(1991 SCA Conference Paper Number 9119)

MEASUREMENT OF "ROCK PROPERTIES" IN COAL FOR COALBED METHANE PRODUCTION

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ABSTRACT

Standard laboratory techniques for measurement of rock properties (porosity, permeability and gas-water relative permeability) must be modified when applied to coal for use in coalbed methane reservoir engineering studies. Coal is unlike most conventional reservoir rock in that fluid flow occurs in a network of naturally occurring microfractures or cleats. Drying coal alters the cleat structure. Therefore, a miscible displacement technique, in which coal cores are not dried, was used to determine an upper limit for cleat porosities of around 2% for cores from coalbed methane wells. There is no significant difference between the cleat porosity measured with the miscible displacement technique and the mobile water porosity for a coal core, indicating there is little or no irreducible water saturation in the cleat network. (The mobile water porosity is the volume of water which is driven out of a water-saturated core by helium injection divided by the bulk volume of the core.) Absolute permeability to water in coal cores can decrease with continued flow by an order of magnitude, probably due to fines migration. Unsteady-state gas-water relative permeability techniques can be modified to handle both the small volumes of water produced from cores with less than 2% porosity and the decreasing absolute permeability. Representative unsteady-state gas-water relative permeability curves for San Juan and Warrior Basin cores which have been used in coalbed methane reservoir engineering studies are presented. In steady-state gas-water relative permeability measurements using sodium iodide as a tracer, sodium iodide adsorption on the coal surfaces will result in systematic error in saturation values. However, within the experimental error with which saturations in the cleat networks can be determined, unsteady-state and steady-state with sodium iodide gas-water relative permeability measurements yield the same results.

INTRODUCTION

Within the past decade, as methane production from coal seams has progressed from demonstration phase to exploration phase and currently to economic production phase, the general aspects of coal structure, its relationship to coal "rock properties" (porosity, permeability, and gas-water relative permeability), and the reservoir engineering aspects of coal rock properties have been described in a constantly expanding body of literature. Porosity in coal consists of matrix porosity wherein the methane is adsorbed on the coal surface, and cleat porosity, i.e., naturally occurring microfracture porosity. The cleat network provides the permeability for fluid flow in coal. For calculation of coalbed methane gas-in-place, gas content of the coal is equivalent to porosity in a conventional gas reservoir.

The coal seam is both the source rock and the reservoir rock for coalbed methane. At discovery, the cleat network is usually saturated with water. When the coal seam is "dewatered" and reservoir pressure lowered, methane desorbs from the matrix and diffuses into the cleat network. Simultaneous flow of methane and water occurs in the cleat network during coalbed methane production. Determination of permeability and gas-water relative permeability are necessary for prediction of methane and water production rates from coalbed methane reservoirs.

At the present time there are no generally accepted methods in the industry for the laboratory measurement of cleat porosity, permeability, or relative permeability in coal, nor are there any published laboratory measurements of coal rock properties which are accepted standards for comparison. The work described in this paper is a part of a systematic study of laboratory measurements of coal rock properties. Only core analysis procedures generally accepted in the industry but appropriately modified for application to coal are considered.

COAL CORE COLLECTION, PRESERVATION, PREPARATION, AND DESCRIPTION

Four coal cores with different characteristics were selected for rock property measurements. Cores A, B, and C are from the San Juan Basin; Core D is from the Warrior Basin. Additional details (coal seam, core dimensions) are in Table 1.

The unique properties of coal place special constraints on collection, preservation, and preparation of coal cores. Drilling fluid in contact with coal intended for rock property measurements should contain nothing which alters the structure of coal. Potassium chloride mud is acceptable. Caustic and many organic chemicals[1] have been observed to alter coal structure and are therefore not acceptable as additives. In so far as possible, coal cores should be kept in contact with water to prevent drying and contact of coal cores with air should be avoided. Cores A and B were collected in aluminum sleeve core barrels (to minimize bending and breaking core material) sealed with rubber endcaps. Core D was collected in a wireline core barrel. Core C was prepared from a block of surface-mined coal shipped in water to prevent drying and contact with air.

Rock property measurements in conventional reservoir rock are generally made on plugs taken parallel to the bedding planes. The dimension of coal cores currently drilled for Amoco and the very low porosity of coal preclude the measurement of rock properties on coal plugs taken parallel to the bedding plane. All the cores used in this study were cut vertically, i.e., perpendicular to the bedding plane. Any observable streaks of shale, etc., were trimmed off.

