Measuring Unsteady-State Gas Displacing Liquid Relative Permeability of High Permeability Samples

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Abstract

High permeability samples create problems in getting reliable unsteady-state gas displacing oil relative permeability because of the difficulty in getting the differential pressure high enough to prevent the capillary forces from dominating the flow. When running the test manually, the reliable rate of data collection limits the maximum flow rate and therefore the differential pressure that can be used. An automated unsteady-state gas displacing liquid permeameter was designed and built to improve the reliability of gas displacing oil data by allowing higher flows without problems with data recording.

The minimum differential pressure for unsteady-state relative permeability tests is discussed in terms of the capillary pressure. By using arguments derived from fractional flow equations and saturation profile measurements, the minimum differential pressure should be 10 times the capillary pressure for the saturations expected during the test.

Introduction

During an unsteady-state gas displacing liquid relative permeability test, the objective is to measure the viscous flow resistance of the gas and liquid in a porous media as a function of their saturations. Therefore, the viscous forces need to dominate the flow. If the differential pressure of the injected gas is too low, capillary forces can dominate making the measured data difficult to analyze and the results unreliable. The objectives of this paper are to discuss the problems of running gas-displacing-liquid unsteady-state relative permeability tests at too low a differential pressure and to present an automated permeameter that helps overcome these problems.

The Problem with Measuring Unsteady-State Gas Displacing Liquid Relative Permeability

Reliable relative permeability data can be characterized as monotonically decreasing relative permeability of the displaced phase as its saturation decreases. The relative permeability curve can be reliably projected back to 100% relative permeability at 100% saturation.(Figure 1)

Poor relative permeability data can appear as in Figure 2 where the injected gas breaks through at a low gas saturation and the oil relative permeability drops very quickly. This behavior is typically due to a high permeability area in the sample resulting in the sample being poorly swept.

On high permeability samples, relative permeability curves as illustrated in Figure 3 can result when the injection pressure of the gas is too low. The behavior is different than the example shown in Figure 2 in that the injected gas does not break through as early and the oil relative permeability curve at low oil saturations can be projected back to 100% relative permeability at 100% oil saturation.

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When data such as shown in Figure 3 are obtained, a common practice is discard enough of the early break-through data to make the data look more reliable. This practice deprives the often needed gas data at low gas saturation.

Figure 4 shows the results for the same sample run at a higher differential pressure. This indicates that the problem with the results in Figure 3 is that the test was run at too low a differential pressure.

Running a Manual Unsteady-State Displacement Relative Permeability Test

The equipment used to manually run an unsteady-state gas-displacing-liquid test includes a sample holder, liquid volume measurement equipment, gas volume measurement equipment, pressure measurement equipment, and a timer.

Performing a gas displacing liquid unsteady-state relative permeability test generally requires two people to run the test and collect the data. One person operates the valves and records the time at incremental liquid volumes while the other person operates the gas burette and records the gas volume (Figure 5). The fastest reliable manual data collection is about 3 seconds per data point. To make the incremental volumes about 0.1-0.2 cc, this means that the differential pressure on a 1 darcy, 2 in. diameter by 3 in. long sample using dodecane will be about 0.5 psi. Using a higher viscosity oil results in higher differential pressures but foaming usually occurs causing oil/gas separation problems and affecting the accuracy of oil volumes being measured.

Experience has shown that the differential pressure for gas displacing oil needs to be above 4 psi. For gas displacing water, the differential pressure needs to be above 6 psi. Operating reliably at these differential pressures with high permeability samples is very difficult.

Automated Unsteady-State Displacement Apparatus

An automated gas-displacing-liquid relative permeameter was designed and built to allow more reliable data to be collected (Figure 6). This design has proven useful in measuring relative permeability on samples ranging from multidarcy to microdarcy. With proper attention to dead space, reliable gas displacing water relative permeability data has been measured on low porosity, low permeability coal.[1]

The design is similar to the manual permeameter except that the liquid volumes are measured by a balance and the gas flow rates are measured by mass flow meters. The data acquisition system was designed to collect data up to 4 times a second. In practice, this data collection rate is too fast. A slower slow rate of about 1 reading per second is used to improve the signal to noise ratio. Higher data acquisition rates produce enough data to eliminate the need to have a regression curve for data interpolation. Generally, a curve is fitted to the data for smoothing and to ease the use of the data in reservoir simulations (Figure 7).

