THE MEASUREMENT OF GAS RELATIVE PERMEABILITY FOR LOW PERMEABILITY CORES USING A PRESSURE TRANSIENT METHOD

SCA Paper 9013

by

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to be presented at the
Fourth Annual SCA Technical Conference
in Dallas, Texas

August 15-16, 1990

INTRODUCTION

Permeability is a measure of the capacity of porous medium to transmit fluids. The permeability of a porous medium is a function of the fluid saturation in the medium. When a porous medium is 100% saturated with a single fluid, the measured permeability to the fluid is the "total" or "absolute" permeability of the medium. When two or three fluids are present, the "effective" permeability to each fluid will be a function of both the volume of the other fluids in the pore space and the saturation history. Relative permeability is defined as the ratio of the effective permeability of a fluid to the absolute permeability of the porous medium.

Generally, there exists three kinds of fluids in petroleum reservoirs, oil, gas, and water. In petroleum engineering, relative permeability of the formation is one of the most important parameters one must use to estimate the fluid flow rates and recoveries of oil and gas from a typical reservoir. However, determining relative permeability accurately, especially for tight formations, has been a challenging problem to petroleum engineers for many years.

Commonly used laboratory methods of measuring relative permeability involve both steady-state and unsteady-state methods. For high permeability cores, a steady-state method can be used to provide reliable results. For low permeability cores, however, steady-state methods are difficult to apply because the measurement of the extremely small flow rate is difficult and time consuming.

The Institute of Gas Technology has developed a steady-state method of measuring permeability of tight sands as a function of water saturation.[1,2] However, due to small flow rates and long equilibration times, it usually takes several weeks to measure and record a typical data set.

Other research laboratories[3] have developed methods of using pressure transient tests across cores to determine the relative permeability to gas. However, the core must be removed from the equipment periodically and weighed to determine the value of water saturation. Removing the core has two disadvantages. First, most low permeability cores are stress sensitive, and as the core is stressed and relaxed in repeated cycles, the measurements of porosity and permeability are difficult to repeat.[4,5] Second, according to Chowdiah,[2] desaturation through evaporation does not yield a true drainage relative permeability curve.

Recently, at Texas A&M University, a method was developed for measuring both the effective gas permeability and gas filled porosity from a single pressure transient test across a core sample.[6] Narahara and Holditch[7] developed the idea that water could be produced out of the core after each test so that a gas relative permeability versus water saturation function could be generated from the core without having to remove the core from the equipment. However, the details of exactly how to run such a test one a routine basis were never developed.

The objective of this research was to improve and perfect the laboratory technique developed at Texas A&M University for measuring gas relative-permeability and water saturation simultaneously in low permeability cores using a pressure transient method.

In this research, the test apparatus has been reconstructed so that water can be produced from the core sample without removing the core from the equipment. Several hundred tests have been conducted to perfect the laboratory technique and investigate the factors affecting the measurements. A complete set of operational procedures has been established for conducting relative permeability measurements and calibrating the system.

The new method has several advantages. First, it is quick when compared with either the steady-state method or with a pressure transient method when the core sample has to be removed from the equipment to measure water saturation. A complete drainage gas relative permeability curve can be obtained in one to five days, depending on the permeability of the core sample. Second, the new method eliminates the problem of stress cycling the core sample during the measurements.

In this paper, the theory of pressure transient testing of core samples is reviewed, the newly constructed pore pressure system is described, the operational procedures for the gas relative permeability measurement are given and the test results on eight Travis Peak cores are presented and discussed.

LITERATURE REVIEW

Conventional Methods of Measuring Relative Permeability

A common method of determining the permeability of a formation is to cut a core sample and conduct measurements with the sample in the laboratory. The conventional means of measuring absolute permeability is to flow a single fluid through the core until steady-state flow is reached. The absolute permeability is calculated using Darcy's law.[8]

To measure relative permeability using steady-state methods, a core sample is mounted in a core holder and two fluids are injected simultaneously at the inlet of the sample. The injection through the core sample continues at a predetermined ratio until the produced ratio is equal to the injected ratio. At this time, the system is considered to be in a steady-state flow condition and the saturation distribution in the core is considered stable. The differential pressure of each phase across the core is measured separately. The saturation of each phase is determined either by means of electric resistivity or by material balance methods. The effective permeability to each phase can be calculated using Darcy's Law and the relative permeabilities are calculated from the values of effective and absolute permeabilities. The injection ratio can then be changed until the system again reaches steady-state. The process is repeated until complete relative permeability curves are obtained.[9]

The steady-state method is most applicable for high permeability cores. For low permeability cores, the steady-state method can be used but is very time consuming. In addition, accurate measurements of the very small flow rates through the core are very difficult. When long testing times are needed for a measurement, the effect of environmental change, such as temperature fluctuation or electromagnetic noise, can introduce error into the raw data measurements. In an effort to solve these laboratory problems, several unsteady-state methods have been developed to provide more practical ways of measuring permeability for low permeability rocks.

Pulse Decay Technique for Determining Absolute Permeabilities

The pulse decay technique was developed in 1968 and has proved to be a fast and effective method for determining the permeability of low permeability cores. Brace *et al.*[10] described a pressure transient method for measuring the permeability of granite to values as low as one nanodarcy (10^{-6} md).

The method of Brace *et al.* has been adopted and discussed by other researchers. A study was performed by Rowe[11] on the application of the Brace method using nitrogen as the pore fluid. He found that the early time portion of the pressure decay was dominated by thermodynamic effects which was caused by gas expansion. The late time response was found to be dominated by boundary effects since the downstream volume was not infinite. He also observed that the "correct" semilog straight line is difficult to determine using data generated in the laboratory.

Yamada and Jones[12] conducted an analytical review of the solution developed by Brace *et al.*[10] and concluded that the upstream volume should be ten times larger than the storage capacity of the core specimen to properly apply the Brace formula.

Several other pulse decay methods have been developed to measure the permeability in low permeability cores. In 1982, Walls *et al.*[3,13] presented a pulse decay method similar to the one described by Brace *et al.*[10] Walls derived an error function solution for the one-dimensional flow equation with a boundary condition of constant upstream pressure. Walls' solution took the fluid compressibility and sample porosity into consideration. Since the solution could not be solved explicitly for permeability, an iterative computer program was used to calculate the value of permeability.

Freeman and Bush[14] developed a pressure transient method that accounted for the nonsteady mass flow through a sample during a downstream pressure buildup test. With their equipment, air was introduced to one end of the core sample. The opposite end of the sample was exposed to a small downstream volume. The pressure buildup data that resulted from the air flowing into the downstream volume were collected and were used to determine the flow rate through the sample. These data could be used to calculate the permeability of the sample. The small downstream volume (3.5 cc) made possible the detection of very small flow rates.

Chen and Stagg[15] presented an alternative solution to the diffusivity equation describing the pressure transient method. The experimental setup used by Chen and Stagg was essentially the same as that used by Walls *et al.*[3] The pressure in the upstream reservoir was kept constant during the test. Chen and Stagg derived a more general analytical solution that could be used to analyze the laboratory data.

Like the method of Brace *et al.*[10], none of the techniques described above could be used to determine both the porosity and the permeability of the sample simultaneously.

In 1972, Odeh and McMillen[16] presented a pulse testing method to determine porosity and permeability simultaneously. Their theory was based on the solution of the diffusivity equation for a core with an infinite length. In their experiment, a constant rate of injection of a known volume of gas was required to generate a pressure pulse across a core sample. The core sample used in their experiment was eight feet in length and two inches in diameter. The pressure transient was observed and recorded as it traveled through the sample. The parameters of interest at the core face were the maximum pulse pressure, pulse duration and the inlet pressure versus time. Two downstream measurements were made: the peak value of the pressure pulse and its arrival time at the downstream volume. These values were used to calculate the porosity and permeability of the sample. Odeh and McMillen reported that the measured values compare very favorably with those determined by conventional methods. However, due to the need of a long sample and the difficulties in generating the constant gas injection rate, the application of their method is limited.

In 1981, P. A. Hsieh *et al.*[17] presented a general analytical solution for the diffusivity equation of the pressure transient test as described by Brace *et al.*[10] The mathematical model described one-dimensional flow of a slightly compressible fluid in a saturated porous medium. The boundary conditions were applicable to any size upstream volume and any size downstream volume. The compressive storage of the core sample was also considered in the derivation. The solution contained, as a limiting case, the solution of Brace *et al.*[10] Hsieh demonstrated that the pressure transient was a function of both the permeability and the porosity of the sample. Neuzil *et al.*[18] showed that, by judiciously adjusting the experimental apparatus, it was possible to obtain data from which both the hydraulic conductivity and the specific storage of the sample could be calculated using the analytical solution.

Relative Permeability Measurements With Low Permeability Cores

Chowdiah[2] performed relative permeability measurements in low permeability cores using a steady-state method. The major problem with his method was the long stabilization time needed for the steady-state measurement. Several days may be needed to obtain a single relative permeability point, while it takes several weeks to obtain a complete relative permeability data set. Therefore, more rapid and practical methods of measuring relative permeability with low permeability cores were needed.

In 1987, G. M. Narahara,[19] at Texas A&M University, presented a method for the simultaneous determination of permeability and porosity in a low permeability core. An analytical solution was derived for the unsteady-state flow of gas through a core plug. A history matching program was developed to calculate the permeability and porosity from pressure transient data measured in the laboratory.

Narahara and Holditch[7] presented a method for measuring relative permeability and water saturation simultaneously in low permeability cores. To do this, a partially water saturated core sample was mounted into the test apparatus and a pressure transient test was run. The effective gas permeability and gas porosity values were determined using the history matching method. Then, the gas relative permeability and water saturation were calculated from the effective permeability and porosity values. Narahara and Holditch developed the idea that water could be produced from the core sample after each test so that a complete set of relative permeability data can be obtained without removing the core from the equipment. However, the details of exactly how to run such a test, on routine basis, were never developed.

The mathematical model and the analytical solutions that have been used in this research were described in Narahara's dissertation.[19]

Effect of Net Stress Cycling on Permeability Measurements

Gobran *et al.*[4] studied the effect of confining stress changes on the absolute permeability of unconsolidated and consolidated cores. They concluded that absolute permeability is a linear function of net confining pressure during the first pressurization. On subsequent stress cycles, however, the relationship was different, but repeatable. Randolph *et al.*[5] also studied the problem of net stress cycling. They gave an example considering a core sample with a permeability of 1.73 μd at a net stress of 1600 psi. On the first application of confining pressure, increasing net stress to 4200 psi reduced permeability to 1.28 μd. Then, lowering net stress to the original 1600 psi resulted in a permeability of 1.58 μd or 91% of the value first measured with this net stress on the core sample. The measurements were then reproducible for additional cycles of net stress between the limits of 1600 and 4200 psi. Randolph *et al.* also found that if the core sample was removed from the core holder and allowed to "relax", the entire history described above was reproducible. They stated that permeability measured during the first cycle of increasing net stress were most likely to be representative of reservoir drawdown.

THEORY OF PRESSURE TRANSIENT TESTING ACROSS CORE PLUGS

Mathematical Model

Fig. 1 is a schematic diagram of the pressure transient test apparatus used in this research. The core sample is loaded into a core holder. A confining pressure is applied to the core sample using confining fluid from outside of the core holder. A pore pressure is applied simultaneously to the upstream volume, the downstream volume and the pore volume of the core sample using nitrogen. The pressures in the three volumes are allowed to reach equilibrium before the test. At the start of the test, the pressure in the upstream volume is rapidly increased by a small amount as compared with the pore pressure. This pressure increase is referred to as the "pressure pulse". As the fluid flows from the upstream volume through the core sample to the downstream volume, the pressure in the upstream volume decreases. The magnitude and time needed for the pressure to decline is affected by both the porosity and the permeability of the core sample.