Commonly used jacketing materials[2] were used to protect the coal cores. Core B was wrapped with Teflon® tape. Cores A, C, and D were coated with Devcon® aluminum putty and then covered with heat shrink tubing.

For porosity, absolute permeability to water, and unsteady-state gas-water relative permeability measurements, a hydrostatic core holder with a Neoprene® liner was used

to ensure a uniform confining pressure. Organic dyes such as fluorescein, which are often added to the annulus fluid of a core holder to detect a leak of annulus fluid through the confining liner, cannot be used for this purpose because of the high adsorption capacity of coal. More than 5 pore volumes of fluorescein solution had to be injected into a coal core before fluorescein could be detected in the effluent. A mineral oil, such as Blandol, used as the annulus fluid provides a better means of detecting leak of annulus fluid.

The cores used in this study were selected to provide examples of various cleat network structures. In Core A, a single large fracture is present across the entire diameter of the core and extends halfway through the length of the core. A cleat network is present in the other half. In Core B, the cleat structure is staggered at the bedding planes (which occur at 1/8 in. to 1/4 in. intervals). In Cores C and D, many individual cleats extend the entire length of each core.

MEASUREMENT OF CLEAT POROSITY IN COAL

Measurement of the porosity of coal is important in determining the saturations necessary for gas-water relative permeability measurements or capillary pressure measurements (which will not be discussed). Coal is a dual porosity rock containing micropores (matrix porosity) and a network of naturally occurring microfractures known as cleats. The bulk of coal porosity is in the micropores, but the cleat network provides the permeability for fluid flow.

In early measurements of coal rock properties including porosity, coal cores were dried in a vacuum oven at 80°C for 24 hours.[3] Subsequent work[4] on coal weathering indicates such drying alters the coal structure and should not be used.

For conventional rocks, an accepted procedure for porosity measurement without drying a core is the miscible drive technique.[2] The fluid saturating the core is displaced from the core by a second fluid with different physical properties but which is miscible with the saturating fluid. Properties such as density, tracer concentration, or ionic composition can be used to determine the displaced volume of the original saturating fluid.

A miscible drive technique using sodium iodide as the tracer and X-ray absorption for monitoring the tracer has been described and used to measure cleat porosity in coal.[5] With this technique, the cleat porosity of Core B with a 1000 psig confining pressure was reported as 2.4% and the mobile water porosity as 1.4%. Two experimental problems make these measurements suspect. First, incorrect measurement of system dead volume can give a high estimate of mobile water porosity. With the procedure of Reference 5, a high estimate of mobile water porosity will result in a high estimate of cleat porosity. Second, adsorption of sodium iodide on the coal surface can lead to erroneously high measurements of cleat porosity. A modification of the technique of Reference 5 is recommended.

A miscible tracer technique, in which deionized water and deionized water containing 100 ppm lithium chloride tracer were the two miscible fluids, was used to determine

the cleat porosity for Cores A, B, C, and D. Lithium chloride was used because totally disassociated salts with small ions are not highly adsorbed on carbon surfaces.[6] Each core was saturated with distilled water initially. In saturating the coal cores with water, helium saturated with water vapor was injected into the core to remove mobile water in the cleats. Helium was always injected from the top of the vertical hydrostatic core holder. The core was then evacuated to remove any free gas, and saturated with water at atmospheric pressure. Water was then injected at 370 psig with a 300 psig backpressure from bottom of the vertical hydrostatic core holder. (Core B was saturated by injecting water at 370 psig with 300 psig backpressure as specified in the procedure of Reference 5.) Lithium chloride solution was injected into the core saturated with distilled water until the lithium chloride concentration in the effluent was the same as the injected concentration. The concentration of the lithium chloride was monitored by measuring refractive index and electrical conductance. Effluent volumes were monitored using an electronic balance. Injection of the lithium chloride solution was then continued for 24 to 72 additional hours. The lithium chloride solution was then displaced with distilled water in the same manner while lithium chloride concentration and effluent volumes were monitored. Lithium chloride concentrations and effluent volumes were used to calculate total displaced volumes, from which the system dead volume (core holder inlet and exit lines) were subtracted to calculate the cleat pore volume. The cleat pore volume was divided by the measured bulk volume of the core to calculate the cleat porosity.