A key feature in the design is the ballast tank installed between the mass flow meters and the back pressure regulator. The mechanical back pressure regulators typically used show hysteresis between the opening and closing pressure. Once open, the regulator does not sharply close, allowing gas to slowly vent and erroneous excessive volumes of gas to be measured. The error caused by the regulator can be reduced to any desired level by scaling the ballast volume to the volume stream of the mass flow controllers. If the ballast volume is 100 times the upstream volume, error caused by the regulator is 1%.

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Before this final design was developed, attempts were made to measure gas volumes by monitoring the produced gas pressure in known volumes as had been used by other laboratories. This, however, proved unreliable because the varying down-stream pressure affected the up-stream differential pressure and flow rate even with a back pressure regulator present. Once mass flow meters with high enough pressure ratings became available, monitoring the produced gas pressure in known volumes was discontinued.

Conditions for Reliable Unsteady-State Relative Permeability Tests

There are several important assumptions in calculating relative permeability from unsteady-state displacement tests. One of the most critical assumptions is that the displacement front has stabilized before the injected phase breaks through the sample. A stabilized displacement front occurs when the saturations that are part of the displacement front move through the core at the same velocities. In an unstable developing displacement front, the saturations at the leading edge of the front have lower velocities than the saturations further back in the front. An unstable developing displacement front will sharpen with continued injection and increasing differential pressure.

Figure 8 illustrates this behavior during a oil displacing water test. The sample is initially at residual water saturation to flowing oil. Brine along with oil is injected into the samples at constant ratio and flow rate. The displacement front is monitored as a function of total liquid injected (brine and oil). The differential pressure is also given in the legend. As the brine/oil is injected, the displacement front becomes sharper from 45 cc injected to 75 cc injected. The differential pressure also increases from 187 psid to 302 psid. At 107 cc injected, the shape of the displacement front is still the same as at 75 cc injected. A stabilized displacement front was developed by the time 75 cc of brine/oil had been injected.

The most common method used to calculate relative permeability from unsteady-state displacement tests is based on the frontal displacement theory, first extended by Welge[2]. and then later by Johnson, Bossler and Naumann (JBN)[3]. Buckley and Leverett developed the frontal displacement theory based on the presence of a stable displacement front[4]. A stable displacement front must be present for the JBN calculation method to apply.

For a stable displacement front to develop prior to breakthrough, the front must be significantly shorter than the length of the sample. Jones-Parra and Calhoun published in 1953[5] an integral equation for determining the length of the stabilized displacement front.(eqn 1) This equation was derived from a fractional flow equation that included capillary pressure effects. The part of the equation that includes the effects of capillary forces is the dP/dS_g term in the integral. The multiplier $kA/q_t\mu_t$ in front of the integral is the inverse of the differential pressure gradient from Darcy's equation.

eqn 1

$$x_t = \frac{kA}{q_t\mu_t}\int_{Sgi}^{S_{gd}}\left[\frac{k_{ro}\dfrac{dP_c}{dS_g}}{1-f_g\left(1+\dfrac{k_{rl}\mu_g}{k_{rg}\mu_l}\right)}\right]dS_g$$

From the Navier-Stokes equation, the differential pressure in a given phase is proportional to the viscous forces during laminar flow when non-viscous forces are absent[6]. Therefore, since the integral term

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represents the capillary force and the multiplier expresses the viscous forces, the length of the stabilized displacement front in the Jones-Parra and Calhoun equation is related ($\approx$) to the ratio of the capillary to viscous forces. This relationship is not rigorous since the relative permeability term (k_{rl}) needed for effective permeability is not in the $kA/q_t\mu_t$ multiplier term but rather is part of the integrand since (k_{ro}) is dependent on the the gas saturation. It should be noted that $\left(1+k_{rl}\mu_g/k_{rg}\mu_l\right)$ is the inverse of the f_g once the displacement front has passed a particular point. During the passage of the front, f_g is less than $\left(1+k_{rl}\mu_g/k_{rg}\mu_l\right)$ because of accumulation of the gas in the pore volume in the displacement front.

eqn (2)

$$X_t \approx \frac{CapillaryForces}{ViscousForces}$$

The most common way of comparing viscous to capillary forces is by using the dimensionless capillary number (N_{cp}) the ratio of viscous to capillary forces.