The diffusivity equation for linear flow of single phase compressible fluid in terms of pseudo pressure and pseudo time is as follows:[19]

$$\frac{\partial^2 p_p}{\partial x^2} - \frac{\mu_p \phi c_{tp}}{k}\frac{\partial p_p}{\partial t_a} = 0, \qquad (1)$$

for $0 < x < L$ and $t_a > 0$,

where: p_p is the pseudo-pressure

$$p_p = 2\int_{p0}^{p} \frac{p}{\mu Z} dp, \tag{2}$$

t_a is adjusted pseudo-time,

$$t_a = \mu_p c_{tp} \int_{t0}^{t} \frac{dt}{\mu c_t}. \tag{3}$$

The boundary conditions are as follows:

$$p_p(x,0) = 0, \qquad 0 < x < L, \tag{4}$$

$$p_p(0,t_a) = p_{pd}(t_a), \qquad t_a \geq 0, \tag{5}$$

$$p_p(L,t_a) = p_{pu}(t_a), \qquad t_a \geq 0, \tag{6}$$

$$\frac{\mu_p c_{gp} V_d}{kA}\frac{\partial p_{pd}}{\partial t_a} - \left(\frac{\partial p_p}{\partial x}\right)_{x=0} = 0, \qquad t_a > 0, \tag{7}$$

$$p_{pd}(0) = 0, \tag{8}$$

$$\frac{\mu_p c_{gp} V_u}{kA}\frac{\partial p_{pu}}{\partial t_a} - \left(\frac{\partial p_p}{\partial x}\right)_{x=L} = 0, \qquad t_a > 0. \tag{9}$$

The analytical solution of these equations is as follows:

$$\frac{p_{pu}}{p_{pp}} = \frac{1}{1+\beta+\gamma} + 2\sum_{n=1}^{\infty} \frac{e^{-\alpha\theta_n^2}(\beta + \gamma^2\theta_n^2/\beta)}{\gamma^2\theta_n^4/\beta^2 + (\gamma^2\beta + \gamma^2 + \gamma + \beta)\theta_n^2/\beta + \beta^2 + \gamma\beta + \beta}, \tag{10}$$

where:

$$tan\theta = \frac{(1+\gamma)\theta}{\gamma\theta^2/\beta - \beta}, \tag{11}$$

$$\alpha = \frac{kt_a}{94812L^2\mu_p\phi c_{tp}}, \tag{12}$$

$$\beta = \frac{16.387AL\phi c_{tp}}{V_u c_{gp}}, \tag{13}$$

$$\gamma = \frac{V_d}{V_u}, \tag{14}$$

Determination of Absolute Porosity and Permeability

Narahara[19] proved that a unique porosity and permeability can be determined simultaneously from a single pressure transient test across the core plug using the above solution. To investigate the uniqueness, he performed a sensitivity analysis with a mathematical simulator for different values of permeability and pore volume. The data used in the simulator are presented in Table 1. The pressure transient curves for four porosity values (5, 10, 15, and 20 percent) at a constant permeability of 0.01 md are shown in Fig. 2. The pressure transient curves for four permeability values (0.1, 0.01, 0.001 and 0.0001 md) at a constant porosity of 10% are shown in Fig. 3. As can be seen in Figs. 2 and 3, the final pressure of the system is a function of the pore volume of the core and the size of the initial pressure pulse, but is independent of permeability. The pore volume can be calculated from the final pressure using Boyle's Law. The time required for the pressure pulse to propagate through the core is a function of permeability. Since permeability and porosity affect different portions of the curve, each can be determined uniquely using a history matching method.

Determination of Relative Permeability and Water Saturation

To measure the relative permeability of a core, the core is first saturated with water and is then mounted into the core holder. Once mounted in the test apparatus, a small volume of water is produced from the core sample to create a gas saturation of about 30%. A pulse of gas is then transmitted across the core and the pressure decay in the upstream volume is measured and recorded.

Assuming the water phase in the core sample does not move during the pressure transient test, both the gas porosity and gas permeability of the core can be determined using the analytical history matching method. After each measurement, additional water is produced out of the core sample to reduce the water saturation in the core. A complete set of apparent gas porosity and gas permeability values are determined by repeating the pulse test and analyzing the laboratory data using the analytical solution.

The water saturation in the core sample for each test can be calculated using the absolute porosity and the apparent porosity obtained from the analysis of the pressure decay as follows:

$$S_w = \frac{\phi_{ab} - \phi_{ap}}{\phi_{ab}}, \tag{15}$$

The gas relative permeability value can be calculated using the apparent gas permeability and the absolute permeability values as follows:

$$k_r = \frac{k_{ap}}{k_{ab}}, \tag{16}$$

Since the saturation of wetting phase (water) is reduced in the core sample successively, the gas relative permeability curve obtained this way is along the water phase drainage path.

The assumption that the water phase is immobile is acceptable only when the water saturation is relatively low and the pressure pulse is relatively small. Our experiments show that for a core with a porosity of around 10% and a permeability of less than one millidarcy, the measured results are valid when water saturation is less than 70%. When water saturation is larger than 70%, it is difficult to keep the water immobile during the test. For high values of S_w, the raw data of the pressure transient test are still valid, but a two-phase flow mathematical model is needed to interpret the laboratory data.

The values of porosity and permeability of a core are functions of the net confining pressure applied to the core during the test. Fig. 4 is a curve of porosity versus net confining pressure for the Ashland S.F.O.T. No. 1 core at 9754.5 ft. Fig. 5 is a graph of absolute permeability versus net confining pressure for the same core sample. As can be seen in Figs. 4 and 5, as the net confining pressure increases, both the porosity and the permeability of the core sample decrease. Therefore, the values of apparent porosity (ϕ_{ap}) and the absolute porosity (ϕ_{ab}) used in Eq. 15 must be measured at the same net confining pressure so that the difference between ϕ_{ap} and ϕ_{ab} depends solely on water saturation. Similarly, the values of the apparent permeability and absolute permeability used in Eq. 16 should also be measured at the same net confining pressure.

DESCRIPTION AND OPERATION OF TEST APPARATUS

Apparatus Description

The main portion of the laboratory equipment used in this research was the Conductivity, Porosity, Damage (CPD) cart originally constructed by Terra Tek. It was described by Rowe in his M.S. thesis.[11] The CPD cart is composed of a confining pressure system, a pore pressure system and a data acquisition system. The confining pressure system is capable of applying a triaxial confining pressure of up to 20,000 psi and temperature of up to 300°F to the core sample.

Significant modifications to the CPD cart have been made to accomplish the goals of this research project. The pore pressure system was rebuilt to accomplish the following goals:

1. Uniformly apply a pore pressure of about 1000 psi to the core sample and, after the system is balanced, generate a pressure pulse of about 50 psi to conduct the pressure transient test;

2. Reduce the water saturation in the core sample after each test by producing a small amount of water out of the sample without removing the core from the equipment;

3. Apply pore pressure from both ends of the core sample to prevent water from leaving the core when pressure is being applied to the core; and

4. Minimize the downstream volume so that the time needed for a test is short and, therefore, the effect of room temperature variation can be minimized.

Fig. 6 is a schematic diagram of the pore pressure system used in this research. The core sample is loaded into the core holder and the core holder is placed into the confining pressure vessel.

The volume in the pipeline isolated by valves H, L and E and the volume associated with the differential pressure transducer constitute upstream volume 1 (V_{up1}). The volume from valve E to the upper end of the core is upstream volume 2 (V_{up2}). The volume from the lower end of the core to valve F is the downstream volume (V_{down}).

The hand pump illustrated in Fig. 6 is used to generate a pressure pulse for the pressure transient test. The nitrogen source is connected to a large cylinder (reference volume 1) to keep the pore pressure stable before the test and to provide a stable reference pressure to the measurement of pressure decline during the test.

The pressure signals from the system pressure transducer, the differential pressure transducer, the confining pressure transducer and the bath temperature thermal couples are measured and sent to a signal conditioner. The data are then transmitted to an HP9836 computer for recording and processing. Software has been written to collect and record the data from the pressure transient test. The data can be processed to determine the values of gas porosity and gas permeability.

Significant thought and effort were applied to the design and construction of the downstream volume in the pore pressure system. The original form of the downstream volume left by Narahara[19] was called the "dead-end assembly" because the core holder was essentially blanked off on the downstream end. This configuration would not work for "flow-through" gas relative permeability measurement.

To solve the problem with the dead-end assembly, several months of engineering were applied and hundreds of trial runs were made to test out different downstream configurations. The early versions tried to use check valves. However, the system that finally proved successful is very simple and is illustrated in Fig. 7. Additional details can be found in the thesis by Ning.[20]

The current laboratory system is composed of the bottom end plug, the control valve F, and the downstream tubing. The bottom plug of the core holder is connected to valve F by a very thin tubing (1/16"). The volume of the connection between the end plug of the core holder and the tubing was minimized by setting a small piece of tubing in it and filling the annular space with epoxy. The control valve F is mounted on the top of the confining pressure vessel for easier and more reliable operation.

With this flow-through system, water can be produced from the core sample by applying a pressure at the upstream end of the sample, and leaving valve F open to the atmosphere. The water produced from the core sample is first stored in the downstream volume and is then blown out from the downstream volume by opening and closing valve F repeatedly after the gas breakthrough. Pore pressure can be applied from both ends of the sample by connecting valve F to the pore pressure system, closing valve G and opening valves F, G and K. Valve F is closed during test. This system has the advantages of easy operation, reliability and minimization of the downstream volume.

The value of the downstream volume is critical in the accuracy of the measurements. If the downstream volume is much larger than the pore volume of the sample, the pressure transient data will be dominated by the downstream volume and will be insensitive to the pore volume of the core sample. As a result, the calculated porosity from the pressure transient data will not be very accurate. Also, when the downstream volume is large, a long time is needed to conduct a test and, consequently, any changes in room temperature can cause large fluctuations in the raw data. If the downstream volume is small (approximately equal to the pore volume), the time needed for a test will be short and the measurements of porosity and permeability will be more accurate. Therefore, using a small downstream volume greatly improves the accuracy of the transient test.

Determination of Upstream and Downstream Volumes

After each revision of the system, the upstream and downstream volumes have to be determined to calibrate the apparatus. Three sets of measurements are required to calculate the three unknown volumes, upstream volume 1, upstream volume 2, and the downstream volume. The first step is to load a solid steel plug into the core holder and run several pressure transient tests. The operational procedure for running these tests is essentially the same as that applied when a core sample is in the apparatus. The initial pressure pulse size and the final value of the pressure pulse are recorded for each run. Second, a solid steel plug and a hollow steel plug with a known pore volume are loaded in to the core holder with the solid plug at the bottom to seal off the downstream volume. Pressure pulse tests are run and the pulse pressure and final pressure are recorded. Using the data obtained from these two sets of runs, the upstream volume 1 and upstream volume 2 can be computed as follows:

$$V_{up1} = \frac{V_{por}}{a_1 - a_2}, \tag{17}$$

$$V_{up2} = a_1 V_{up1}, \tag{18}$$

where:

$$a_1 = \frac{p_{p1} - p_{f1}}{p_{f1}}, \tag{19}$$

$$a_2 = \frac{p_{p2} - p_{f2}}{p_{f2}}, \tag{20}$$

The third step is to load a hollow steel plug with a known pore volume into the core holder without the solid plug so that gas can flow through the steel plug to the downstream volume during the tests. The downstream volume is calculated using the known values of the two upstream volumes and the data from the last group of tests:

$$V_{down} = a_3 V_{up1} - V_{up2} - V_{pore}, \tag{21}$$

where:

$$a_3 = \frac{p_{p3} - p_{f3}}{p_{f3}}, \tag{22}$$

The valves of the upstream and downstream volumes for the final version of the flow-through system were determined to be

$$V_{up1} = 10.1238 cm^3,$$

$$V_{up2} = 3.2650 cm^3,$$

and

$$V_{down} = 1.3017 cm^3.$$

Operation of the Test Apparatus

The following briefly describes the operation of the test apparatus. Details concerning the operation are included in the thesis by Ning.[20]

- Core is cut into cylinders 1 inch long and 1 inch in diameter.

- The core is loaded into the CPD cart.

- Confining pressure and pore pressure are established.

- The entire system is checked for leaks.

- Water is produced from the core by applying a pressure differential across the core using nitrogen. The volume of water produced can be controlled by adjusting the pressure differential across the core. Data from a gas-water capillary pressure curve can be used to choose the appropriate level of differential pressure.

- After the water has been produced, the sample is allowed to reach saturation and pressure equilibrium. Normally, several hours will be required.

- A test can then be run by applying a 50-100 psi pulse in the upstream volume. The test is started by opening Valve E in Fig. 6. The pressure decay in the upstream volume is then measured and recorded as a function of time. The time needed for a pressure transient test varies from a few seconds to a few hours, depending on the permeability of the sample. Table 2 presents the approximate times needed to run tests with cores of different permeabilities.

- After a test, additional water is produced out of the core, and another test can be run to obtain another point on the relative permeability curve.

- The pulse test data are then analyzed to compute gas porosity, gas permeability, water saturation, and gas relative permeability.

RESULTS OF MEASUREMENT AND DISCUSSION

After the final reconstruction of the apparatus, eight Travis Peak cores were used to test our equipment. The description of the cores are presented in Table 3.

A series of core analysis measurements should be associated with the relative permeability tests to obtain complete information about the properties of a core sample. The following measurements are considered necessary:

1. Absolute porosity versus net confining pressure;

2. Absolute permeability versus net confining pressure;

3. Capillary pressure versus water saturation; and

4. Relative gas permeability versus water saturation.

In this research, the following processes were conducted with the core samples:

1. The cores were cut into cylinders of one inch long and one inch in diameter.

2. The dimensions of the cylinders were recorded.

3. The cores were then put into the humidity oven with a constant temperature of 60°C and a humidity of 45% until the weights of the cores had stabilized.