The tracer tests were replicated on the four cores so that 95% confidence limits for random error could be calculated. These data, and the confining pressures at which the porosities were measured are in Table 2. The values in Table 2 are upper limits on the actual cleat porosity since any adsorption of the lithium chloride results in the tracer test porosity being systematically larger than the actual cleat porosity. The cleat porosities determined by the tracer tests for all four cores are 1.6% $\pm$ 0.3 or less.

Another measurement of the cleat porosity is the "mobile water" porosity. This represents the volume of water which is driven out of a water-saturated core by helium injection (mobile water volume) divided by the bulk volume of the core. (The "mobile water" volume is determined in the measurement of an unsteady-state relative permeability measurement.) The mobile water porosities for Cores A, B, C, and D are also in Table 2. The 95% confidence limits associated with the mobile water porosities in Table 2 are for random error, i.e., reproducibility of the measurements. The difference between the cleat porosity as determined by the tracer test and the mobile water porosity measured on a core may be due to an irreducible (or capillary) water saturation. The differences are not significant when compared to the standard deviations for the measurements. Any adsorption of the lithium chloride tracer will result in the cleat porosity (determined by the tracer test) being systematically larger than the mobile water porosity even if the actual cleat porosity and mobile water porosity were the same.

The measured cleat porosities determined by the tracer test and the mobile water porosities indicate that there is very little if any irreducible (or capillary) water saturation associated with the cleat network in coal. This suggests the cleat network has a narrow distribution of fracture widths.

MEASUREMENT OF ABSOLUTE PERMEABILITY TO WATER IN COAL

Absolute permeabilities to water measured for Cores A, B, C, and D are tabulated in Table 2. Confining pressures were the same as those used in the tracer porosity tests. Injection was at 370 psig with a 300 psig backpressure. An electronic balance was used to measure water effluent volumes for these measurements. The absolute permeabilities in Table 2 are the highest and lowest observed values. Several measurements of absolute permeability to water were made on Cores B and C which had fluids flowing through them for as long as two months. In both these cores, the absolute permeability to water decreased with time. Decreasing permeability was observed to some extent in Cores A and D, but these cores were not subjected to long periods of testing. The decrease in absolute permeability to water in coal with continued flow has been observed in numerous other coal cores but has not been noted or systematically studied.

One factor involved in the observed decreases in water permeability is migration of fine particles, which is also observed in conventional reservoir rock.[7] Coal is a friable material and in some instances (though not with Cores A, B, C, and D), fines have been observed in the effluent from water injection into coal cores. Figure 1 is a plot of a series of absolute permeability to water measurements made on Core B as deionized water was injected into the core at around 10 cc/hr. Prior to the period shown in Figure 1, two previous periods of declining permeabilities similar to Figure 1 were observed for Core B. The first two times that the water permeability decreased to the range of 0.05 md, reversing the direction of flow through the core increased the permeability to around 0.15 md (the first observed value after water injection was initiated into the core). Restoration of water permeability when flow is reversed is often an indication of fines migration. The third reversal of flow (after the period shown in Figure 1) increased the water permeability, but the water permeability was never again restored to the original value. The water permeability in Core B continued to decline to the 0.04 md value in Table 2. In line filters at the effluent end of this core showed no evidence of coal fines.

Injection of brine containing sodium chloride or lithium chloride was observed to increase the permeability of Core B suggesting that clay minerals in the cleat network may play a role in the observed permeability decline in this core. Injection of deionized water will cause Berea sandstone to lose around 95% of its permeability due to clay blocking. The sodium chloride and lithium chloride brines did not restore the permeability of Core B to the original value. Injection of these brines into Cores A, C, and D had no effect on the permeability. Cores into which only simulated reservoir brines were injected have exhibited permeability decrease. A decrease in permeability has also been observed in coal cores into which only sodium iodide brines have been injected.[8]

Figure 2 is a plot of a series of water permeability measurements made on Core C as deionized water was injected into the core at around 10 cc/hr for approximately 1 month. The water permeability declined rapidly during the first 24 hours. This rapid decline in water permeability is probably due to compression of the coal due to the confining pressure ("coal creep"). After the first 24 hours, the water permeability decline does not appear to be associated with any change in the cleat volume, since

the mobile water porosity did not change significantly although the permeability significantly decreased. (Values are noted on Figure 2.) This suggests that the water permeability reduction after the first 24 hours is not due to compression of the coal under confining pressure. (Increases in permeability in Figure 2 are the result of reversing flow.)