eqn (3)

$$N_{cp} = \frac{ViscousForces}{CapillaryForces} = \frac{V\mu}{\sigma}$$

The capillary number ratio is the inverse of the ratio given in eqn (2). Therefore, the length of the displacement front is related to the inverse of the capillary number.

eqn (4)

$$X_t \approx \frac{1}{N_{cp}}$$

For gas displacing liquid tests, it is common to use constant differential pressure injection and allow the flow rates to vary. Since the viscous force is proportional ($\propto$) to the differential pressure and the capillary pressure represents the capillary force, the capillary number is proportional to the ratio of differential pressure to capillary pressure.

eqn (5)

$$N_{cp} \propto \frac{\Delta P}{P_c}$$

Combining eqns. (4) and (5) show that the length of the displacement front should be related to the ratio of the capillary pressure to differential pressure.

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eqn (6)

$$X_t \approx \frac{1}{N_{cp}} \propto \frac{P_c}{\Delta P}$$

Figure 8 shows that as the differential pressure increases the length of the displacement front decreases.

For high permeability samples, an experimentalist's question is "What is the minimum differential pressure that should be used for unsteady-state gas displacing oil tests?" Figure 9 shows a displacement front for a differential pressure of 2.4 psi. The length of this displacement front is almost as long as the sample. In Figure 10, the differential pressure has been doubled to 5 psi and the length of the displacement front has decreased to about 1/5 of the length of the sample. Experience has shown that if the differential pressure is above 4 psi, well behaved relative permeability curves are measured. For gas displacing water, the minimum differential pressure is about 6 psi since the gas-water capillary pressure is higher than the gas-oil. The minimum differential pressure is independent of the sample dimensions.

A capillary pressure curve for a high permeability sample is shown in Figure 11. The measurements were done using mercury injection and the pressures have been adjusted for a nitrogen-oil system. Since the maximum gas saturation at the end of a gas-oil test is 40-50%, a convenient capillary pressure to use is 0.4 psi. For most high permeability samples, the minimum differential to capillary pressure ratio needs to be about 10.

Summary and Conclusions

A major problem that high permeability samples present is getting reliable gas displacing oil unsteady-state relative permeability. High permeability samples make it difficult to get the differential pressure high enough to prevent the capillary forces from dominating the flow. An automated permeameter was designed and built to allow higher flow rates than can be reliably recorded manually. The automated permeameter produces reliable data for samples ranging from microdarcy to multidarcy permeability.

Based on relative permeability measurements using different differential pressures, a minimum differential pressure of 10 times the capillary pressure is a reasonable criterion to use for unsteady-state displacement tests. The length of a stabilized displacement front was discussed and shown to depend on the ratio of capillary pressure to differential pressure.

Nomenclature

Symbols

A - cross sectional area of core sample

q - volumetric flow rate

μ - viscosity

μ_g - gas viscosity

μ_l - liquid viscosity

X_t - length of stable displacement front

k - base permeability

k_l - liquid relative permeability

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S_g - gas saturation
S_{gd} - displacement gas saturation
S_{gi} - initial gas saturation
f_g - fraction flow of gas
V - linear velocity of fluid
σ - surface tension
N_{cp} - capillary number
P_c - capillary pressure
ΔP - differential pressure

Relational Operators

$\propto$ - proportional
$\approx$ - related

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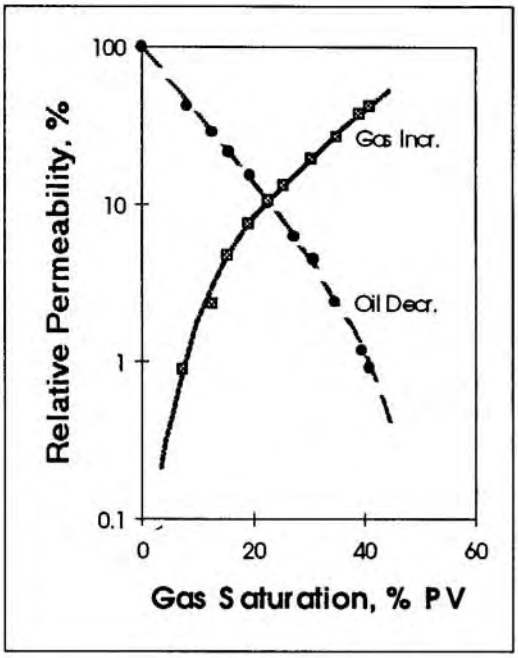