4. The absolute porosity of the cores were measured using the helium porosimeter at a net confining pressure of 2000 psi.

5. The absolute porosity and absolute permeability of the cores were measured using CPD cart at a net confining pressure of 2000 psi.

6. The cores were saturated with fresh water and the capillary pressure was measured using the ultra centrifuge. Because some original salt was in the new cores, the salinity of the water coming out from the cores during the centrifuge run was measured to be 30,000 PPM.

7. The cores were resaturated to 100% water saturation.

8. The relative permeabilities of the samples were measured using the CPD cart at a net confining pressure of 2000 psi.

9. Finally, the cores were dried in the humidity oven again and were measured for absolute porosity and permeability as functions of net confining pressure using the CPD cart.

Measurement of Absolute Porosity and Permeability

After the core samples were dried in the humidity oven, they are measured for absolute porosity values using the helium porosimeter. The measured results are listed in Table 4. The net confining pressure used in these measurements was around 2,000 psi and the pore pressure in the core was around 100 psi.

The cores were then measured for the values of absolute porosity and absolute permeability using the CPD cart with a net confining pressure of about 2,000 psi and a pore pressure of about 1,000 psi. The results are also listed in Table 4.

In addition, the absolute porosity values later determined by the dry weight and the saturated weight are also listed in Table 4 for comparison. As can be seen, the porosity values determined from different methods are consistent for most of the cases. The biggest difference happened on the Ashland S.F.O.T. No. 1 core at 9754.5 ft. The difference was probably caused by the low permeability of the core (4.09 microdarcy). It is suspected that the time allowed for the pressure to equilibrate during the measurement using the helium porosimeter was insufficient. The porosity value measured using the CPD cart for the core S.F.O.T. No. 1 9754.5 ft is very close to that obtained using the weight method. For the other cores, the differences among the absolute porosity values measured using different methods are within 5%. The consistency indicates that our pressure transient method is accurate.

<u>Measurement of Absolute Permeability Versus Net Confining Pressure</u>

The measured permeability of a core sample is a function of the net confining pressure applied to the core sample during the measurement. As the net confining pressure increases, the size of the pore throats in the core sample will be reduced and, hence, the permeability will also be reduced. This effect is more significant in low permeability cores because the pore throats in low permeability cores are smaller to begin with. Therefore, a permeability versus net confining pressure curve is necessary for us to understand and compare the properties of a core.

The relationship between the absolute permeability versus net confining pressure was measured for the six Travis Peak cores. Table 5 and Fig. 8 present the measured results. The net confining pressure was increased from about 500 psi to about 3000 psi for the two cores from

Holditch Howell No. 5 well and to about 4000 psi for the remaining cores, with an increment of about 500 psi for all cores. As can be seen in Fig. 8, as the net confining pressure increases, the absolute permeabilities of the core samples decrease. The curves for the two cores from Holditch Howell No. 5 fluctuate because both of the two cores were left in the equipment for extended time periods and the room temperature fluctuated during the measurements. For the remaining four cores, the room temperature did not change as much and better results were obtained. Hence, the room temperature should be kept as stable as possible during these experiments.

The permeability values were not corrected for gas slippage. According to the investigation conducted by Narahara,[19] the slope of the Klinkenberg plots were essentially zero which meant that gas slippage correction was very little (if any) under our experiment conditions. In addition, since the pore pressure used in our experiments was high (1000 psi), the measured permeability values should be very close to the Klinkenberg permeability (k_∞).

Measurement of Capillary Pressure Versus Water Saturation

Capillary pressure data are often needed in reservoir engineering calculations. Capillary pressure curves are also needed to direct our laboratory procedures for measuring relative permeability. The differential pressure needed to reduce water saturation to a desired value during relative permeability measurement is directly related to the capillary pressure at the particular water saturation. Therefore, a curve of capillary pressure versus water saturation must be obtained after the absolute porosity and permeability measurements and before the relative permeability measurements.

The Beckman Ultra Centrifuge was used to conduct the capillary pressure measurements. The samples were saturated with water before being loaded into the core buckets of the centrifuge. The rotary speed of the rotor was set to 1,000, 2,000, 3,000, 4,000, 5,000, 6,000, 8,000, 10,000, 12,000, 15,000, and 20,000 RPM consecutively with a time duration of more than two hours for each speed. The maximum speed of the centrifuge is 20,000 RPM which corresponds to a capillary pressure of about 1,220 psi. The expelled water volume can be read while the centrifuge is in operation. The results from the capillary pressure measurements are illustrated in Figs. 9 and 10.

Measurement of Relative Permeability Versus Water Saturation

After measuring capillary pressure, the cores were saturated again with water and the relative permeability measurements were conducted using the CPD cart. The results of the relative permeability measurements are presented in Table 6.

The net confining pressure used for the relative permeability measurements was around 2,000 psi. The pore pressure for these tests was about 1,000 psi, while the pressure pulse was approximately 50 psi. The differential pressure used to produce water out of the core was set initially at 100 psi, then the pressure was increased to 1,000 psi, using 100 psi increments. At least three relative permeability measurements were conducted at each value of water saturation. The apparent gas porosity and gas permeability values were obtained by eliminating the abnormal measurements and averaging the normal measurements. The time needed to measure the relative permeability curve for a typical core sample was from three to seven days depending on the permeability of the sample.

Fig. 11 contains the relative permeability curve for Sam Hughes No. 1 core at 7098.95 ft. The data for this core appear to be normal. The curve is fairly smooth although the points are a little scattered. The absolute permeability of the core is 0.0563 md.

Fig. 11 also contains the relative permeability curve for Sam Hughes No. 1 core at 7099.4 ft. For the data points where the water saturation was larger than 70%, the measurements were difficult to interpret and the analytical solution did not match the data very well. For the third data point, the water production process was not controlled well and a large reduction of water saturation occurred.

Fig. 12 contains the relative permeability curves for the cores from Holditch Howell No. 5. The data from core sample HH5 5961.5 ft appear to be reasonable and provide a smooth curve. The absolute permeability of this sample was 0.626 md. The gas porosity determined by weight method after the relative permeability measurement was 5.43% while the gas permeability measured using the CPD cart was 5.24%. The difference was less than 4%.

A second measurement was conducted with this sample to check the repeatability of the measurements. The data are also illustrated in Fig. 12 and indicate acceptable repeatability. This can also be seen in the data from core sample Holditch Howell No. 5 6037.0 ft.

As can be seen in Fig. 12, there is a large decrease in the value of water saturation, from 78.9% to 29.4% in the first measurement with core HH5 6037.0 ft. The capillary pressure of this core is very high which made controlling the water production from the core sample difficult. A second measurement was conducted with this sample to obtain better data in the high water saturation range.

Fig. 13 presents the relative permeability curves for Ashland S.F.O.T. No. 1 cores. Two measurements were made with the S.F.O.T. No. 1 core at 9754 ft which had an absolute permeability of 4.09 microdarcies. Because the room temperature in the laboratory fluctuated during the measurements and because the time period for a pressure transient test was long (10 to 30 minutes), the results were affected and, consequently, the data were scattered.

The relative permeability curve for Ashland S.F.O.T. No. 1 core at 10,112.2 ft is also included in Fig. 13. The absolute permeability of this core sample was 0.0179 md. The time needed for the experiment was four days. The experiment could have been accomplished in two days, if necessary.

Fig. 14 presents the relative permeability curves for the two Prairie Mast No. 1 cores. The data for core PM 9181 ft are a little scattered. The main reason was that the room temperature fluctuated greatly during the seven day experiment. The results could have been improved by keeping a more constant room temperature and shortening the experiment time. The absolute permeability of the core sample was 8.54 microdarcies.

The relative permeability curve for core Prairie Mast No. 1 9952.5 ft are smooth even though there was a large decrease in water saturation from 66.1% to 41.0% at one point in the experiment. The absolute permeability of the core sample was 0.0317 millidarcies.

From the above results we have concluded that our pressure transient method is capable of measuring the gas relative permeability and water saturation simultaneously without having to remove the core sample from the equipment. The proper absolute permeability range for our test apparatus is from 0.1 microdarcy to 1.0 millidarcy. Accordingly, the apparatus is capable of measuring gas relative permeabilities for cores with absolute permeability ranging from one microdarcy to one millidarcy. The test apparatus has now been moved into a much better laboratory and recent measurements have yielded less scattered results.

CONCLUSIONS

Based on the research work of this project, the following conclusions can be drawn:

1. The modified test apparatus satisfies the requirements for measuring the gas relative permeability with low permeability cores using a pressure transient method.

2. The new flow-through system of the test apparatus can produce water from the sample as desired so that a complete gas relative permeability curve can be obtained without removing the core from the equipment.

3. The new flow-through system can apply pore pressure from both ends of the core sample, which prevents the water in the sample from moving during the pressure-up procedure which also allows the system to reach pressure equilibrium more quickly.

4. For most of the low permeability cores, when water saturation in the core sample is lower than 50%, the data interpretation with one phase flow model is accurate. When water saturation is between 50% and 70%, the interpretation is acceptable.

5. The proper absolute permeability range of core samples is from one microdarcy to one millidarcy for our current test apparatus and data interpretation technique to provide reliable relative permeability data.

6. Further research effort is needed to investigate the effect of water distribution in the sample on relative permeability measurement. A two phase flow mathematical model counting for capillary end effects is needed to interpret the pressure transient data more accurately for gas relative permeability measurement.

NOMENCLATURE

A	cross sectional area of the sample, in^2
c_{gp}	gas compressibility at initial pore pressure, psi^{-1}
c_{tp}	total compressibility at initial pore pressure, psi^{-1}
k	permeability of the sample, md
k_{ap}	apparent gas permeability of the core, md
k_{ab}	absolute permeability of the core, md
k_r	relative gas permeability of the core, fraction
p	pressure in the sample, psia
p_{f1}	final pressure for the first run, psi
p_{f2}	final pressure for the second run, psi
p_{f3}	final pressure for the third run, psi
p_{pd}	pseudo-pressure at the downstream volume, $psia^2/cp$
p_{pp}	pseudo-pressure evaluated at maximum (pulse) pressure, $psia^2/cp$
p_{pu}	pseudo-pressure at the upstream volume, $psia^2/cp$
p_{p1}	pulse pressure for the first run, psi
p_{p2}	pulse pressure for the second run, psi
p_{p3}	pulse pressure for the third run, psi
S_w	average water saturation in the core, fraction
t	time from the start of test, sec
V_d	downstream volume, cm^3
V_{down}	downstream volume, cm^3
V_{por}	pore volume of the steel plug, cm^3
V_u	upstream volume, cm^3
V_{up1}	upstream volume 1, cm^3
V_{up2}	upstream volume 2, cm^3

x	the distance along the sample, in., $x = 0$ at the downstream face, $x = L$ at the upstream face
Z	gas deviation factor
ϕ	porosity of the sample, fraction
ϕ_{ab}	absolute porosity of the core, fraction
ϕ_{ap}	apparent gas porosity of the core, fraction
μ	viscosity of gas, cp
μ_p	gas viscosity at initial pore pressure, cp

REFERENCES

1. Chowdiah, P.: "Effects of Pore Water Distribution and Stress on the Laboratory Measurement of Tight Sandstone Properties," paper SPE 15210 presented at the Unconventional Gas Technology Symposium of the Society of Petroleum Engineers held in Louisville, KY, May 18-21, 1986.

2. Chowdiah, P.: "Laboratory Measurements Relavent to Two-Phase Flow in a Tight Gas Sand Matrix," paper SPE 16845 presented at the 62nd Annual Technical Conference and Exhibition of SPE held in Dallas, TX, September 27-30, 1987.

3. Wall, J. D., Nur, A. M., and Bourbie, T.: "Effects of Pressure and Partial Water Saturation on Gas Permeability in Tight Sands: Experimental Results," *JPT* (April 1982) 930-36.

4. Gobran, B. D., Brigham, W. E., and Ramey, H. J.: "Absolute Permeability as a Function of Confining Pressure, Pore Pressure and Temperature," paper SPE 10156 presented at the 56th Annual Fall Technical Conference and Exhibition of the SPE of AIME held in San Antonio, TX, October 5-7, 1981.

5. Randolph, P., Soeder, D. J., and Chowdiah, P.: "Effects of Water and Stress Upon Permeability to Gas of Paludal and Coastal Sands," IGT project 61071 topical report for the period December 1983 through July 1984, Institute of Gas Technology, Chicago, IL (April 1985) 13.