The above observations rule out clay blocking and compression of the coal as the major causes of the observed permeability decline. The observations are consistent with fines migration as a cause of the permeability decline. Fines might be produced during methane evolution from a coal core, when the pressure rapidly decreases to atmospheric pressure as the core is brought to the surface. However, the permeability decrease is also observed in Core C which was prepared from a block of outcrop coal. The fines are most likely generated during the preparation of the coal cores. Fines produced during the facing of the core could plug it as they migrate into the core when water is injected. Face plugging would account for the reduction in permeability without a loss in mobile water porosity. If face plugging is the problem, the representative permeability for the coal core is the value after the rapid decline caused by initial compression. Experimental work is underway to determine whether face plugging with coal fines is the cause of the observed permeability decline.

MEASUREMENT OF GAS-WATER RELATIVE PERMEABILITY IN COAL

There are two standard methods for gas-water relative permeability measurement in conventional reservoir rocks; namely, unsteady state and steady state. In the unsteady-state technique the core is saturated with brine which is subsequently displaced by injection of gas. Saturation is continuously changing and is computed by material balance. In the steady-state technique both gas and brine are simultaneously injected at constant measured rates (or constant pressure) until equilibrium is established. Fluid saturations in the core are then measured. The use of both the unsteady-state and steady-state methods to measure gas-water relative permeability in coal are discussed below.

Wettability is generally considered a governing factor in relative permeability.[9] In conventional reservoir rocks the surface is usually water-wet compared to gas. As a result helium or nitrogen is often used instead of methane in gas-water relative permeability measurements in conventional reservoir rock. Methane is readily adsorbed in the coal matrix; the coal matrix may therefore be methane-wet compared to water. However, the cleat network is often observed to contain mineral deposits. It is possible, therefore, that the cleat networks of various coals could be methane-wet, water-wet or exhibit intermediate wettability depending on the degree of mineralization. In the relative permeability measurements discussed below (both unsteady-state and steady-state) helium which is not adsorbed on the coal surface is used as the gas phase for ease of experimentation. The use of helium instead of methane may have an additional effect on gas-water relative permeability in coal since adsorption of methane "swells" coal[10], and thus may alter the cleat structure.

UNSTEADY-STATE METHODS

The procedures and apparatus for measurement of gas-water relative permeability by the unsteady-state method in conventional reservoir rock must be modified for the application of the method to coal. As shown in the preceding sections, porosity and permeability in coal are very low. Automated data collection using mass flow meters to monitor total effluent (gas plus water) production after gas breakthrough and a gas-water separator placed on an electronic balance to monitor water production were used to achieve the accuracy required for unsteady-state relative permeability measurements in coal. Helium was saturated with water vapor in a humidifier prior to injection. Figure 3 is a schematic diagram of the apparatus used for the unsteady-state gas-water relative permeability measurements presented in this paper.

Because the porosity of coal is so low, the dead volume (the volume of inlet and exit lines and distribution plates of the core holder) is roughly equal to the volume of water produced from the coal core during gas injection in the unsteady-state technique. The magnitude of the effect of inaccuracies in determining dead volume on gas-water unsteady-state relative permeability measurements is shown in Figure 4. In performing the calculations for Figure 4, the dead volume was assumed to be water-filled at the start of gas injection. The displacement of the water in the dead volume was assumed to be piston-like so that the dead volume was subtracted from the water produced. The Johnson, Bossler, and Naumann[11] (JBN) method was used to calculate the relative permeability curves. Figure 4 shows that inaccuracies in determining the dead volume can result in significant inaccuracy in the calculated relative permeability curves. The original data measured for the relative permeability of Core B as presented in Reference 5 were used to prepare Figure 4. The dead volume of the system used in collecting the data in Reference 5 was uncertain; the values 3.9 cc and 5.8 cc were both originally recorded. Use of the 3.9 cc value with the original data results in a predicted mobile water volume for Core B which is much greater than that measured in the present work. If a value of 7.0 cc is assumed as the dead volume for the system used in Reference 5, then both the mobile water porosity and the relative permeability calculated from the original data agree with the present measurements.

In the current work the dead volume was water-filled at the start of helium injection and helium injection was always from the top of the vertical hydrostatic core holder. This was done to ensure piston-like displacement of the dead volume. Helium injection was at 370 psig with a 300 psig backpressure. A translucent 1/16 in. ID exit line was used to accurately determine the water volume produced before gas breakthrough. This measurement provides an upper limit for the system dead volume if piston-like displacement of the dead volume occurs. The unsteady-state technique cannot be used to measure gas-water relative permeabilities at saturations below the saturation at which gas breakthrough occurs.

