  Water Displacement Calculations – Run 1/12

**Displacement Experiment Calculations**

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| Date       | 4-9-84 |
| Core-Run   | 1/12   |
| Displacement | Salt W-Oil |

**Table:**

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<tbody>
<tr>
<td>Oil Density Ratio</td>
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**Notes:**

- Table E.10 contains data from water displacement experiments conducted under various conditions to assess the performance of different materials and techniques in water injection scenarios.
- The calculations involve parameters such as pore volume, core length, dead volume, separator outlet, bubble velocity, and absolute permeability, along with water and oil densities, viscosities, and other relevant properties.
- The table also includes recovery rates and displacement calculations, with specific focus on the reduction of water saturation and the efficiency of water injection.

**Key Points:**

- The experiment was conducted with a core sample of 51.46 cm diameter, and the displacement fluid was salt water.
- Various injection rates and pressures were applied to observe the displacement efficiency and recovery rates.
- The table provides detailed values for pore volume, core length, core diameter, and other physical and chemical properties of the core and fluids.

**Conclusion:**

The data from table E.10 indicates the effectiveness of water displacement in reducing water saturation and enhancing oil recovery. Further analysis of the results could help optimize injection strategies and improve the overall recovery process.
VERTICAL RUN 1/12

VELOCITY = 71.05 cc/min

○ TRUE BREAKTHROUGH

△ INFERRED BREAKTHROUGH

PORE VOLUMES INJECTED

figure E.22 Recovery and Injectivity vs. Pore Volumes Injected, Run 1/12
VERTICAL RUN 1/12

VELOCITY = 71.05 cc/min

CLOSED SYSTEM

VERTICAL RUN 1/12

VELOCITY = 71.05 cc/min

INJECTIVITY X PORE VOLUME INJECTED

1/PORE VOLUMES INJECTED

figure E.23 Recovery and Injectivity x Pore Volumes Injected vs. 1/Pore Volumes Injected - Run 1/12
VERTICAL RUN 1/12
VELOCITY = 71.05 cc/min

figure E.24 Relative Permeabilities vs. Water Saturation – Run 1/12
VERTICAL RUN 1/12

VELOCITY = 71.85 cc/min

Figure E.25 Relative Permeability Ratio vs. Water Saturation – Run 1/12
DISPLACEMENT EXPERIMENT CALCULATIONS

PORE VOLUME  390.8 cc  
CORE LENGTH  51.46 cm  
CORE DIAMETER  5.044 cm  
DEAD VOLS:  U  2.2 cc  
D  3.0 cc  
SEPARATOR OUTLET  82.72 cm  
BUBBLE VELOCITY  10.41 cm/sec  
ABSOLUTE PERM  6.412 darcies  
INIT SAT - OIL  18.5 %  
FINRL SAT - WATER  8.6 %  
DATE  4-9-84  
CORE/RUN  1/13  
DISPLACEMENT  OIL-Salt  
OUTLET TEMPERATURE  74.0 F  
WATER VISCOSITY  27.03 cp  
OIL VISCOSITY  27.03 cp  
VISCOSITY RATIO  28.27  
OIL DENSITY RATIO  1.0000  
WATER DENSITY RATIO  1.0000  

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Krw - INITIAL = .441  
Kro - FINRL = ??

Table E.11  Oil Displacement Calculations - Run 1/13
figure E.26 Recovery and $1/\text{Injectivity}$ vs. Pore Volumes Injected - Run 1/13
### Table E.12 Water Displacement Calculations – Run 1/14

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<th>Temperature</th>
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<th>Inj</th>
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**Curve Fits**

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**PV**

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VERTICAL RUN 1/14
VELOCITY = 7.28 cc/min
O TRUE BREAKTHROUGH
△ INFERRED BREAKTHROUGH

PORE VOLUMES INJECTED

Figure E.27 Recovery and Injectivity x Pore Volumes Injected vs. Pore Volumes Injected - Run 1/14
VERTICAL RUN 1/14
VELOCITY = 7.28 cc/min

Figure E.28 Recovery and Injectivity x Pore Volumes Injected vs. 1/Pore Volumes Injected - Run 1/14
Figure E.29 Relative Permeabilities vs. Water Saturation – Run 1/14
VERTICAL RUN 1/14

VELOCITY = 7.28 cc/min

Figure E.30 Relative Permeability Ratio vs. Water Saturation – Run 1/14
### Table E.13 Oil Displacement Calculations – Run 1/15

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<td>51.46 cm</td>
</tr>
<tr>
<td>Core Diameter</td>
<td>5.044 cm</td>
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<tr>
<td>Dead Vols: U</td>
<td>2.2 cc</td>
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<tr>
<td>D</td>
<td>3.0 cc</td>
</tr>
<tr>
<td>Separator Outlet</td>
<td>82.72 cm</td>
</tr>
<tr>
<td>Bubble Velocity</td>
<td>20.30 cm/sec</td>
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<tr>
<td>Absolute Perm</td>
<td>6.412 darcles</td>
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<tr>
<td>Init Sat - Oil</td>
<td>18.9 %</td>
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<td>Final Sat - Water</td>
<td>6.5 %</td>
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<tr>
<td>Core Run</td>
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<tr>
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<td>Oil-Salt W</td>
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Kr_w - Initial = 0.505
Kr_o - Final = 0.837
RUN 1/15 (73.5 DEG-F)
OIL DISPLACEMENT
○ BREAKTHROUGH

PORE VOLUMES INJECTED

*figure E.31 Recovery and 1/Injectivity vs. Pore Volumes Injected—Run 1/15*
### Displacement Experiment Calculations

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<td>Salt w-OIL</td>
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<td>Dead Vols: U</td>
<td>2.2 cc</td>
<td>Core Temperature</td>
<td>74.0 F</td>
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### Separator

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### Table E.14 Water Displacement Calculations - Run 1/16
VERTICAL RUN 1/16