6. Narahara, G. M. and Holditch, S. A.: "Improved Rock Property Measurement Using Core from the Travis Peak Formation," paper SPE 17730 presented at the SPE Gas Technology Symposium held in Dallas, TX, June 13-15, 1988.

7. Narahara, G. M., Holditch, S. A., and More, K. R.: "A New Method for the Measurement of Gas Relative Permeability and Water Saturation Simultaneously in Low Permeability Cores," paper SPE 18318 presented at the 63rd Annual Technical Conference and Exhibition of SPE held in Houston, TX, Octobe 2-5, 1988.

8. Bradley, H. B.: *Petroleum Engineering Handbook*, Society of Petroleum Engineers, Richardson, TX (1987) 26-11.

9. Amyx, J. W., Bass, D. M., and Whiting, R. L.: *Petroleum Reservoir Engineering*, McGraw-Hill Book Company, New York, NY (1960) 184-202.

10. Brace, W. F., Walsh, J. B., and Frangos, W. T.: "Permeability of Granite Under High Pressure," *J. Geophysical Research* (1968) 73, No. 6, 2225-236.

11. Rowe, W. D.: "The Determination of Permeability Using a Pulse Decay Technique," M.S. Thesis, Texas A&M University, College Sstation, TX (1985).

12. Yamada, S. E. and Jones, A. H.: "A Review of a Pulse Technique for Permeability Measurements," *SPEJ* (Oct. 1980) 357-58.

13. Bourbie, T. and Walls, J. D.: "Pulse Decay Permeability: Analytical Solution and Experimental Test," *SPEJ* (Oct. 1982) 719-21.

14. Freeman, D. L. and Bush, D. C.: "Low Permeability Laboratory Measurements by Nonsteady State and Conventional Methods," *SPEJ* (Dec. 1983) 928-36.

15. Chen, T. and Stagg, P. W.: "Semilog Analysis of the Pulse-Decay Technique of Permeability Measurement," *SPEJ* (Dec. 1984) 639-42.

16. Odeah, A. S. and McMillen, J. M.: "Pulse Testing: Mathematical Analysis and Experimental Verification," *SPEJ* (Oct. 1972) 403-09.

17. Hsieh, P. A., Tracy, J. V., Neuzil, C. E., Bredehhoeft, J. E., and Silliman, S. E.: "A Transient Laboratory Method for Determining the Hydraulic Properties of 'Tight Rocks' - I. Theory," *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* (1981) 18, 245-52.

18. Neuzil, C. E., Silliman, S. E., Bredehhoeft, J. E., and Hsieh, P. A.: "A Transient Laboratory Method for Determining the Hydraulic Properties of 'Tight' Rocks - II. Application," *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* (1981) 18, 253-58.

19. Narahara, G. M.: "Rock Property Measurements and Measurement Techniques for Low Permeability Cores," Ph.D. Dissertation, Texas A&M University, College Station, TX (1987).

20. Ning, Xiuxu: "The Measurement of Gas Relative Permeability for Low Permeability Cores Using a Pressure Transient Method," M.S. Thesis, Texas A&M University, College Station, TX (1989).

Table 1

Simulated Parameters Used in Examples

Upstream Volume	12.36 cm^3
Downstream Volume	0.65 cm^3
Core Length	2.54 cm
Core Diameter	2.54 cm
Temperature	80°F
Pore Pressure	1500 psia
Pulse Pressure	38 psia
Pore Fluid	Nitrogen

Table 2

Approximate Time Needed For a Pressure Transient Test

Apparent Gas Permeability (md)	Time Needed for a Test (seconds)
0.001	600-700
0.01	50-60
0.1	10-20

Table 3

Description of the Travis Peak Cores Used in Expeirments

Core Name	Description	Absolute Porosity (%)	Absolute Permeability (md)
Sam Hughes No. 1			
7,098.95 ft		8.71	0.0563
7,099.4 ft		7.89	0.210
Holditch Howell No. 5			
5.961.5 ft	Clean, rippled sandstone	7.95	0.626
6,037.0 ft	Rippled sandstone	9.02	0.128
Ashland S.F.O.T. No. 1			
9,754.5 ft	Planar laminations, carbinate cement	6.12	0.00409
1,0112.2 ft	Crossbedded, abundant secondary porosity	7.59	0.0179
Prairie Mast No. 1-A			
9,181.0 ft	Crossbedded, abundant quartz cement	4.54	0.00854
9,952.5 ft	Crossbedded, abundant quartz cement	5.22	0.0317

Table 4

Results of Absolute Porosity And Permeability Measurements

	Absolute Porosity (%)			
Core Name	Helium* Porosimeter	CPD* Cart	Weight** Method	Absolute Permeability (md)*
Sam Hughes No. 1 7,098.95 ft 7,099.4 ft	 8.25 7.58	 8.71 7.89	 8.40 7.97	 0.0563 0.210
Holditch Howell No. 5 5,961.5 ft 6,037.0 ft	 7.91 8.76	 7.95 9.02	 7.75 9.09	 0.626 0.128
Ashland S.F.O.T. No. 1 9,754.5 ft 1,0112.2 ft	 5.65 7.45	 6.12 7.59	 5.88 7.47	 0.00409 0.0179
Prairie Mast No. 1-A 9,181.0 ft 9,952.5 ft	 4.56 5.29	 4.54 5.22	 4.44 5.06	 0.00854 0.0317

*At net confining pressure of 2000 psi
**At atmospheric pressure

Table 5

Results of Absolute Permeability Versus Net Confining Pressure Measurements

Confining Pressure (psi)	Absolute Permeability (md)	Confining Pressure (psi)	Absolute Permeability (md)
Holditch Howell No. 5 - 5,961.5 ft		Holditch Howell No. 5 - 6,037 ft	
452	0.933	406	0.115
887	0.913	989	0.085
1,437	0.826	1,486	0.081
1,965	0.820	1,984	0.078
2,449	0.837	2,464	0.077
2,947	0.814	2,997	0.071
Ashland S.F.O.T. No. 1 - 9,754.5 ft		Ashland S.F.O.T. No. 1 - 10,112.2 ft	
1,000	7.60E-3	959	2.46E-2
1,528	5.77E-3	1,554	2.12E-2
1,980	4.58E-3	2,022	1.90E-2
2,948	2.82E-3	3,012	1.88E-2
3,492	2.66E-3	3,557	1.75E-2
3,956	2.13E-3	4,029	1.56E-2
4,494	2.03E-3	4,483	1.52E-2
Prairie Mast No. 1-A - 9,181.1 ft		Prairie Mast No. 1-A - 9,952.5 ft	
956	9.82E-3	1,018	4.70E-2
1,526	7.28E-3	1,500	4.44E-2
2,001	6.42E-3	2,013	3.86E-2
2,508	5.33E-3	2,525	3.60E-2
3,001	4.55E-3	2,991	3.32E-2
3,457	4.05E-3	3,587	3.13E-2
3,995	3.47E-3	4,017	3.02E-2

Table 6

Results of Relative Permeability Measurements

Core Name	Apparent Gas Porosity (%)	Apparent Gas Permeability (md)	Water Saturation (%)	Gas Relative Permeability (fraction)
Sam Hughes No. 1 7,098.95 ft	3.30	2.03D-3	62.4	0.036
	4.15	4.95E-3	52.7	0.088
	4.53	4.03E-3	48.4	0.072
	4.54	4.92E-3	48.3	0.087
	5.20	6.39E-3	40.8	0.113
	5.37	9.68E-3	38.8	0.172
	6.10	1.57E-2	30.5	0.279
	6.31	1.60E-2	28.1	0.284
	7.27	2.00E-2	17.2	0.355
	8.71	5.63E-2	0.00	1.000
Sam Hughes No. 1 7,099.4 ft	1.66	2.49E-3	79.0	0.012
	1.78	3.11E-3	77.4	0.015
	4.56	1.71E-2	42.2	0.08
	4.61	6.43E-2	41.6	0.31
	4.64	7.25E-2	39.9	0.35
	5.06	8.02E-2	34.8	0.38
	5.28	9.62E-2	33.0	0.46
	7.89	0.21	0.00	1.00
Holditch Howell No. 5 5,961.5 ft	2.34	4.77E-3	70.6	0.00762
	3.07	2.33E-2	61.4	0.0372
	3.62	6.86E-2	53.2	0.110
	4.36	0.261	45.2	0.417
	4.55	0.334	42.8	0.535
	5.00	0.400	37.1	0.639
	5.04	0.429	36.6	0.685
	5.24	0.426	34.1	0.681
	7.95	0.626	0.00	1.00
Holditch Howell No. 5 6,037.0 ft	1.90	1.77E-3	78.9	0.0138
	6.37	5.72E-2	29.4	0.447
	7.30	6.20E-2	19.1	0.484
	7.90	6.38E-2	12.4	0.498
	8.04	6.81E-2	10.9	0.532
	9.02	0.128	0.00	1.00
Ashland S.F.O.T. No. 1 9,754.5 ft	3.16	2.69E-4	48.4	0.0658
	4.03	3.03E-4	34.2	0.0741
	4.42	1.34E-3	27.8	0.328
	6.12	4.09E-3	0.00	1.00

Table 6
(Continued)

Core Name	Apparent Gas Porosity (%)	Apparent Gas Permeability (md)	Water Saturation (%)	Gas Relative Permeability (fraction)
Ashland S.F.O.T. No. 1 10,112.2 ft	4.33 4.94 5.35 5.69 5.96 6.56 6.85 7.14 7.31 7.59	1.93E-3 3.08E-3 3.76E-3 5.55E-3 6.08E-3 7.86E-3 8.86E-3 1.10E-2 1.19E-2 1.79E-2	43.0 34.9 29.5 24.0 21.5 13.6 13.3 5.93 3.69 0.00	0.107 0.172 0.210 0.31 0.340 0.439 0.495 0.615 0.665 1.00
Prairie Mast No. 1-A 9,181.0 ft	1.89 2.59 3.50 3.90 4.02 4.23 4.54	3.99E-4 7.17E-4 1.07E-3 1.86E-3 3.91E-3 6.30E-3 8.54E-3	58.4 43.0 22.9 14.1 11.5 6.83 0.00	0.0467 0.0840 0.125 0.218 0.458 0.738 1.00
Prairie Mast No. 1-A 9,952.5 ft	1.77 3.08 3.22 3.83 4.26 4.67 5.22	4.92E-4 4.36E-3 5.01E-3 6.40E-3 9.73E-3 1.90E-2 3.17E-2	66.1 41.0 38.3 26.6 18.4 10.5 0.00	0.0155 0.138 0.158 0.202 0.307 0.599 1.00
Holdith Howell No. 5 5961.5 ft Second Measurement	2.28 3.83 3.04 4.18 4.65 4.80 5.29 7.95	4.78E-3 1.22E-2 1.07E-2 0.120 0.152 0.376 0.489 0.626	71.3 51.9 62.0 47.4 41.4 39.7 33.4 0.00	0.0076 0.0248 0.0171 0.120 0.243 0.602 0.782 1.000

Table 6
(Continued)

Core Name	Apparent Gas Porosity (%)	Apparent Gas Permeability (md)	Water Saturation (%)	Gas Relative Permeability (fraction)
Holditch Howell No. 5 6037 ft Second Measurement	3.73	4.94E-3	58.7	0.0386
	3.90	5.03E-3	56.8	0.0393
	4.49	1.07E-2	50.6	0.131
	5.67	3.24E-2	37.1	0.253
	5.12	2.98E-2	43.2	0.233
	5.28	3.09E-2	41.5	0.241
	5.84	3.66E-2	35.3	0.286
	5.81	3.69E-2	35.6	0.288
	6.24	4.34E-2	30.8	0.339
	6.65	4.54E-2	26.3	0.355
	9.02	0.128	0.00	1.000
Ashland S.F.O.T. No. 1 9754.5 ft Second Measurement	2.49	3.53E-4	59.3	0.0863
	3.78	5.48E-4	38.3	0.134
	3.94	8.32E-4	35.6	0.203
	3.85	1.88E-3	37.0	0.460
	3.73	1.90E-3	39.1	0.466
	5.38	2.23E-3	12.1	0.562
	6.12	4.09E-3	0.00	1.000