Figure 1
Typical Well Behaved Gas Displacing Oil Relative Permeability

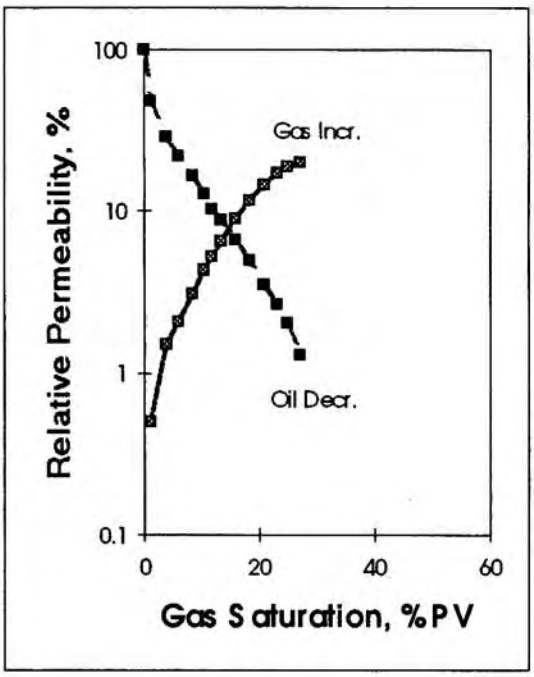

Figure 2
Gas Displacing Oil Relative Permeability with a High Permeability Zone

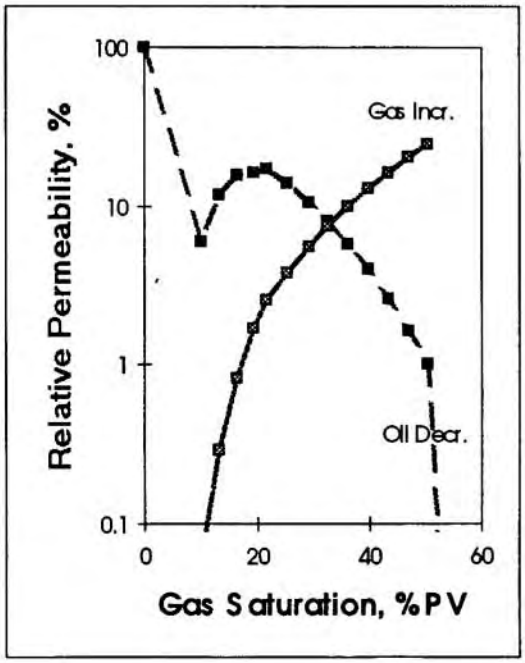

Figure 3
Gas Displacing Oil Relative Permeability for 800 mD Sandstone with 2.5 psi Differential Pressure

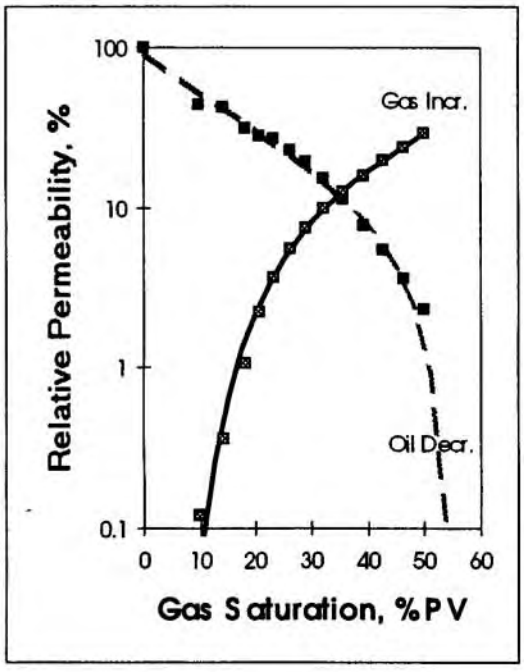

Figure 4
Gas Displacing Oil Realtive Permeability for 800mD Sandstone with 11 psi Differential Pressure