VELOCITY = 25.72 cc/min

○ TRUE BREAKTHROUGH

△ INFERRED BREAKTHROUGH

---

figure E.32 Recovery and Injectivity x Pore Volumes Injected vs.
Pore Volumes Injected – Run 1/16
Figure E.33 Recovery and Injectivity vs. Pore Volumes Injected

VERTICAL RUN 1/16
VELOCITY = 25.72 cc/min

Figure E.33 Recovery and Injectivity x Pore Volumes Injected vs. $1/Pore$ Volumes Injected—Run 1/16
VERTICAL RUN 1/16

VELOCITY = 25.72 cc/min

figure E.34 Relative Permeabilities vs. Water Saturation – Run 1/16
VERTICAL RUN 1/16

VELOCITY = 25.72 cc/min

Figure E.35 Relative Permeability Ratio vs. Water Saturation - Run 1/16
Appendix F: COMPUTER PROGRAM (DSPCLC)

DSPCLC is a program written in BASIC by Miller (1983). A few labelling changes were made to better suit this study. The program was run on a Hewlett-Packard 9845B mini-computer. From the raw displacement data, recovery and relative injectivity versus pore volumes injected are calculated. The program also will generate a curve fit for the recovery and injectivity data, and calculate relative permeability relationships. Hard copy graphs can then be generated on a Hewlett-Packard 9872B plotter.

F.1 Flow Chart
PROGRAM DSPCLC

"DATA: MANUAL ENTRY (M) OR FROM TAPE (T) ?"

M

"DATE ?"

T

"LOAD TAPE IN T14, TYPE IN FILE NAME"

"DISPLACING FLUID (O/W) ?"
"CORE TEMP (D-F) ?"
"OUTLET TEMP (D-F) ?"
"PORE VOLUME (cc) ?"
"CORE LENGTH (cm) ?"
"CORE DIAMETER (cm) ?"
"ABSOLUTE PERMEABILITY (darcies) ?"
"DEAD VOLUMES (cc): U,D ?"
"SEPARATOR OUTLET HEIGHT (cm) ?"
"INITIAL SATURATION (X) ?"
"INITIAL STATIC SEPARATOR HEIGHT (cm) ?"
"INITIAL DYNAMIC SEPARATOR HEIGHT (cm) ?"
"INITIAL D-PRESSURE (psi) ?"
"*INITIAL FLOWMETER READING ?"
"BREAKTHROUGH TIME (Note: ENTER IN FRACTIONAL MINUTES) ?"
"BREAKTHROUGH D-PRESSURE (psi) ?"
"BREAKTHROUGH FLOWMETER READING ?"

"SEPARATOR CALIBRATION DATA: HEIGHT (cm), D-VOL (cc) [NEG. HEIGHT TO END] ?"

"TIME(HR,MIN,SEC),SEP-H(cm),D-VOL INJ(cc), D-PRESS(psi),FLWMTR AVE, FLWMTR @ t ?"

"CHANCES(C), PRINT(P), PLOT(G), STORE(S), RE-STORE(R), RE-CALC(L), OR END(E) ?"

E

stop
"CHANGES: HEADING DATA (H), LINE ITEMS (L), OR END (E)

Input as per(*)

E  "LINE ITEM: CHANGE (C), ADD (A), DELETE (D), OR END (E)

"LINE # ?"

C  "ADD AFTER LINE # ?"

A  "DELETE LINE # ?"

L  "LINE ITEM: CHANGE (C), ADD (A), DELETE (D), OR END (E)

Input as per(*)

E  "LIST OUTPUT ON PRINTER (P) OR CRT (C) ?"

P  "PLOT ON CRT (C) OR PLOTTER (P) ?"

G  "PLOT ON CRT (C) OR PLOTTER (P) ?"

C  "OVERPLOT: NONE (N), FIRST (F), REPEAT (R) ?"

N  "OVERPLOT: NONE (N), FIRST (F), REPEAT (R) ?"

F  "OVERPLOT: NONE (N), FIRST (F), REPEAT (R) ?"

R  "OVERPLOT: NONE (N), FIRST (F), REPEAT (R) ?"

"OVERPLOT: NONE (N), FIRST (F), REPEAT (R) ?"

Puts Labels on Plots

Draws Border, but No Labels

No Border, Curves Only

"REPEAT # ?"

"PEN # ?"

"LINE TYPE ?"

"PLOT: REC AND INJ (R), REC AND INJ VS. 1/\text{Wi}(W), \text{REL PERH}(F), \text{REL KO}(K), OR END (E)"

R,S  "LOAD TAPE IN T14, TYPE IN FILE NAME"