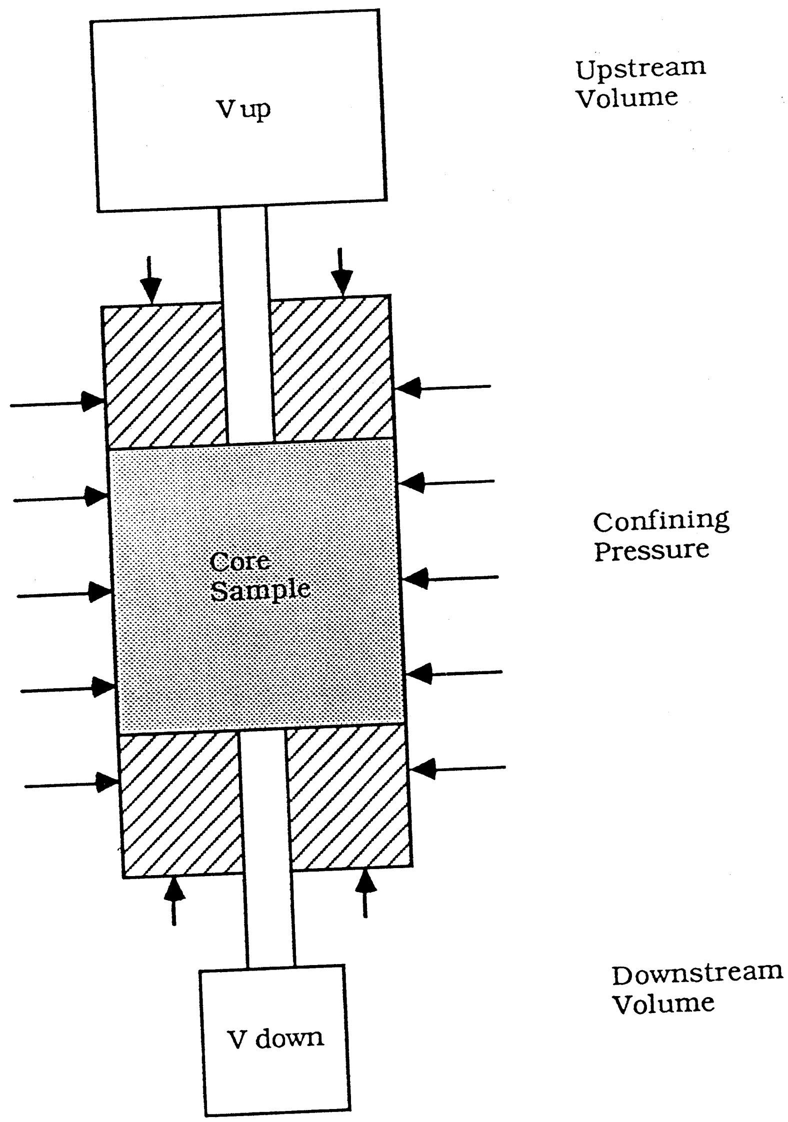

Fig. 1 A Schematic Diagram of Pressure Transient Test

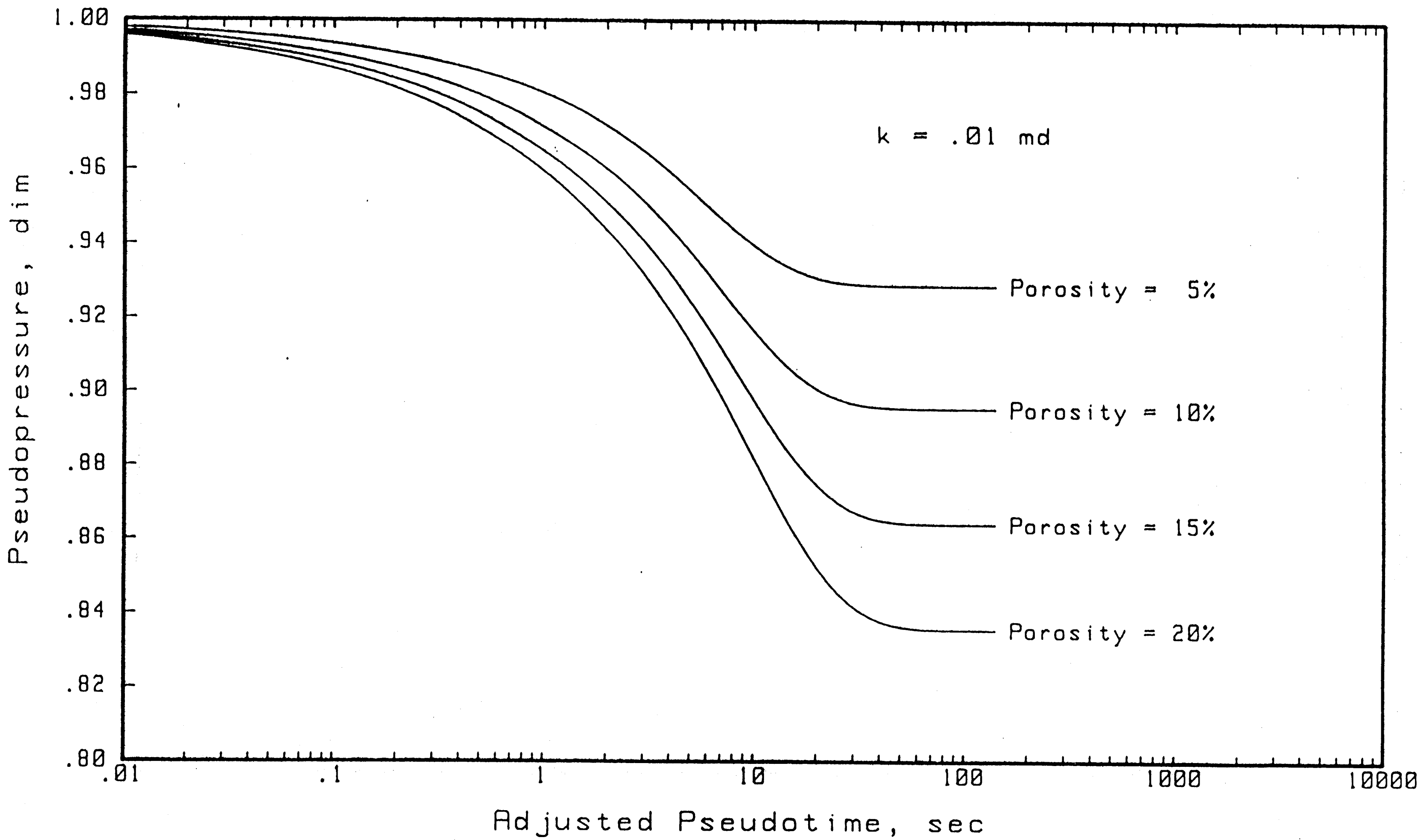

Fig. 2. Pressure Transients for Various Porosities at a Constant Permeability

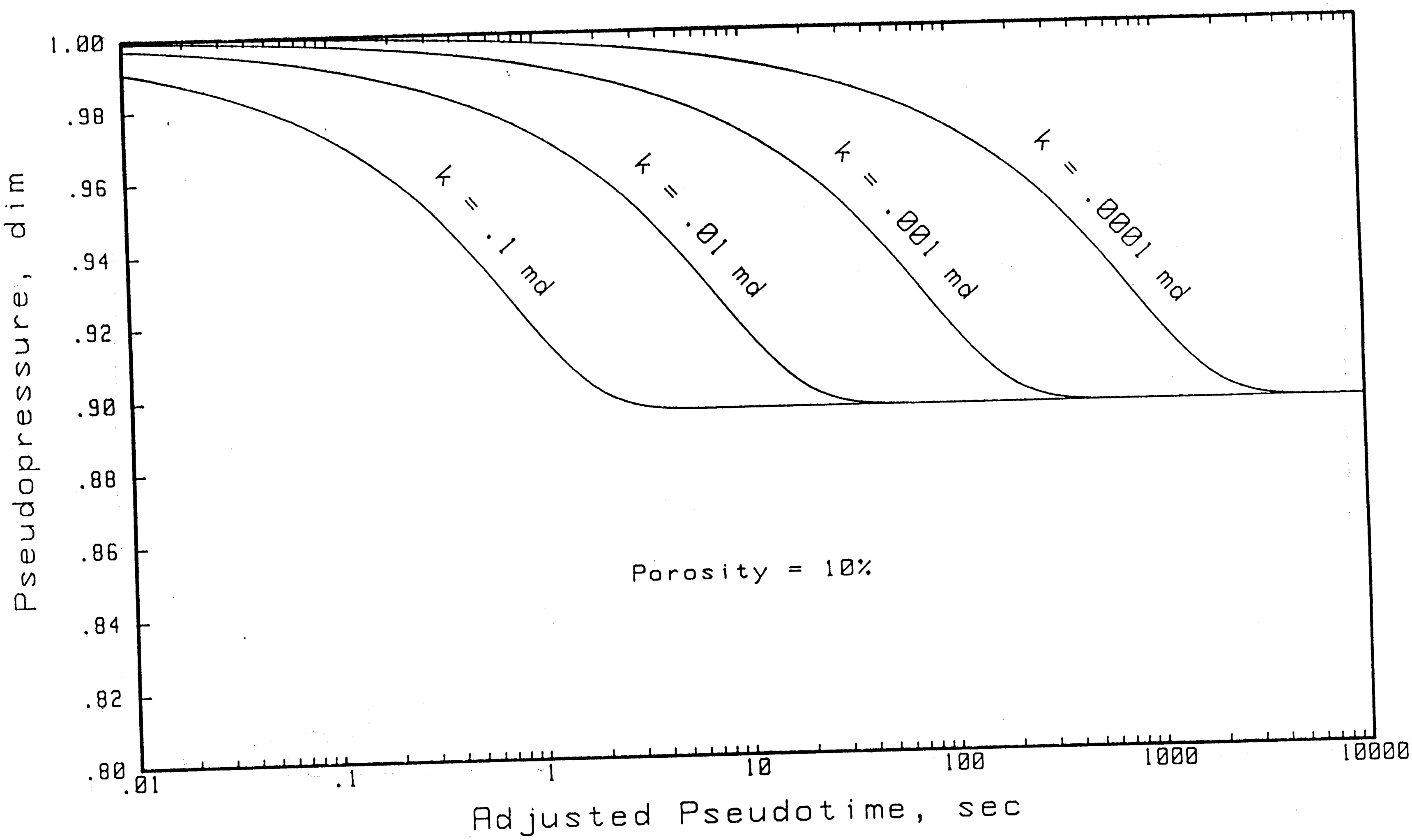

Fig. 3 Pressure Transients for Various Permeabilities at a Constant Porosity

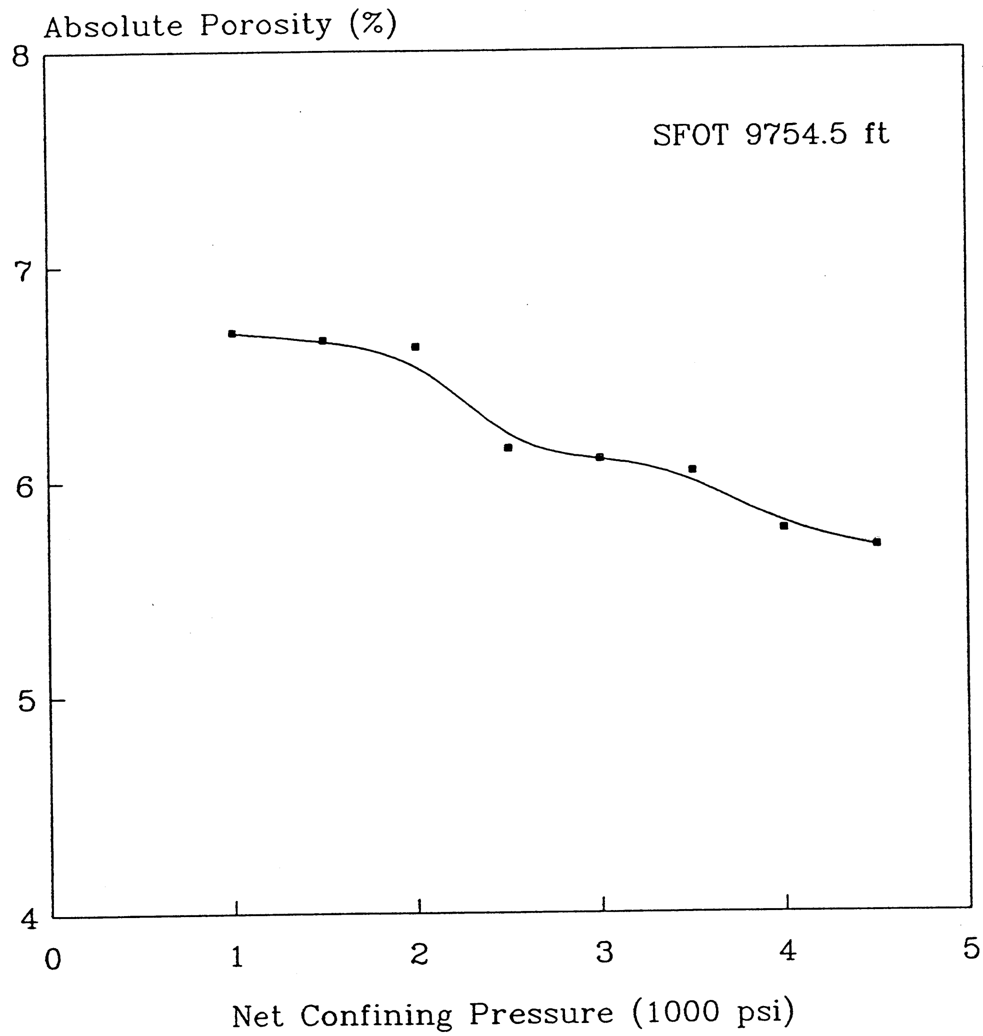

Fig. 4. Absolute Porosity Versus Net Confining Pressure Curve for Core Ashland S.F.O.T. No. 1 9754.5 ft