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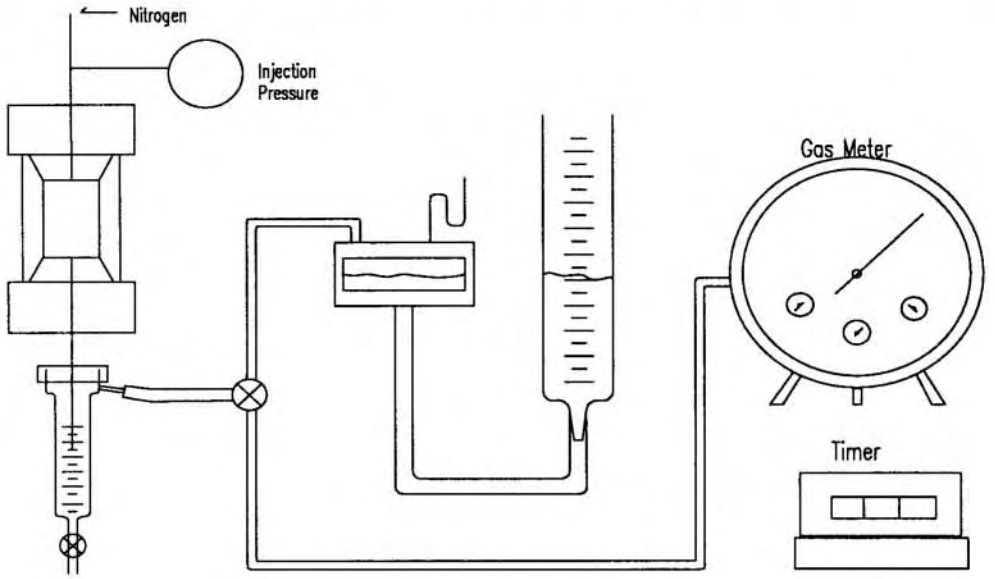