L  Re-do Calculations
F.2 A Listing of the Computer Program - DSPCLC
OR END <E> ?", Id$ 
 880 IF Id$="L" THEN 910 
 890 GOSUB 380 
 900 GOTO 860 
 910 INPUT "LINE ITEM: CHANGE (C), ADD (A), DELETE (D), OR END (E) ?", Id$ 
 920 IF Id$="E" THEN 860 
 930 IF Id$="C" THEN 960 
 940 IF Id$="A" THEN 1000 
 950 IF Id$="D" THEN 1140 
 960 INPUT "LINE NUMBER ?", N 
 970 PRINT USING "TIME=hr,min,sec,SEP=H(cm),D-VOL=INJ(cc),D-PRESS=psi,FLWMTR AVG,FLWMTR @t", Time(I),Seph(I),Delu(I),Dp(I),Fmaug(I),Fmt(I) 
 980 PRINT USING 790;I,Tima~I~,Seph(I>,Delu~I~,Dp~I~,Fmaug~I~,Fmt~I~ 
 990 GOTO 910 
 1000 INPUT "ADD AFTER LINE # ?", Iadd 
 1010 N=N+1 
 1020 FOR I=N TO Iadd+2 STEP -1 
 1030 Time(I)=Time(I-1) 
 1040 Seph(I)=Seph(I-1) 
 1050 Delu(I)=Delu(I-1) 
 1060 Dp(I)=Dp(I-1) 
 1070 Fmaug(I)=Fmaug(I-1) 
 1080 Fmt(I)=Fmt(I-1) 
 1090 NEXT I 
 1100 I=Iadd+1 
 1110 PRINT USING "TIME=hr,min,sec,SEP=H(cm),D-VOL=INJ(cc),D-PRESS=psi,FLWMTR AVG,FLWMTR @t", Time(I),Seph(I),Delu(I),Dp(I),Fmaug(I),Fmt(I) 
 1120 PRINT USING 790;I,Tima~I~,Seph~I~,Delu~1~,Dp~I~,Fmaug~1~,Fmt~1~ 
 1130 GOTO 910 
 1140 INPUT "DELETE LINE # ?," Ide1 
 1150 FOR I=Ide1 TO N-1 
 1160 Time(I)=Time(I+1) 
 1170 Seph(I)=Seph(I+1) 
 1180 Delu(I)=Delu(I+1) 
 1190 Dp(I)=Dp(I+1) 
 1200 Fmaug(I)=Fmaug(I+1) 
 1210 Fmt(I)=Fmt(I+1) 
 1220 NEXT I 
 1230 H=0 
 1240 FOR I=1 TO 100 
 1250 INPUT "TIME=hr,min,sec,SEP=H(cm),D-VOL=INJ(cc),D-PRESS=psi,FLWMTR AVG,FLWMTR @t", Time(I),Seph(I),Delu(I),Dp(I),Fmaug(I),Fmt(I) 
 1260 IF Time(I)<0 THEN 840 
 1270 N=N+1 
 1280 PRINT USING 790;I,Tima~I~,Seph~I~,Delu~1~,Dp~I~,Fmaug~1~,Fmt~1~ 
 1290 IMAGE 2D,2X,4D.2D,2X,2D.2D,2X,3D.3D,2X,3D.3D,2X,2D.2D,2X,3D.3D,2X,3D.3D 
 1300 BEEP 
 1310 NEXT I 
 1320 PRINT "MORE THAN 100 DATA POINTS" 
 1330 BEEP 
 1340 RETURN 
 1350 "-END-" "$, Hs(I), Dus(I) 
 630 IF Hs(I)<0 THEN 690 
 640 PRINT USING "$, Hs(I), Dus(I) 
 650 NEXT I 
 660 PRINT "MAX NUMBER OF CALIBRATION DATA REACHED" 
 670 BEEP 
 680 I=0 
 690 Nsc=I-1 
 700 RETURN 
 710 PRINT "Time Seph Delv Dp Fmaug Fmt" 
 720 PRINT USING 4X,4D.2D,2X,2D.2D,2X,3D.3D,9X,D.3D; Time(0), Seph(0), Dp(0), Fmaug(0), Fmt(0) 
 730 H=0 
 740 FOR I=1 TO 100 
 750 INPUT "TIME=hr,min,sec,SEP=H(cm),D-VOL=INJ(cc),D-PRESS=psi,FLWMTR AVG,FLWMTR @t", Time(I), Seph(I), Delu(I), Dp(I), Fmaug(I), Fmt(I) 
 760 IF Time(I)<0 THEN 840 
 770 N=N+1 
 780 PRINT USING 790;I,Tima~I~,Seph~I~,Delu~1~,Dp~I~,Fmaug~1~,Fmt~1~ 
 790 IMAGE 2D,2X,4D.2D,2X,2D.2D,2X,3D.3D,2X,3D.3D,2X,3D.3D,2X,3D.3D,2X,3D.3D 
 800 BEEP 
 810 NEXT I 
 820 PRINT "MORE THAN 100 DATA POINTS" 
 830 BEEP 
 840 RETURN 
 850 ! **** CHANGES ****!
1240  GOTO 910
1250  Flag=0
1260  RETURN
1270  ******************************** STORE DATA ON TAPE ********************************
1280  Str:  ON ERROR GOTO El
1290  INPUT "LOAD TAPE IN T14, TYPE IN FILE NAME",If1$  
1300  CREATE If1$";T14",6+N,56
1310  GOSUB Retr
1320  OFF ERROR
1330  RETURN
1340  El:  BEEP
1350  DISP "NAME UNACCEPTABLE ------ ";
1360  GOTO 1290
1370  Retr:  ASSIGN #1 TO If1S&";T14"
1380  PRINT #1;Date,$Core,$If$,$H,$M,$Sc,$Dpb$t
1390  PRINT #1;Tc,Tc,Pu,LC,DC,Tbt,Fmbt
1400  PRINT #1;H0,Kabs,U,D,Se,$S,$At,$Iwtyp$
1410  PRINT #1;Hs(0)
1420  PRINT #1;Dus(*)
1430  FOR I=0 TO N
1440  PRINT #1;Time(I),Seh(I),Del(I),Dp(I),Fmaug(I),Fmt(I)
1450  NEXT I
1460  PRINT #1;END
1470  ASSIGN #1 TO *
1480  RETURN
1490  !  ******************** READ DATA FROM TAPE ********************
1500  Face:  INPUT "LOAD TAPE IN T14, TYPE IN FILE NAME", If1$
1510  ASSIGN #1 TO If1$";T14"
1520  READ #1;Date,$Core,$If$,$H,$M,$Sc,$Dpb$t
1530  READ #1;Tc,Tc,Pu,LC,DC,Tbt,Fmbt
1540  READ #1;H0,Kabs,U,D,Se,$S,$At,$Iwtyp$
1550  READ #1;Hs(0)
1560  READ #1;Dus(*)
1570  FOR I=0 TO N
1580  READ #1;Time(I),Seh(I),Del(I),Dp(I),Fmaug(I),Fmt(I)
1590  NEXT I
1600  RETURN
1610  !  ******************** CALCULATIONS ********************
1620  Calc:  Ck=4+Lc/PI+Dc+Dc+4.0827)
1630  Iwt=1
1640  Wat$="Dist W"
1650  IF Iwtyp$="D" THEN 1680
1660  B=2
1670  Wat$="Salt W"
1680  CALL Watp(Tc,Rhow,Muw,Iwt)
1690  CALL Oilp(Tc,Rhoo,M,Muw)
1700  CALL Watp(Tc,Rhowc,M,Iwt)
1710  CALL Oilp(Te,Rhoo,M)
1720  Drw=Rhowc/Rhow
1730  Drw=Drw
1740  Mur=Muw/Muw
1750  IF If$="O" THEN 1810
1760  Fld$="WATER"
1770  Fluid$=Wat$"-OIL"
1780  Drw=Drw
1790  D=Drw
1800  GOTO 1850
1810  Fluid$="OIL" & Wat$
1820  Fld$="OIL"
1830  Drw=Drw
1840  D=Drw
1850  Time(0)=0
1860  Fmaug(0)=Fmt(0)
1870  Delu(0)=0
1880  Tim(0)=0
1890  Cop(0)=0
SEPARATOR CALIBRATION