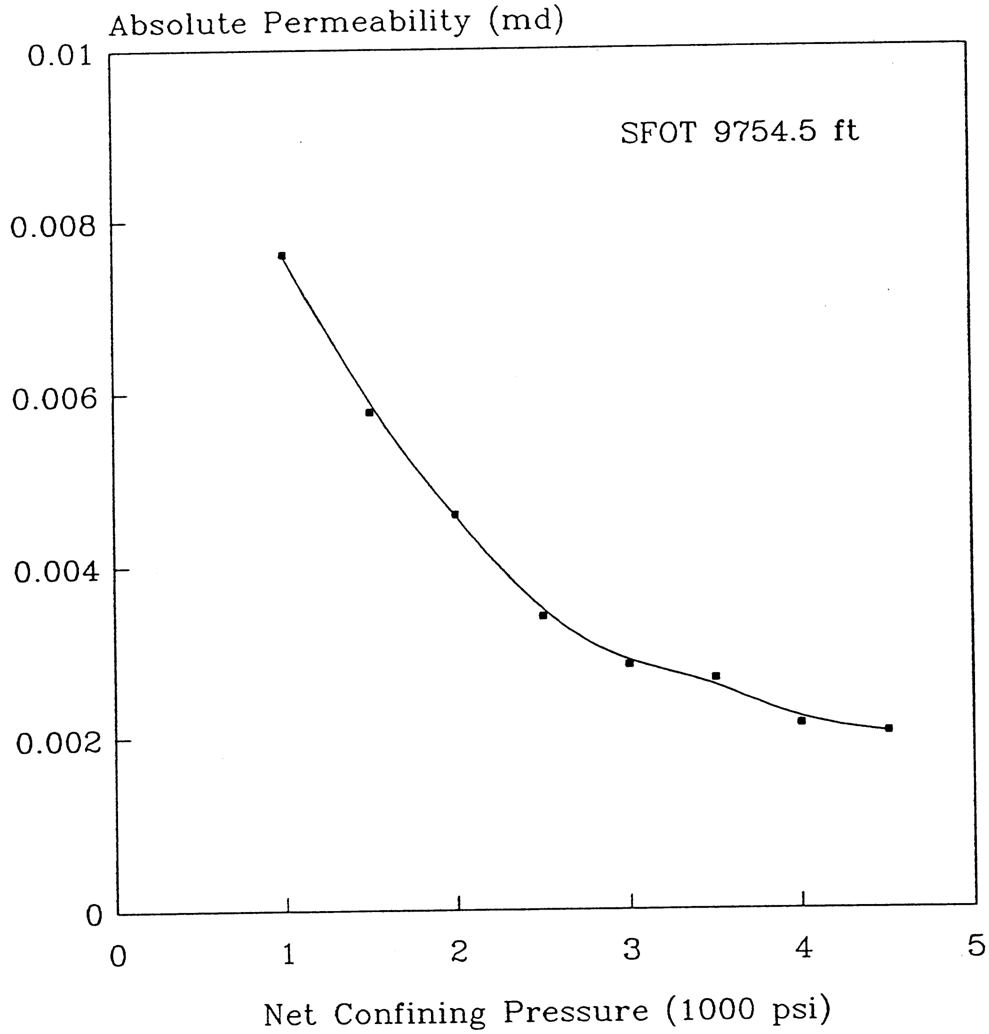

Fig. 5 Absolute Permeability Versus Net Confining Pressure Curve for Core Ashland S.F.O.T. No. 1 9754.5 ft