The JBN method was used to compute gas and water relative permeability curves from the fluid production and differential pressure data. Measured dead volumes were subtracted from the water production. The JBN method assumes a uniform saturation distribution at each cross-section of a core. If the cleat network of coal does not fulfill this assumption, then the gas and water relative permeabilities could differ even for

adjacent coal cores. All four varied cores used in this study have very similar relative permeabilities using unsteady-state measurements and the JBN method.

Figures 5-8 show the gas-water relative permeability curves for Cores A, B, C, and D. The relative permeabilities for Cores A, B, and D have been used in Amoco's coalbed methane reservoir simulation studies. On the abscissa of each figure, gas saturation is based on mobile water saturation. The 100% gas saturation is the point during gas injection at which no more water is produced. Given the discussion on cleat porosity and mobile water porosity, the abscissa as plotted is also the actual gas saturation, i.e., at 100% gas saturation on the abscissa the cleats are within experimental error 100% gas saturated, there being little or no irreducible water saturation. Absolute permeability to water is used as the base permeability. The calculated data points are included in Figure 5 to show the resolution of the data obtainable with the automated data system. The data points are omitted in the other figures.

Figure 7 presents three relative permeability measurements on Core C made at three different base water permeabilities, 0.6 md, 0.5 md, and 0.1 md. In spite of the base water permeability changing, the relative permeability does not change significantly. The base water permeability decrease discussed above, thus, has no significant effect on unsteady-state relative permeability measurements as long as the permeability is not rapidly changing during the measurement. The permeability behavior and relative permeability of Core C, which is a core taken from a block of surface-mined coal, is similar to that measured on Core A, B, and D. This coal is being used in a continuation of the present study of the measurement of coal rock properties.

Figure 9 is a comparison of all the relative permeability data. The ordinate of this plot is the logarithm of the relative permeability ratio k_{rg}/k_{rw}. In the relative permeability ratio, the absolute permeability to water used as the base permeability for both the gas and water relative permeabilities cancels out. Figure 9 illustrates the points made above on Core C, i.e., the relative permeabilities measured at different base water permeabilities are similar and the relative permeability of Core C is similar to that of the other cores. The relative permeability ratio plots for all the coal cores are very similar. Over the range of saturations shown, all the ratio plots appear to be straight lines with similar slopes. The saturation at which $k_{rg} = k_{rw}$ ($k_{rg}/k_{rw} = 1$) differs. This saturation is reproducible within ± 5 saturation percent for a given coal core. For comparison, in unsteady-state relative permeability measurements in conventional reservoir rocks (with mobile water volumes greater than 5 times that for coal cores) the saturation at which $k_{rg} = k_{rw}$ is reproducible within ± 2 saturation percent.

THE STEADY-STATE METHOD

The measurement in this section was performed by Core Laboratories, Tulsa, as part of a study funded by the Gas Research Institute. Amoco Production Company donated Core B and previous unsteady-state measurements on that core made by both Amoco and Core Laboratories to this study. Although system dead volume is not a problem in the steady-state method, there are problems with the sodium iodide tracer when applied to coal. The steady-state gas-water relative permeability measurement used sodium iodide tracer and X-ray absorption by sodium iodide to determine water saturation. Water saturation is not determined directly in this measurement. The meas-

urement was performed in a Hassler holder in which the cleat network does not receive a uniform confining pressure. The X-ray instrument at Core Laboratories does not scan the entire width of the core. (A band approximately 1 in. in width is scanned.) Therefore, uniform saturations at any cross-section must be assumed in measuring saturations.

For this test 147 gm/liter of sodium iodide was used as the tracer. This is roughly 1.25 times the concentration normally used. The increased concentration was required because of the lower sensitivity of the technique when applied to coal which has a much lower porosity than most conventional reservoir rock. Sodium iodide brine was pumped through the core at approximately 11 cc/hr for 9 days until the X-ray absorption background stabilized. The background changes are probably due to sodium iodide adsorption on coal. Adsorption of the sodium iodide tracer will result in systematic error in calculated saturation values.