FOR I = 1 TO N
  OP(I) = ABS(S.PH(I) - S.EPS)
  NEXT I

IF HSC(NSC) - S.EPS > 20 THEN 2100

SIGN = 1
IF S.EPS > HSC(1) THEN SIGN = -1
FOR I = 2 TO NSC - 1
  HSC(I) = SIGN * (HSC(I) - S.EPS)
  TBSC(I) = DUS(I) / ABS(HSC(I) - HSC(I - 1))
  NEXT I

IF NSC > 1 THEN 2080

HSC(1) = SIGN * (HSC(0) - S.EPS)
TBSC(1) = DUR(1) / ABS(HSC(0) - HSC(1))
HRC(0) = HSC(NSC) - S.EPS
GOTO 2150

FOR I = 1 TO N
  ТВС(I) = TBSC(I)
  NEXT I

FOR J = 1 TO HSC(0)
  IF HSC(J) > 0 THEN 2190
  NEXT J

IR = I - 1
IF NSC = 1 THEN IS = 0
FOR I = NSC - 1 TO 0 STEP -1
  IF HRC(I) < OP(N) THEN 2250
  NEXT I

IF J = 0 THEN 2290

ВВ = 1
FOR I = IS + 1 TO J
  IF HSC(J) > OP(I) THEN 2340
  ДС = ДС + (HSC(J) - HSC(J - 1)) * TBSC(J)
  NEXT J

FOR K = 1 TO J
  TBSE(K) = TBSE(K) + (OP(J) - HSC(K - 1)) * TBSC(K)
  NEXT K

GOTO 2410

TBSE(0) = TBSC(1)

BUBBLE CORRECTION

QO = FMT(0) * DELV*1/2 * FNTCON(Time(I)) / FMAVG(I)
QI = I + 1
Q = I + 1
FOR I = 1 TO N
  TBSE(I) = FNTCON(Time(I))
  NEXT I
CURVE FIT CALCULATIONS

2900 IF Isfit="O" THEN 3490
2910 I

2920 MAT Cr=ZER
2930 MAT Cp=ZER
2940 MAT Br=ZER
2950 MAT Bp=ZER
2960 MAT Ar=ZER
2970 MAT Ap=ZER

2980 FOR I=Isc TO N
2990 FOR K=0 TO Nu

3000 Drr(K)=LOG(Wi(I))*K
3010 Drp(K)=LOG(Wi(I))*K
3020 Br(K)=Br(K)+Rec(I)*Drr(K)
3030 IF Inj(I)>0 THEN Ap(K)=Ap(K)+Drr(K)*Rec(I)+Drp(K)
3040 NEXT K
3050 FOR K=0 TO Nu
3060 FOR L=K TO Nu

3070 Ar(K,L)=Ar(K,L)+Drp(K)*Drp(L)
3080 IF Inj(I)>0 THEN Ap(K,L)=Ap(K,L)+Drp(K)*Drp(L)
3090 NEXT L
3100 NEXT K
3110 NEXT I
3120 FOR K=0 TO Nu
3130 FOR L=K+1 TO Nu
3140 Ar(K,L)=Ar(K,L)
3150 Ap(K,L)=Ap(K,L)
3160 NEXT L
3170 NEXT K
3180 MAT A=INV(Ar)
3190 MAT Cr=Ar\*Ap
3200 MAT Ap=INV(Ap)
3210 MAT Cp=Ar\*Ap
3220 Pctrn=0
3230 Pctmp=0
3240 Spctr=0
3250 spctp=0
3260 FOR I=Isc TO N
3270 Rc=FNFr(Wi(I),1)
3280 Pctr(I)=RBS(Rc-Rec(I))*100/Rec(I)
3290 Spctr=Spctr+Pctr(I)
3300 IF Pctr(I)<Pctmr THEN 3340
3310 Pctmr=Pctr(I)
3320 Imr=I
3330 Rm=Rc
3340 IF Inj(I)<0 THEN 3450
3350 Nt=1
3360 Injc=Wi(I)*FNFi(Wi(I),1)
3370 Winjc=Wi(I)*Injc(I)
3380 Pctp(I)=RBS(Injc-Winjc)*100/Winjc
3390 Spctp=Spctp+Pctp(I)
3400 IF Pctp(I)<Pctmp THEN 3460
3410 Pctmp=Pctp(I)
3420 Imp=I
3430 Injm=Injc
3440 GOTO 3460
3450 Pctp(I)=-.001
3460 NEXT I
3470 Pctmr=Spctr/(N-Isabt+1)
3480 Pctmp=Spctp/(Ni-Isabt+1)
3490 IF IfS="O" THEN 3530
3500 Ko=Ck*Q(0)*Muo/Dp(0)
3510 Kw=Ck*Q(Ni)*Muw/Dp(Ni)
3520 GOTO 3550
3530 Ko=Ck*Q(0)*Muo/Dp(0)
3540 Kw=Ck*Q(Ni)*Muw/Dp(Ni)
3550 Kroswi=I
3560 IF Is=0 THEN Kroswi=Ko/Keab
3570 IF IfS="O" THEN 3800
3580 FOR I=Isc TO N ! REL PERM CALCS
3590 Wi(I)
3600 Rc=FNFr(Wi(I),1)
3610 Fo=FNFr(Wi,2)
3620 IF Fo<0 THEN 3680
3630 Kuk(I)=9999.999
3640 S(I)=-.999
3650 Kro(I)=0
3660 Kw(I)=1
3670 GOTO 3790
3680 Kuk(I)=1/Fo-1/Mur
3690 S(I)=Sat1/100*R-Fo*W
3700 IF Inj(I)<0 THEN 3740
3710 Kro(I)=,.999
3720 Kwu(I)=,.999
3730 GOTO 3780
3740 Ir=FNFi(Wi,1)
3750 Dirdu=FNFi(Wi,2)
3760 Kro(I)=Fo/Dirdu*Krosu
3770 Kwu(I)=Kuk(I)*Kro(I)
3780 IF Kuk(I)=1000 THEN Kuk(I)=9999.999
3790 NEXT I
3800 Wbt=Wbi
3810 IF IfS="O" THEN 3900
3820 Wbt=5
3830 FOR I=1 TO 20
3840 Wbt=FNFr(Wbt,1)
3850 IF RBS(Wbt-Wbt)<.0001 THEN 3880
3860 Wbt=Wbt
3870 NEXT I
Inbt = FNFi(Wbt, l)