Figure 5
Manual Gas-Liquid Unsteady-State Permeameter

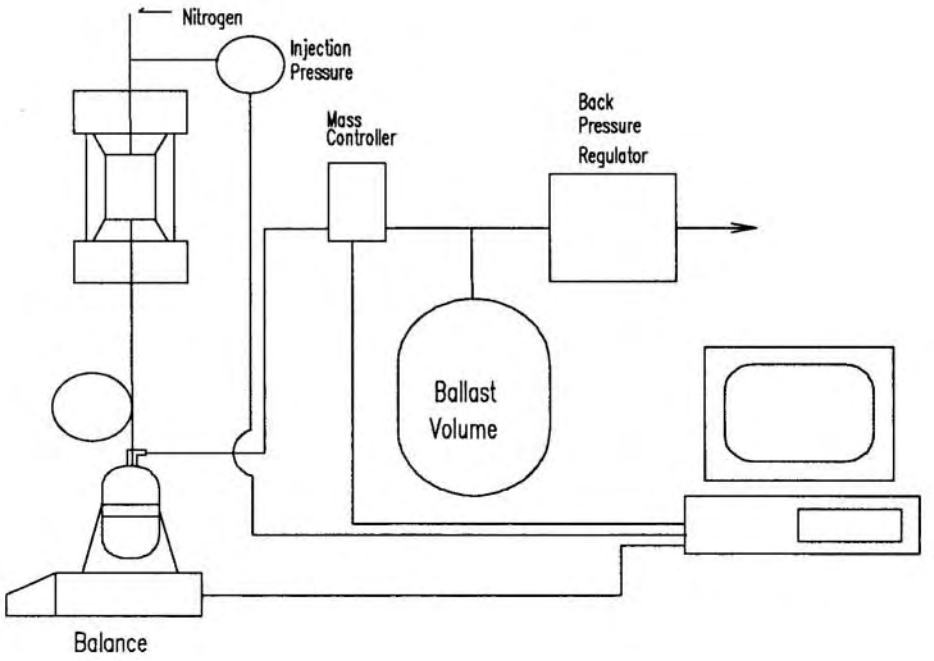

Figure 6
Automated Gas-Liquid Unsteady-state Permeameter

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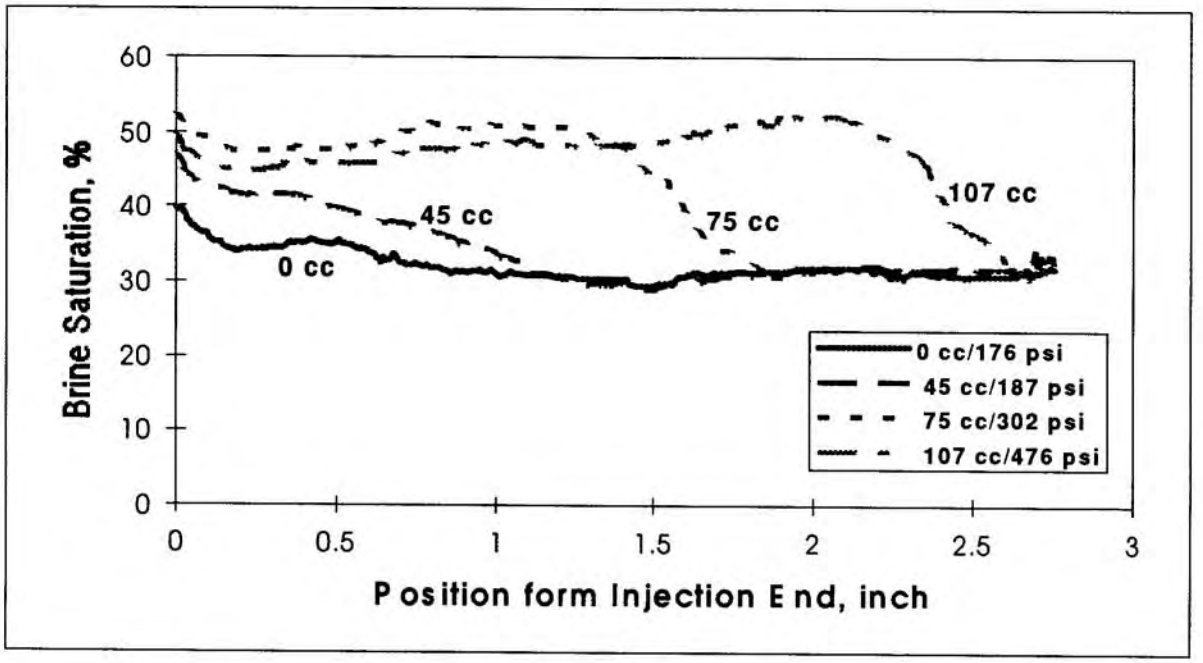