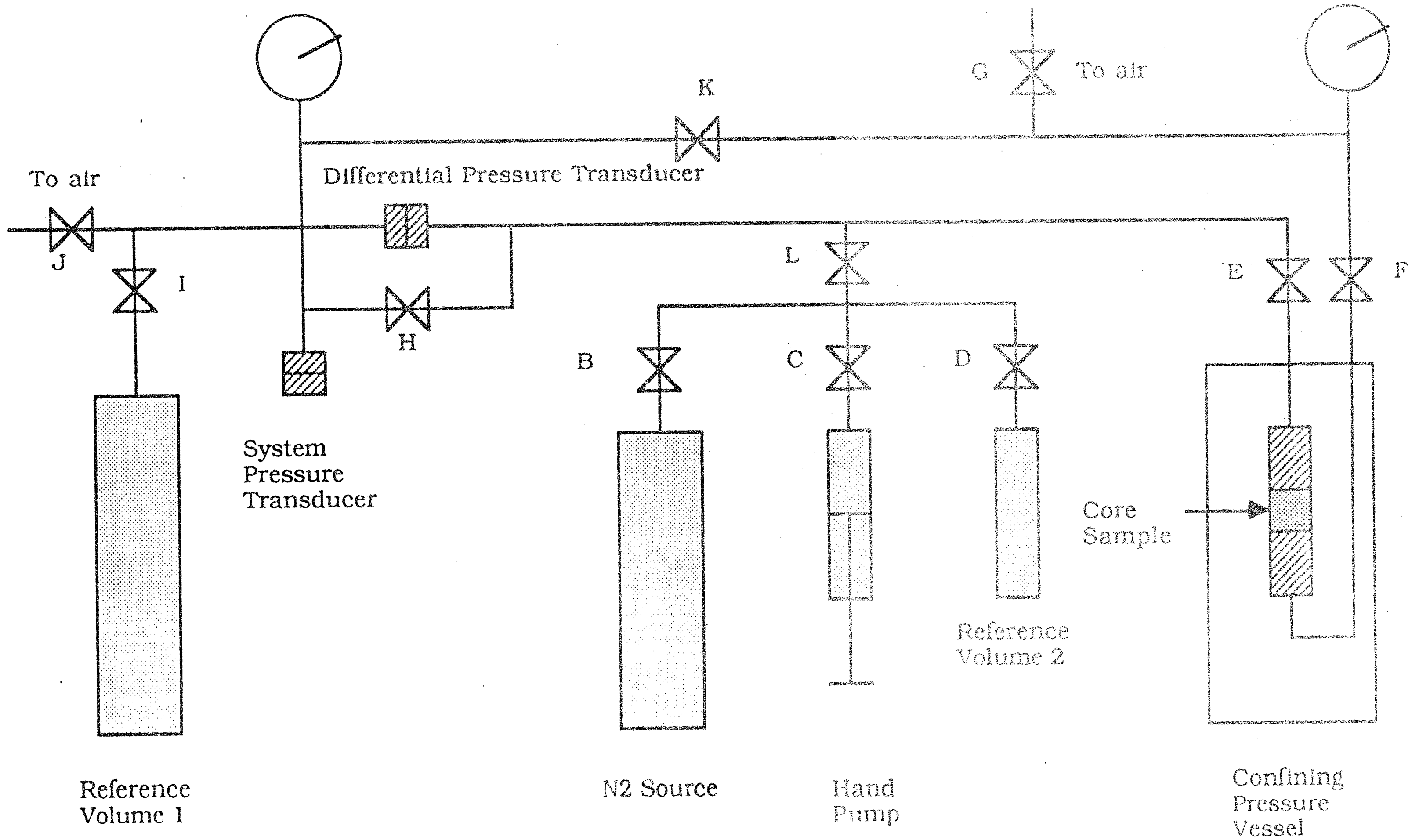

Fig. 6 Schematic Diagram of the Pore Pressure System

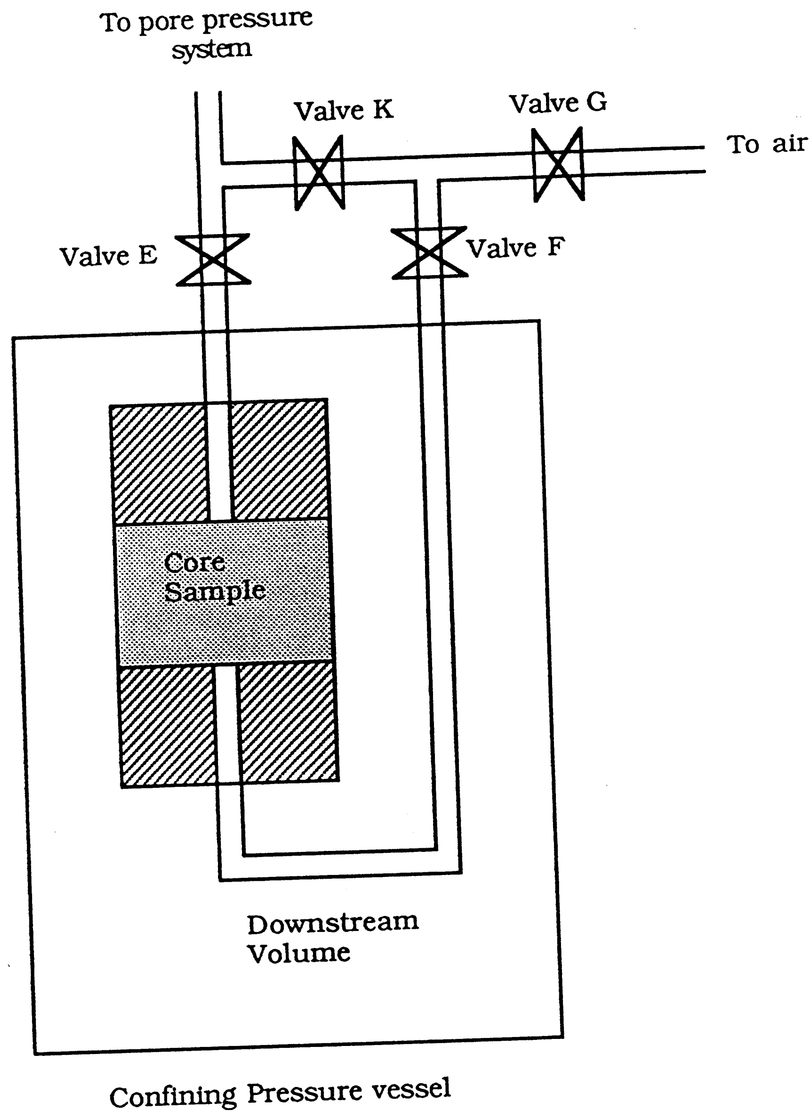

Fig. 7 Schematic of the Current Flow-Through System

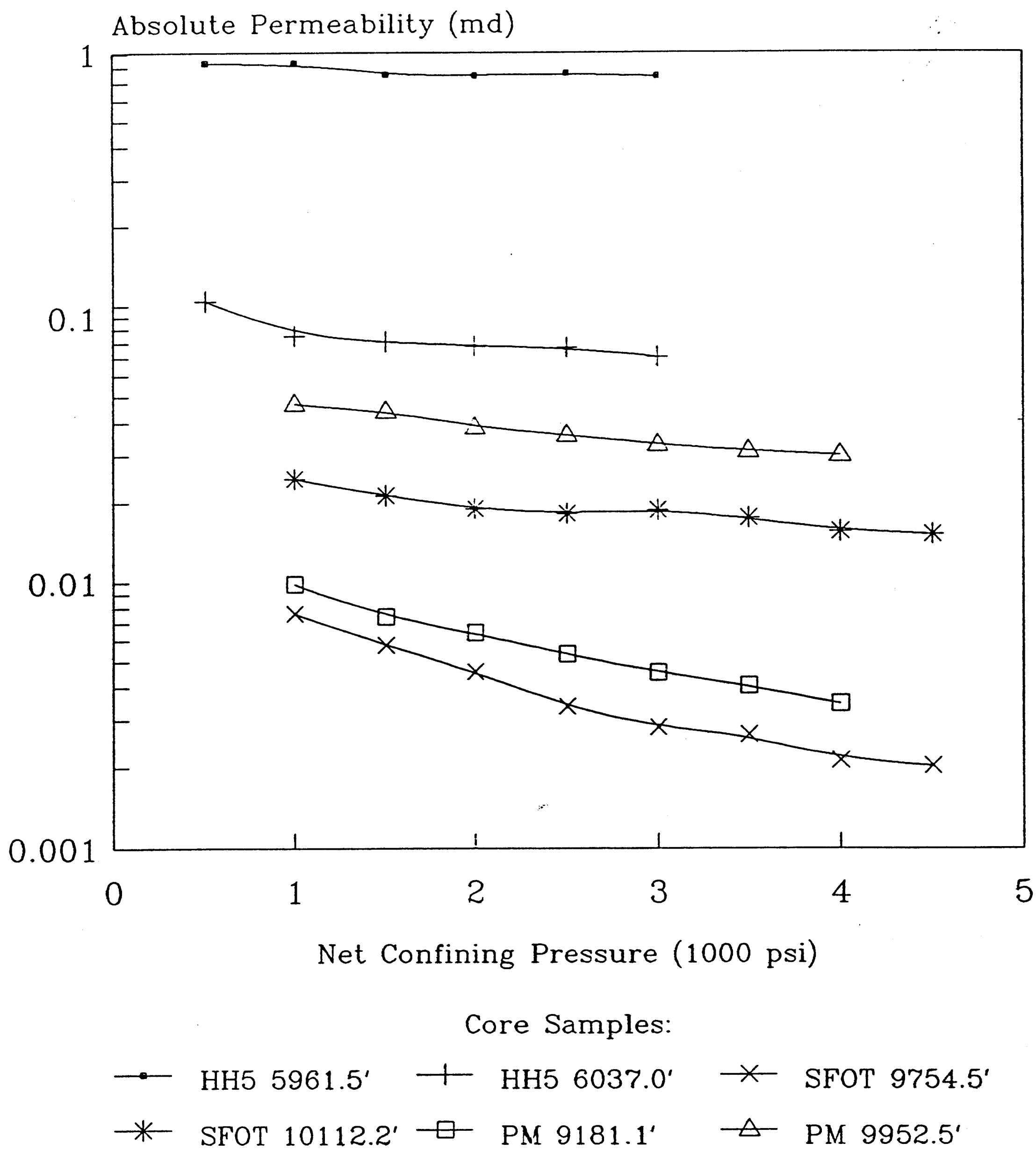

Fig. 8 Absolute Permeability Versus Net Confining Pressure for Travis Peak Cores

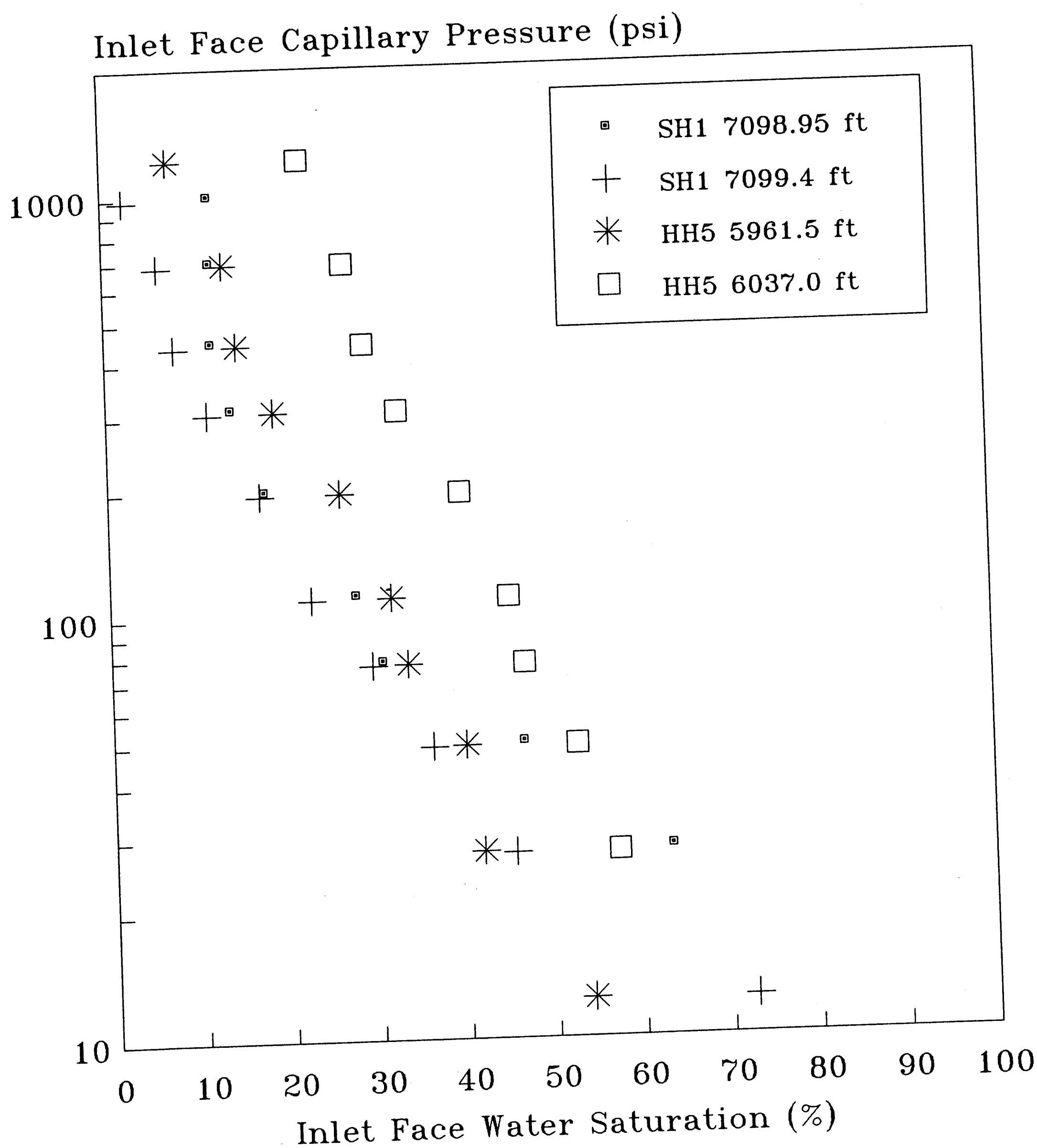

Fig. 9 Capillary Pressure Curves for Sam Hughes and Holditch Howell Cores

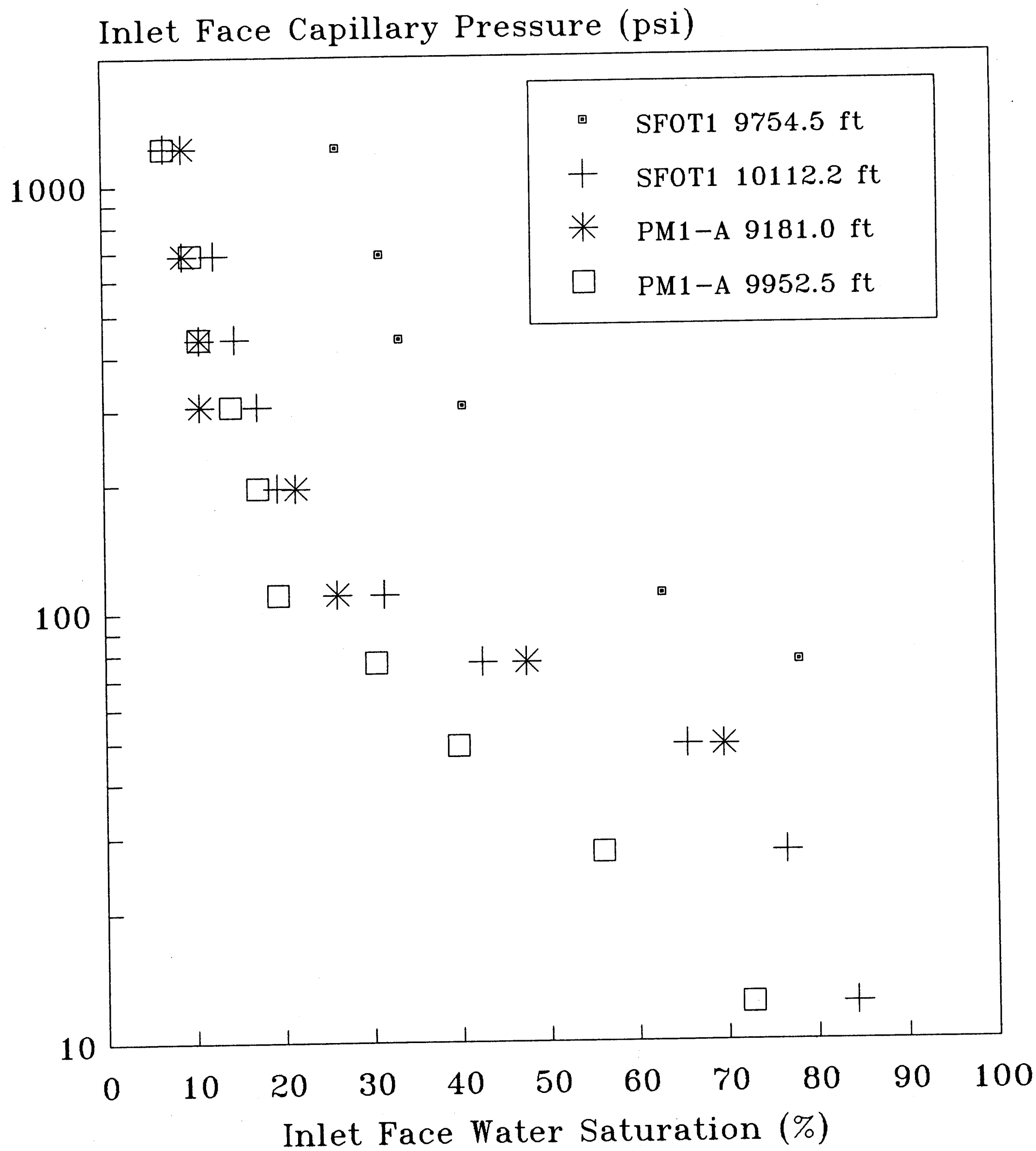