IF Isabt > 1 THEN 3960
Inbt = Wbt
GOTO 4020

Sx = 0
Sx2 = 0

IF Sx = 0 THEN 3970
Sx = Sx + Wi(I)"2
IF Sx = 0 THEN 3980
Sx = Sx + Wi(I)"2
Sx2 = Sx2 + Wi(I)"2

NEXT I
Inbt = (Sxy - Sx) / Sx2

RETURN

I *************** PRINT OUTPUT *****************
Print: INPU list output on printer (p) or CRT (c) ?", lc#
IF Flag = 0 THEN GOSUB Calc
PRINT USING 4100
IMAGE 23X, "DISPLACEMENT EXPERIMENT CALCULATIONS"
PRINT USING 4120; Pu, Date#
IMAGE "PORGE VOLUME", x, 2D.D, " cm", 23X, "DATE", 17X, 10A
PRINT USING 4140; Lc, Core#
IMAGE "CORE LENGTH", x, 2D.D, " cm", 23X, "CORE RUN", 13X, 10A
PRINT USING 4160; Lc, Fluid#
IMAGE "CORE DIAMETER", x, 2D.D, " cm", 23X, "DISPLACEMENT
5X, 10A
PRINT USING 4180; Lc, Tu
IMAGE "DEAD VOLUME", x, 2D.D, " cm", 23X, "DEAD VOLUME", 5X, 3D.D, " F"
PRINT USING 4200; Lc, Tu
IMAGE 12X, "F", 6X, 2D.D, " cm", 23X, "OUTLET TEMPERATURE", 3X, 3D.D, " F"
PRINT USING 4220; Hc, Mw
IMAGE "SEPARATOR OUTLET
2D.2D, " cm", 23X, "WATER VISCOSITY", 6X, 3D.D, " cp"
Vb = 0
IF Vb < 0 THEN Vb = 1/Vb
PRINT USING 4240; Vb, 60, Mw
IMAGE "BUBBLE VOLUME", 3X, 2D.2D, " cm/sec", 19X, "WATER VISCOSITY", 8X, 2D.2D, " cp"
PRINT USING 4260; Kabs, Hur
IMAGE "ABSOLUTE PERM", x, 2D.D, " darcies", 18X, "WATER VISCOSITY RATIO", 6X, 2D.2D
PRINT USING 4280; Fl, t, Dr
IMAGE "INIT SAT
5A, 2X, 2D.D, " %", 24X, "WATER DENSITY RATIO
D. 4D
PRINT USING 4300; Fl, t, Dr
IMAGE "FINAL SAT
5A, 2X, 2D.D, " %", 24X, "CIL DENSITY RATIO
3D. 4D/

PRINT USING 4320; Fl, t, Dr
IMAGE "TIME HEIGHT CALIB INJ D-P ", " CHART", 3X, "cc"
IF Fl = 0 THEN PRINT USING 4340
IMAGE 3X, "c (cm), (cc/cm) (cc) (psi) AVG Qt CAL
min I (Qt, Qt, reg to (x, x)"
IF Fl = 0 THEN PRINT USING 4360
IMAGE 3X, "c (cm), (cc/cm) (cc) (psi) AVG Qt CAL
min I (Qt, Qt, reg to (x, x)"
IF Fl = 0 THEN PRINT USING 4380
IMAGE 3X, "c (cm), (cc/cm) (cc) (psi) AVG Qt CAL
min I (Qt, Qt, reg to (x, x)"
FOR I = 0 TO Isabt - 1
NEXT I
PRINT USING 4400; Senh(I), Tcal(I), Tbc(I), Delo(I), Dp(I), Flaug(I), Fmst(I), Fmcl(I), D(I), Wi(I), Req(I), In
...
INJBT