Figure 8
Oil Displacing Brine Test, 0:1 to 1:20 WOR

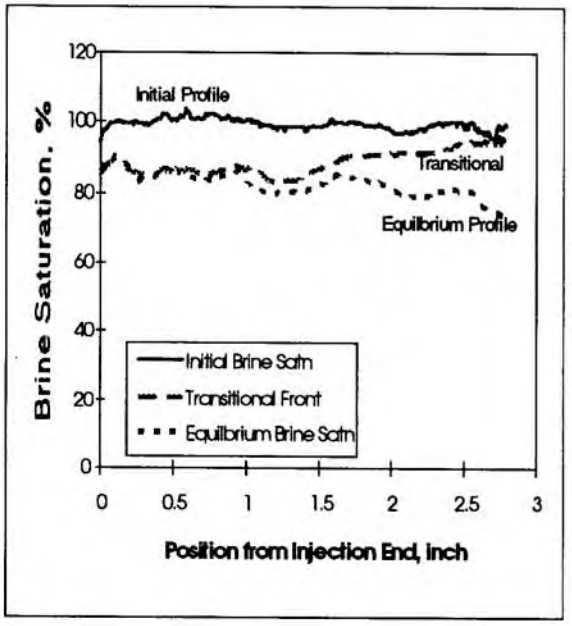

Figure 9
Gas Displacing Water at 2.4 psi Differential

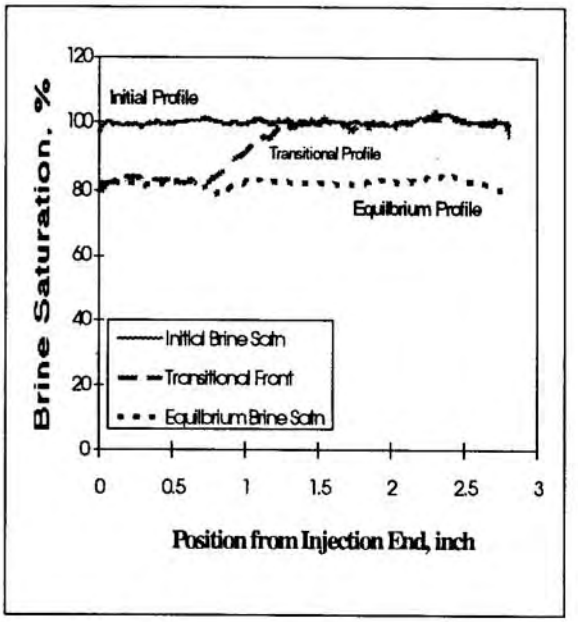

Figure 10
Gas Displacing Water at 5.1 psi Differential

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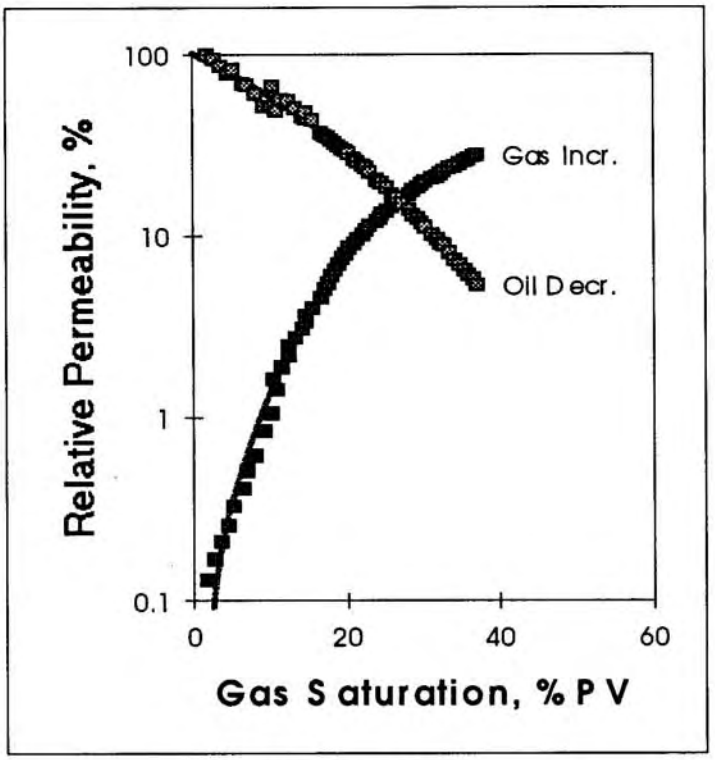

Figure 7
Gas Displacing Oil Relative Permeability for 1200 mD Sample Using Automated Permeameter

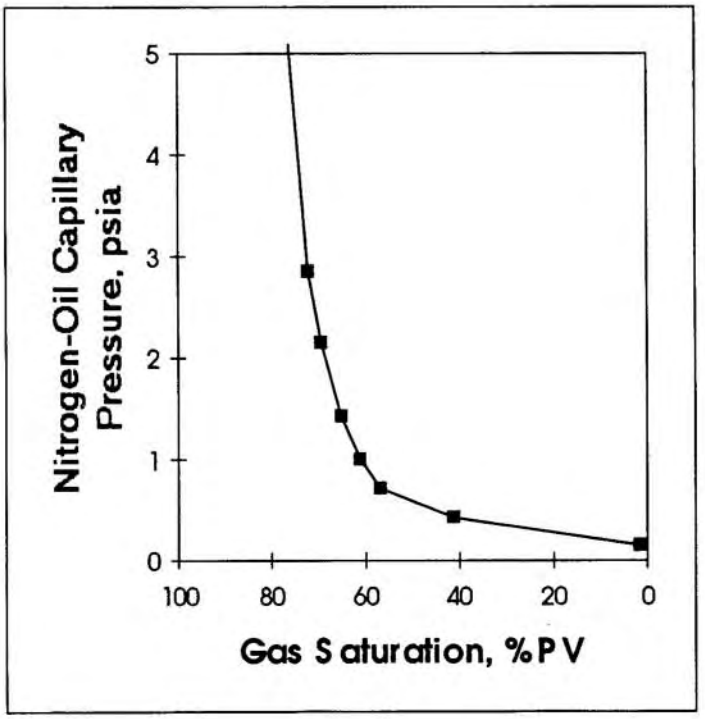

Figure 11
Capillary Pressure Curve for a High Permeability Sample