Fig. 10 Capillary Pressure Curves for Ashland S.F.O.T. and Prairie Mast Cores

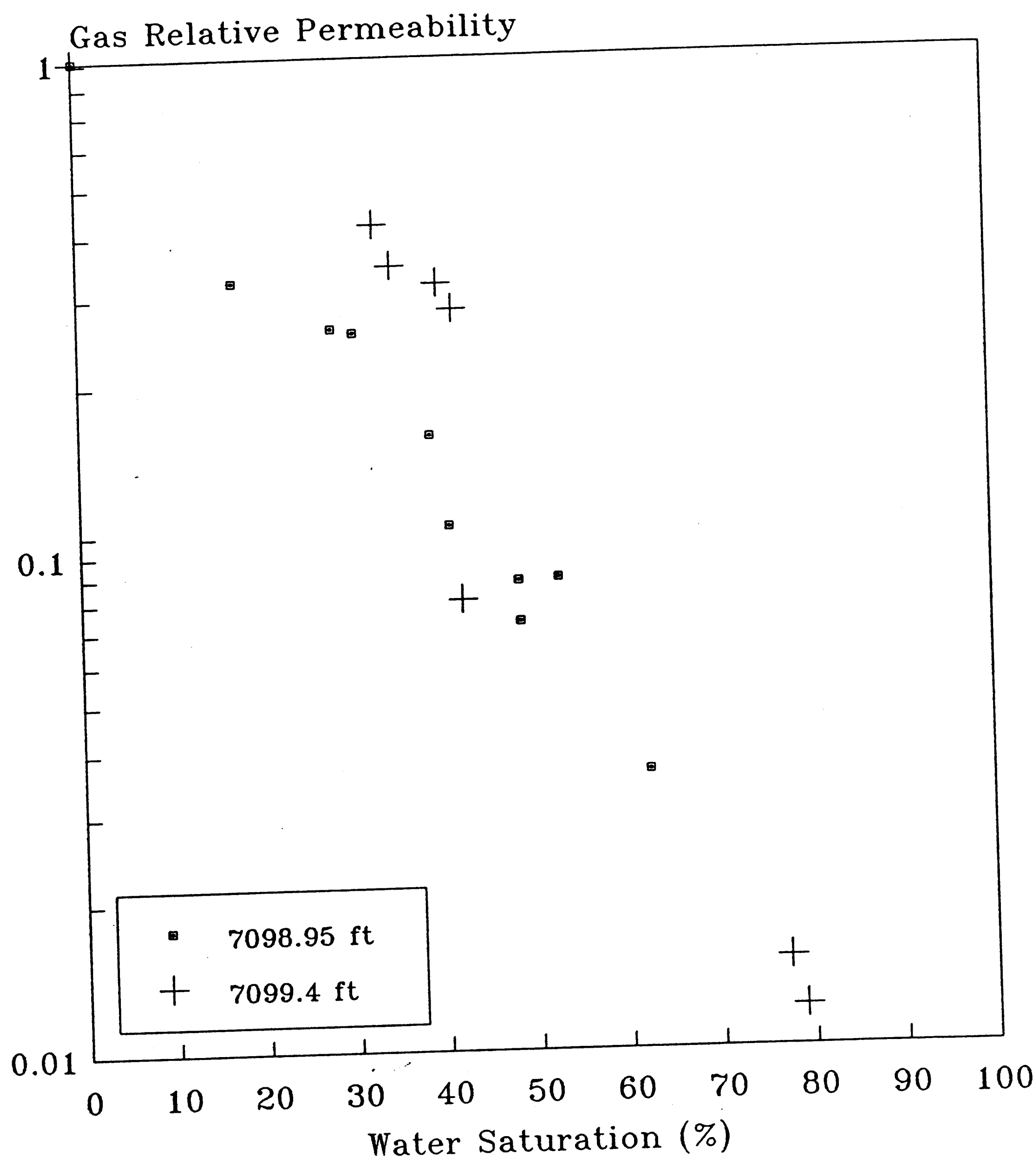

Fig. 11 Relative Permeability Curves
for Sam Hughes No. 1 Cores

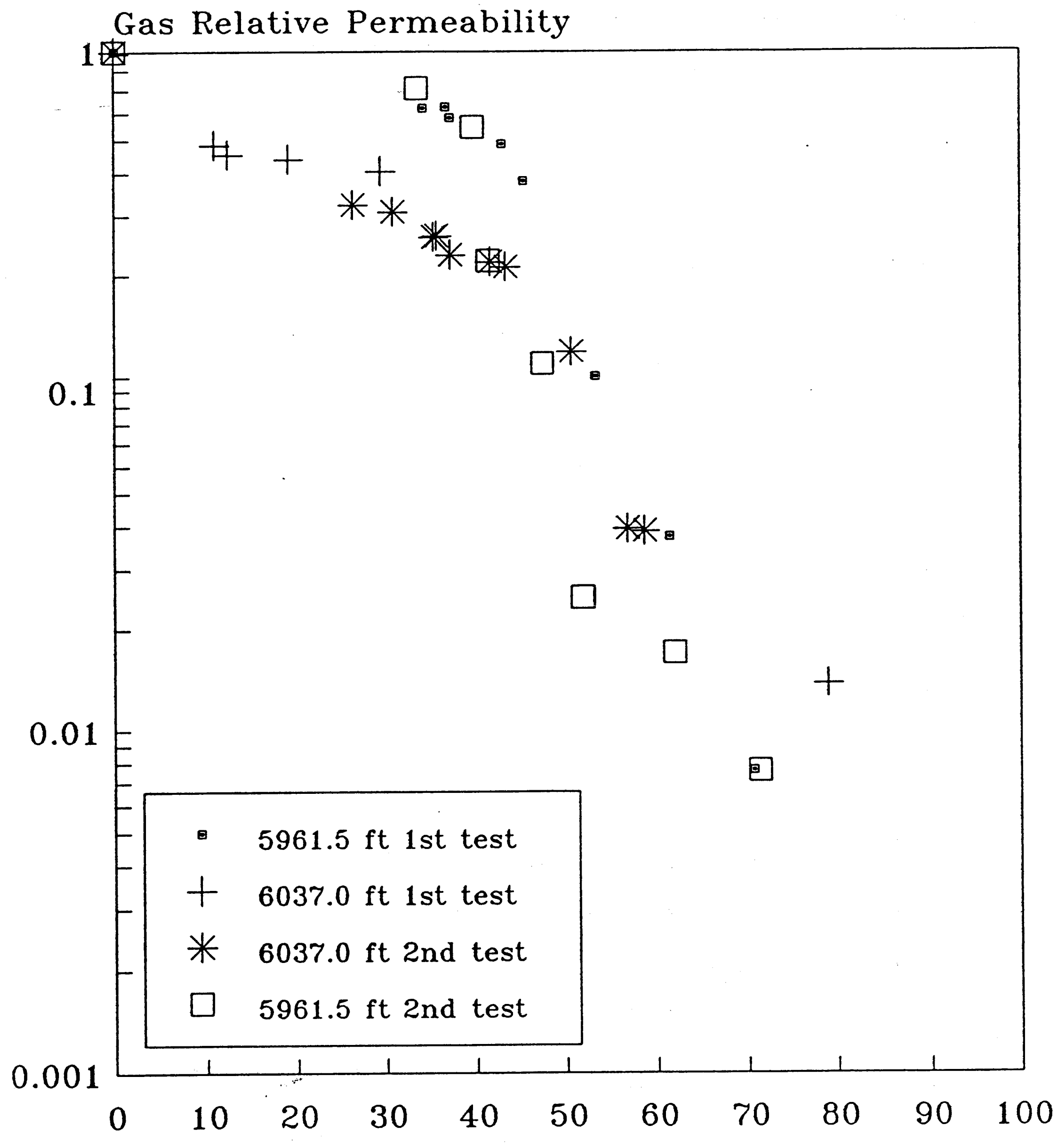

Fig. 12 Relative Permeability Curves
for Holditch Howell No. 5 Cores

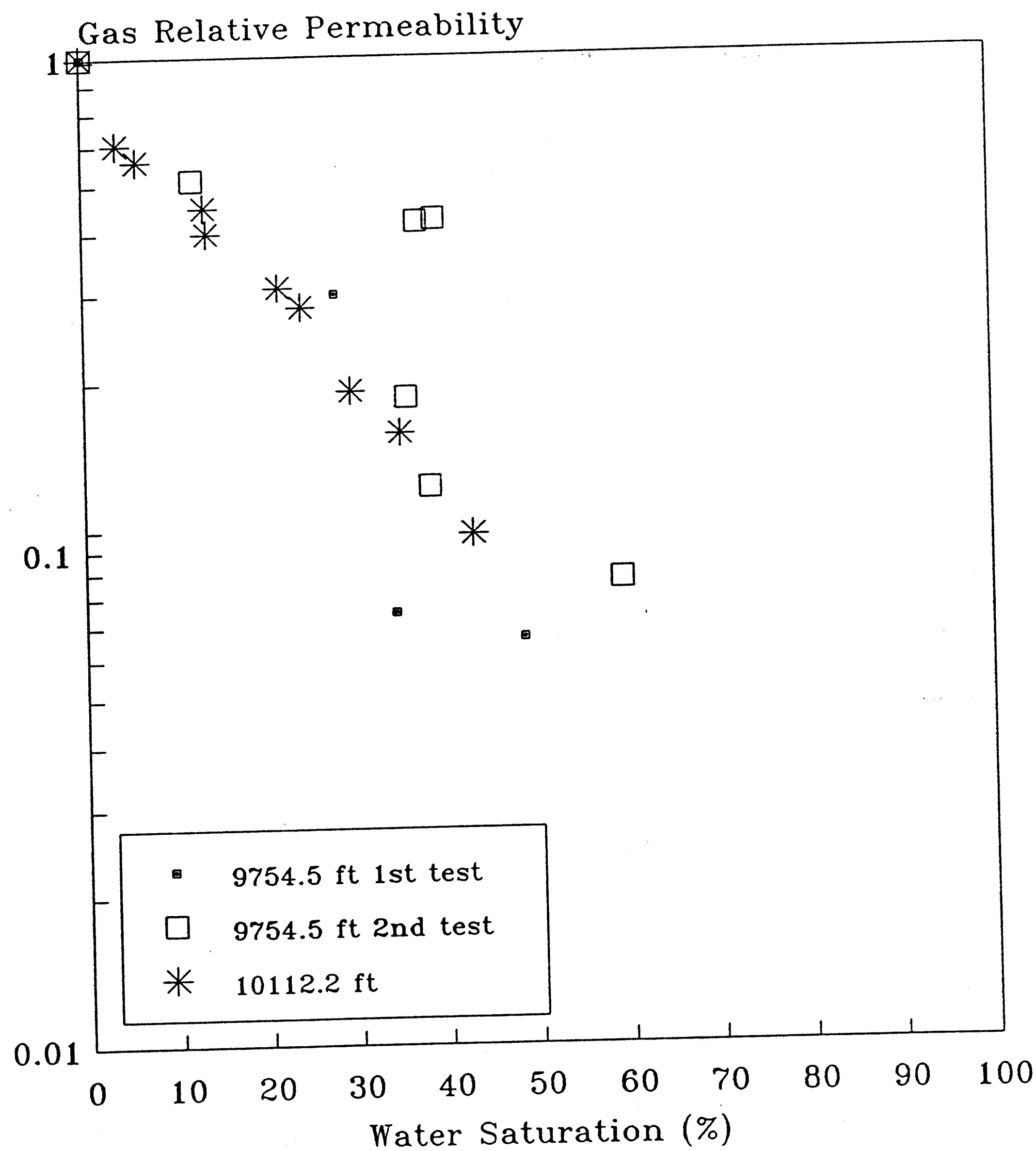

Fig. 13 Relative Permeability Curves
for Ashland S.F.O.T. No. 1 Cores

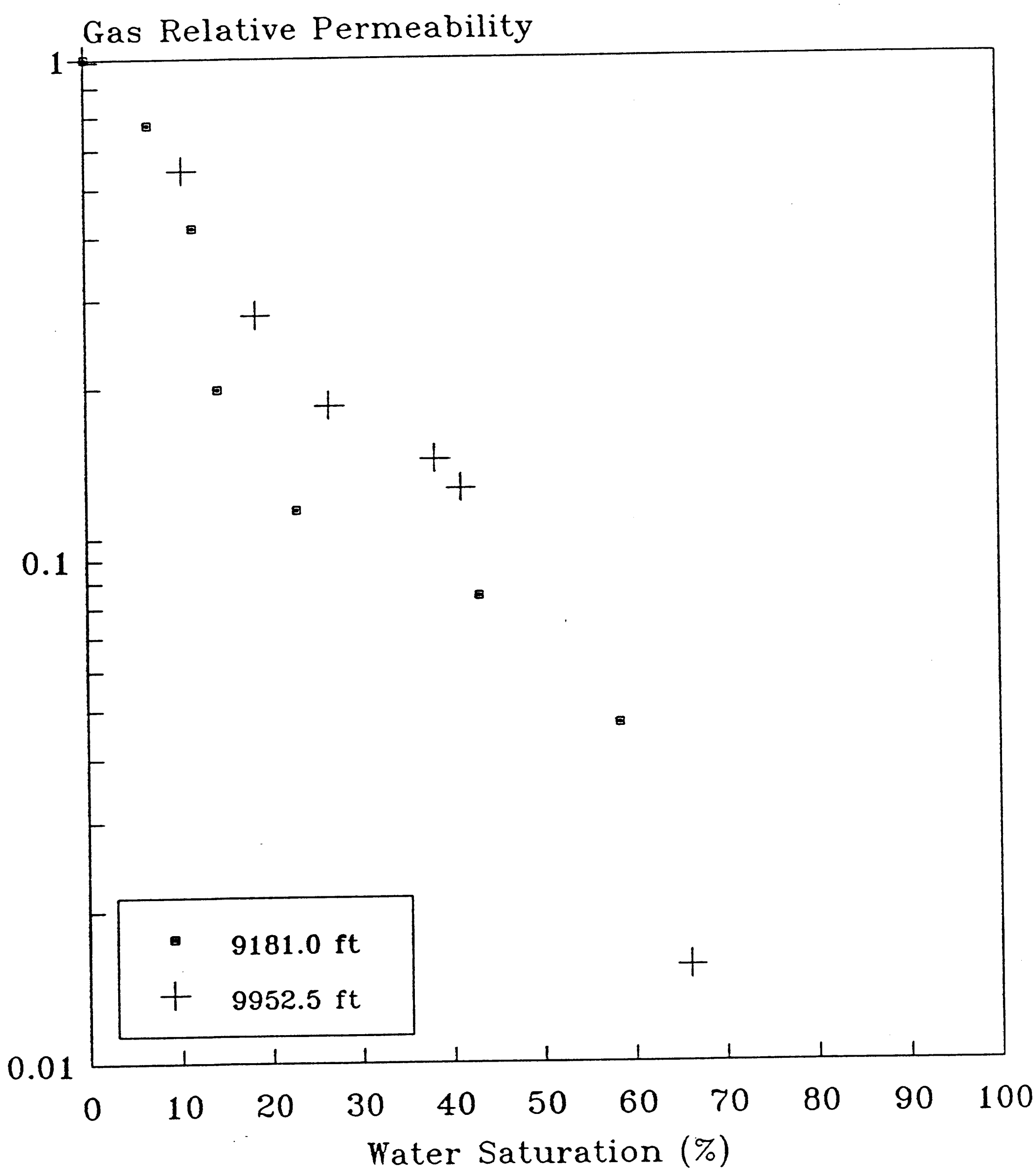

Fig. 14 Relative Permeability Curves
for Prairie Mast No. 1-A Cores