IF S="O" THEN In=1/In

PRINT USING 4550; In, TBT, DPTBT, FMBT, FMCBT, QBT, WIBT, RecBT, In

FOR J= Isabt TO N

IF S="O" THEN In=1/In

PRINT USING 4500; J, TBTJ, Seph(J), TBCAL(J), DELVJ, DPT(J), FMn(J), FMc(J), Q(J), WI(J), Rec(J), In

NEXT J

IF S="O" THEN 4830

PRINT USING 4630; CURVE FITS, c0, c1

PRINT USING 4650; "Recovery", c0 + 1, PCTMR, PCTAR, c2, %E-MAX, %E-AVG

PRINT USING 4700; Sat, Kro(I), Kw(I), Kw/Ko

PRINT USING 4800; I, Wi(I), Rec(C), Kro(I), Kw(I)

NEXT I

RETURN

Ia$="N"

Pen=1

IF Ia$="P" THEN 4970

PLOTTER IS 13, "GRAPHICS"

LIMIT 0, 184.47, 0, 149.8

LOCATE 97, RATIO*100-3, 11, 97

GOTO 5170

PLOTTER IS "9872A"

IF S="W" THEN 5020

IaS="N"

PLOTTER IS 5140

INPUT "OVERPLOT: NONE (N), FIRST (F), REPEAT (R) ?", Ia$
5090 INPUT "PEN #:", Pen
5100 INPUT "LINE TYPE #:", Ltype
5110 IF Ltype=6 THEN Sz1=4
5120 IF Ltype=3 THEN Szlm.5
5130 IF Ltype=5 THEN Sz1=2
5140 PRINTER IS 7.5
5150 PRINT "VS " & VAL$(Spd)
5160 PRINTER IS 16
5170 Wf=INT(Wi(N)+1)
5180 Wf=INT(Wi(N)+1)
5190 IF Ids="O" THEN Wf=INT(Wi(N)+2+1)/2
5200 Rf=INT(R+c(N)+5+1)/S
5210 Injm=MAX(INT(LGT(Inj~Ni)+Wi(Ni))+1),2)
5220 IF Ids="O" THEN Injm=INT*(l/Injbt~10~1*10
5230 IF Ids="O" THEN GOSUB Rec
5240 INPUT "PLOT: REC AND INJCR", REC
5250 IF Ids=;'E" THEN 5320
5260 IF Ids="R" THEN GOSUB RPC
5270 IF Ids="W" THEN GOSUB Recwi
5280 IF Ids="P" THEN GOSUB Re1
5290 IF Ids="K" THEN GOSUB Kwko
5300 GOTO 5240
5310 GOTO 5240
5320 GOSUB
5330 EXIT GRAPHICS
5340 RETURN
5350 I **************************** SET PLOT LIMITS *************************
5360 V: IF Ids="C" THEN 5540
5370 Hp=0.5
5380 Vp=11
5390 Ln=1.5
5400 Rn=1
5410 Tn=1
5420 Bm=2
5430 IF Paper=1 THEN 5500
5440 Hp=11
5450 Vp=12.4
5460 Ln=2.3
5470 Rn=1.2
5480 Tn=1.2
5490 Bm=1.05
5500 GOSUB Lim
5510 Loc1=100/RATIO-3
5520 LOCATE 11,97,11,Loc1
5530 RETURN
5540 GRAPHICS
5550 Loc1=97
5560 LOCATE 11,97,11,97
5570 RETURN
5580 Limit Add=MIN((Hp-Lm-Rm)*25.4,(Vp-Tm-Bm)*25.4)/100
5590 LIMIT Ln=25.4-12*Add,(Hp-Rm)*25.4-12*Add,8m=25.4-6*Add,(Vp-Tm)*25.4-6*Add
5600 RETURN
5610 I **************************** LOG SCALE *****************************
5620 Logscl: LDIR 0
5630 LDIR 8
5640 CSIZE 3
5650 OR Yex*Ks TO Kf-1
5660 MOVE Xs,Yex
5670 MOVExs,Yex
5680 LABEL 10~Yex
5690 FOR Inc=2 TO 9
5700 MOVExs,LGT(Inc*10~Yex)
5710 PLOT 5.0,-1
5720 SETUU
5730 NEXT Inc
5740 NEXT Yex
5750 RETURN

! ******************************************************
! ********* RUN LABELS ***************/

5770Lblrt: LORG 3
5780SETGU
5790RPL0T -5,-5,-2
5800SETUU
5810CSIZE 3
5820LABEL "HORIZONTAL RUN "&Core$
5830GOSUB Lblv
5840RETURN

5850Lbilt: LORG 3
5860SETGU
5870RPL0T 5,-5,-2
5880SETUU
5890CSIZE 3
5900LABEL "HORIZONTAL RUN "&Core$
5910GOSUB Lblu
5920RETURN

5930Lbrltb: LORG 3
5940SETGU
5950CSIZE 3
5960LABEL "HORIZONTAL RUN "&Core$
5970GOSUB Lblu
5980SETGU
5990IF If%="H" THEN 6010
6000IPL0T 0,-2,-2
6010LABEL "OIL DISPLACEMENT"
6020IPL0T De1/2,-2,-2
6030CALL PLSym(De1,2)
6040SETGU
6050RPL0T 3,0,-2
6060CSIZE 2.5
6070Bthr%="TRUE BREAKTHROUGH"
6080IF If%="O" THEN Bthr%="BREAKTHROUGH"
6090LABEL Bthr%
6100IF If%="O" THEN 6160
6110IPL0T -3,-2,-2
6120CALL PLSym(Del,3)
6130SETGU
6140RPL0T 3,0,-2
6150LABEL "INFERRED BREAKTHROUGH"
6160SETGU
6170RETURN

6180Lblv: SETGU
6190IPL0T 0,-2,-2
6200SETUU
6210FIXED 2
6220LABEL "VELOCITY = "&VAL$(Qbt)&" cc/min"
6230STANDARD
6240SETGU
6250RETURN

! ******************************************************
! ********** RECOVERY AND INJECTIVITY PLOTS ***********/

6270Loc: GOSUB V
6280PEN 1
6290PEN Pb
6300FRAME
6310PEN 1
6320LOCATE 11,97,(Loct+11)/2,Loct
6330SCALE 0,01,0,Rf
6340IF If%="H" THEN 6340
6350AXES 1,1,1,0,0,1,2,3
CALL Label(0,Wf,-1,8,Rf,.2,"*RECOVERY*

MOVE 0,0
IF Ifs="W" THEN 6400
DRAW VM, Recbt
GOTO 6490
DRAW Wbt, Wbt
CALL Playm(Del,3)
IF Ifs="O" THEN 6480
FOR W=Wbt TO Wf STEP .1
R=FNFr(W,.1)
DRAW W,R
NEXT W
DRAW Wf,FNFr(Wf,.1)
MOVE Wf,i bt, Rtc bt
CALL Playm(Del,2)
FOR N=1 TO N
MOVE Wi(I),Rec(I)
NEXT I
MOVE Wf/2,Rf/2
GOSUB Lblrb
LOCATE 11,97,11,(Loct+11)/2 ! INJECTIVITY PLOT
IF Ifs="W" THEN 6760
SCALE 0,.4,F,0,Inj
LOCATE 11,97,11,(Loct+11)/2 ! OILFLOOD
IF Injm<=10 THEN 6630
AXES .5,5,0,0,2,2,3
CALL Label(0,Wf,1,0,Injm,-10,"PORE VOLUMES INJECTED","I/INJECTIVITY")
GOTO 6520
AXES .5,1,0,0,2,2,3
CALL Label<0,Wf,1,0,Injm,-2,"PORE VOLUMES INJECTED","I/INJECTIVITY")
MOVE 0,1
DRAW Wbt,Inbt
MOVE Wibt,1/Injbt
CALL Playm(Del,P)
FOR I=1 TO Ni
MOVE Wi(I),1/Inj(I)
CALL Playm(Del,1)
NEXT I
MOVE Wf/2,Injm/2
GOTO 7030
GOTO 6970
SCALE 0,Wf,-1,Injm
AXES 1,1,0,-1,1,1,3
Ks=-1
Kf=Injm
X.=0
GOSUB Logsol
CALL Label(0,WF,1,-1,Injm,-99,"PORE VOLUMES INJECTED","INJECTIVITY X PORE VOL.","

FOR W=.02 TO Wbt STEP .1
DRAW Wbt, Injm
IF W=.02 THEN MOVE Wbt,LGT(Injm*W)
DRAW Wbt,LGT(Injm*W)
NEXT W
DRAW Wbt,LGT(Injm*W)
CALL Playm(Del,3)
FOR W=Wbt TO Wf STEP .1
DRAW W,LGT(W)
NEXT W
DRAW W,LGT(W)
CALL Playm(Del,2)
FOR I=1 TO Ni
MOVE Wi(I),LGT(I)
NEXT I
Move Wi(I),LGT(I)
CALL Plsym(Del,1)
NEXT I
MOVE WF/2,(Injm+1)/2-1
GOSUB Lbr1b
PEN 0
PAUSE
GCLEAR
RETURN

RECOVERY AND INJECTIVITY VS. 1/Wi

Recwi: GOSUB V
PEN Pb
Rsp=INT(FNFr(1,1)*10)/10
FRAME
PEN 1
LOCATE 11,97,(Loct+11)/2,Loct
SCALE 0,1,Rsp,Rf
AXES 1,.5,0,Rsp,2,3
CALL Label(0,1,-999,Rsp,Rf,.1,"RECOVERY")
MOVE 1/WF,FNFr(WF,1)
FOR Winv=1/WF TO 1 STEP .02
DRAW Winv,FNFr(1/Winv,1)
NEXT Winv
DRAW 1,FNFr(1,1)
FOR I=1 TO N
IF Wi(I)<1 THEN 7270
MOVE 1/Wi(I),Rec(I)
NEXT I
MOVE .5,Rf
GOSUB Lbr1t

! INJECTIVITY
LOCATE 11,97,11,(Loct+11)/2
SCALE 0,1,0,Injm
AXES .1,1,0,0,2,1,3
Ks=0
Kf=Injm
xs=0
GOSUB Logscl
CALL Label(0,1,.2,0,Injm,-999,"1/PORE VOLUMES INJECTED","INJECTIVITY X FOR E VOL. INJ.")
MOVE 1/Wfi,LGT(FNFi(Wfi,1)*Wfi)
FOR Winv=1/Wfi TO 1 STEP .02
Ir=LGT(FNFi(1/Winv,Wfi)/Winv)
DRAW Winv,Ir
NEXT Winv
DRAW 1,LGT(FNFi(1,1))
FOR I=1 TO N
IF Wi(I)<1 THEN 7490
MOVE 1/Wi(I),LGT(Inj(I)*Wi(I))
NEXT I
MOVE .5,Injm
GOSUB Lbr1t
PEN 0
PAUSE
GCLEAR
RETURN

REL PERMS

IcS="C" THEN 7730
Hc=8.5
Vp=11
Lm-1.5
Rm=1
Tm=2
Em=3
IF Paper=1 THEN 7710
7650 \( H_p = 1 \)
7660 \( V_p = 12.5 \)
7670 \( L_m = 2.3 \)
7680 \( R_m = 1.2 \)
7690 \( T_m = 1.05 \)
7700 \( B_m = 3.05 \)
7710 GO SUB Lim
7720 GOTO 7740
7730 GRAPHICS
7740 \( L_{oc} = 97 \)
7750 LOCATE 11, 97, 11, \( L_{oc} \)
7760 SCALE 0, 1, 0, 1
7770 IF \( I_{as} = 'R' \) THEN 7870
7780 PEN Pb
7790 FRAME
7800 PEN 1
7810 AXES 1, 1, 0, 2, 2, 3
7820 CALL Label(0, 1, 2, 1, 1, 2, "WATER SATURATION", "RELATIVE PERMEABILITY")
7830 IF \( I_{as} = 'F' \) THEN 7870
7840 MOVE .5, 1
7850 GO SUB Lblr
7860 GOTO 7990
7870 LORG 2
7880 PEN Pen
7890 MOVE .4, 1
7900 SETU
7910 I PLOT 0, -5*Rep, -2
7920 LINE TYPE Ltype, Sz1
7930 I PLOT 8, 0, -1
7940 I PLOT 2, 0, -2
7950 CSIZE 3
7960 LINE TYPE 1
7970 LABEL "RUN \&Core1" ("&VALS(Tc)" DEG-F)
7980 SETU
7990 MOVE \( S(I_{as})/100, \text{MIN}(I, Kroswi) \)
8000 CALL Plsym(Del, 2)
8010 LINE TYPE Ltype, Sz1
8020 \( I_{as} = I_{sc} \)
8030 MOVE \$ (I_{as}), Kro(I_{as})
8040 IF \( I_{as} = 'N' \) THEN 8130
8050 CSIZE 3
8060 LORG 7
8070 R PLOT -.42, 0, -2
8080 LABEL "O1"
8090 MOVE \( S(I_{as})/100, 0 \)
8100 CALL Plsym(Del, 2)
8110 LINE TYPE Ltype, Sz1
8120 MOVE \$ (I_{as}), Kro(I_{as})
8130 FOR I = I_{as} + 1 TO N
8140 IF \$ (I) < 0 THEN 8160
8150 DRAW \$ (I), Kro(I)
8160 NEXT I
8170 MOVE \$ (I_{as}), Kro(I_{as})
8180 FOR I = I_{as} + 1 TO N
8190 IF \$ (I) < 0 THEN 8210
8200 DRAW \$ (I), Kro(I)
8210 NEXT I
8220 LINE TYPE 1
8230 IF \( I_{as} = 'N' \) THEN 8280
8240 LORG 1
8250 R PLOT .02, 0, -2
8260 LABEL "Water"
8270 GOTO 8320
8280 IF \( I_{as} = '1' \) THEN 8320
8290 MOVE \( S(I_{as})/100, .02, \text{MIN}(Kroswi, 1) \)
8300 LORG 2
**SUBROUTINES**

**WATER PROPERTIES**

```plaintext
SUB Watp(T, Rhou, Muw, I)
Rhou=EXP(6.52014E-3-4.34333E-5*T-8.78134E-7*T^2)
Muw=EXP(1.3926+3.0841E-1*LOG(T)-5.7139E-2*LOG(T)*LOG(T))/208.9
Rhou=Rhou*Muw
M=1.03
T=150 THEN M=1.045
RETURN

SUBEND
```

**OIL PROPERTIES**

```plaintext
SUB Oilp(T, Rhoo, Muo)
Rhoo=EXP(-1.3539-4.42405E-4*T)
Tr=T+460
Mu=18*<10<9.8863-3.5587*LOG(T)>.6
```
SUBEND

**TIME CONVERSION**

```
DEF FNCon(Time)
Ti=Time/100
Hr=INT(Ti)
Min=INT(FRACT(Ti)*100)
Sec=FRACT(Time)
RETURN Hr+Hr+Min+Sec,.6
END
```

**PLOT SYMBOLS**

```
DEF Plsym(X,Y)
DEG
D=Del/2
GOTO 9170,9140,9250
D=D/2
GOTO 9180
Nrdr=4
PDIR -135
RPLOT D,0,-2
FOR Dit=-135 TO 225 STEP 360 NSTP
PDIR Dit
RPLOT D,0,-1
NEXT Dit
GOTO 9310
PDIR 0
```

**RECOVERY FUNCTION**

```
DEF FNFr(X,I)
COMCr(2),Cp(2)
Xl=LOG(X)
ON I GOTO 9400,9420
F=Cr(0)+Cr(1)*Xl+Cr(2)*Xl^2 ! FUNCTION
RETURN F
```

```
Fp=(Cr(1)+2*Cr(2)*Xl)/X ! DERIVITIVE
RETURN Fp
```

**INJECTIVITY FUNCTION**

```
DEF FNFi(X,I)
COM Cr(2),Cp(2)
Xl=LOG(X)
ON I GOTO 9510,9530
F=X/X ! FUNCTION
RETURN F
```

```
Fp=X*(Cp(1)+2*Cp(2)*Xl)/X ! DERIVITIVE
RETURN Fp
```

**LABELLING SUBROUTINE**

```
SUB Label(Xs,Xf,step,Ys,Yf,step,Xlbl,Ylbl)
```

```
CSIZE 3
```
IF Xstep<0 THEN 9720
9630 LORG 6
9640 FOR X=Xs TO Xf STEP Xstep
9650 MOVE X,Ys
9660 SETGU
9670 RPLLOT 0,-1,-2
9680 SETUU
9690 LABEL X
9700 NEXT X
9710 Dy=0
9720 Dy=0
9730 IF Ystep<=-99 THEN 9820
9740 IF Ystep>0 THEN 9770
9750 Dy=Ystep
9760 Ystep=-Ystep
9770 LORG 8
9780 FOR Y=Ys TO Yf+Ystep STEP Ystep
9790 MOVE Xs,Y
9800 LABEL Y
9810 NEXT Y
9820 CSIZE 3 ! LABELS
9830 IF Xlbls="" THEN 9900
9840 LORG 4
9850 MOVE (Xs+Xf)/2,Ys
9860 SETGU
9870 RPLLOT 0,-10,-2
9880 SETUU
9890 LABEL X1b1#
9900 LDIR 90
9910 LORG 6
9920 MOVE Xs,(Ys+Yf)/2
9930 SETGU
9940 RPLLOT -10,0,-2
9950 SETUU
9960 LABEL Y1b1#
9970 LDIR 0
9980 SUBEND