Figure 10 presents the results of the steady-state test on Core B at Core Laboratories, Tulsa, and the results of an unsteady-state test performed at Amoco Production Research. Both tests were run with the core in a horizontal position. The gas saturations in the unsteady-state test are based on the mobile water porosity. The results of the two tests are similar in spite of the problems which have been pointed out for both techniques. The crossover points ($k_{rw} = k_{rg}$) of both tests occur at nearly the same saturation and relative permeability. Both gas relative permeability curves exceed 100% (based on the initial absolute permeability to water) at gas saturations lower than 100%. (This was also observed in a duplicate horizontal unsteady-state run but not in two replicate vertical unsteady-state runs on Core B.) Core Laboratories, Tulsa, experienced difficulties in controlling the gas flows during the steady-state measurement probably because the absolute permeability of Core B had declined to 0.04 md by the time the steady-state measurement was made. The water relative permeability curves are similar. The gas and water relative permeability curves for the steady-state measurement are to the left of the unsteady-state measurement. This is the expected result due to sodium iodide adsorption. The similarity of the steady-state measurement which is based on total cleat porosity and the unsteady-state measurement based on mobile water porosity confirm there is very little if any irreducible water saturation. This is in agreement with the porosity measurements discussed above. Core Laboratories has performed another comparison of unsteady-state and steady-state with sodium iodide tracer relative permeability measurements with similar results.[7]

CONCLUSIONS

1. A miscible displacement technique, in which coal cores are not dried, was used to determine an upper limit for cleat porosities of around 2% for cores from coalbed methane wells.

2. There is no significant difference between the cleat porosity measured with the miscible displacement technique and the mobile water porosity for a coal core, indicating there is little or no irreducible water saturation in the cleat network. (The mobile water porosity is the volume of water which is driven out of a

water-saturated core by helium injection divided by the bulk volume of the core.)

3. Absolute permeabilities to water in coal cores can decrease with continued flow by an order of magnitude (down to 0.04 md), probably due to fines migration.

4. The decrease in absolute permeability to water has no significant effect on unsteady-state relative permeability measurements as long as the permeability is not rapidly changing during the measurement.

5. Unsteady-state gas-water relative permeability techniques can be modified to handle the small volumes of water produced from cores with less than 2% porosity. Unsteady-state gas-water relative permeability curves for San Juan and Warrior Basin cores have been measured and used in coalbed methane reservoir engineering studies.

6. In steady-state gas-water relative permeability measurements utilizing sodium iodide as a tracer, sodium iodide adsorption on the coal surfaces will result in systematic error in saturation values. However, within the experimental error with which saturation in the cleat network can be determined, unsteady-state and steady-state with sodium iodide tracer gas-water relative permeability measurements yield the same results.

ACKNOWLEDGEMENTS

The author wishes to thank Amoco Production Company for the opportunity to present this work, La Plata Coal Mine for permitting the collection of coal used in this work and the Gas Research Institute and Core Laboratories, Tulsa for the steady-state measurement on Core B. A number of the members of the Rock Properties Group at Amoco Production Research Center must be recognized for their contributions to this work: Lee Baker who wrote Amoco's RELK program, Gary Potter and Tim Crawford who pioneered the automated data collection system used in this work and provided the data used to calculate confidence limits for conventional rock, and John Corgan who assembled the apparatus, wrote the data acquisition and reduction programs and made the measurements. Special thanks to Surendra Gupta, Larry Treiber, Bob Metcalfe and Dan Yee, of Amoco who reviewed the manuscript for this paper and Mercer Brugler of Core Laboratories, Tulsa, for his assistance.

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TABLE 1

INFORMATION ON COAL CORES USED IN THIS STUDY

Core	A	B	C	D
Location	Cahn Seam San Juan Basin	Ignacio Seam San Juan Basin	Seam No. 1 Sundance Pit LaPlata Mine San Juan Basin	Blue Creek Seam Warrior Basin
Diameter (in.)	3.5	3.5	3.5	2
Bulk Volume (cc)	514	471	672	191

TABLE 2

CLEAT POROSITIES AND ABSOLUTE PERMEABILITIES TO WATER IN COAL CORES

Core	A	B	C	D
Confining Pressure (psig)	1000	450	450	450
Cleat Porosity (%) (Tracer Test)	1.6 ± 0.3	0.9 ± 0.2	0.8 ± 0.3	1.2 ± 0.7
Mobile Water Porosity (%)	1.1 ± 0.1	0.9 ± 0.1	0.6 ± 0.1	1.0 ± 0.3
Absolute Permeability to Water (md)	2.6 – 0.44	0.13 – 0.04	0.78 – 0.04	4.6 – 1.4

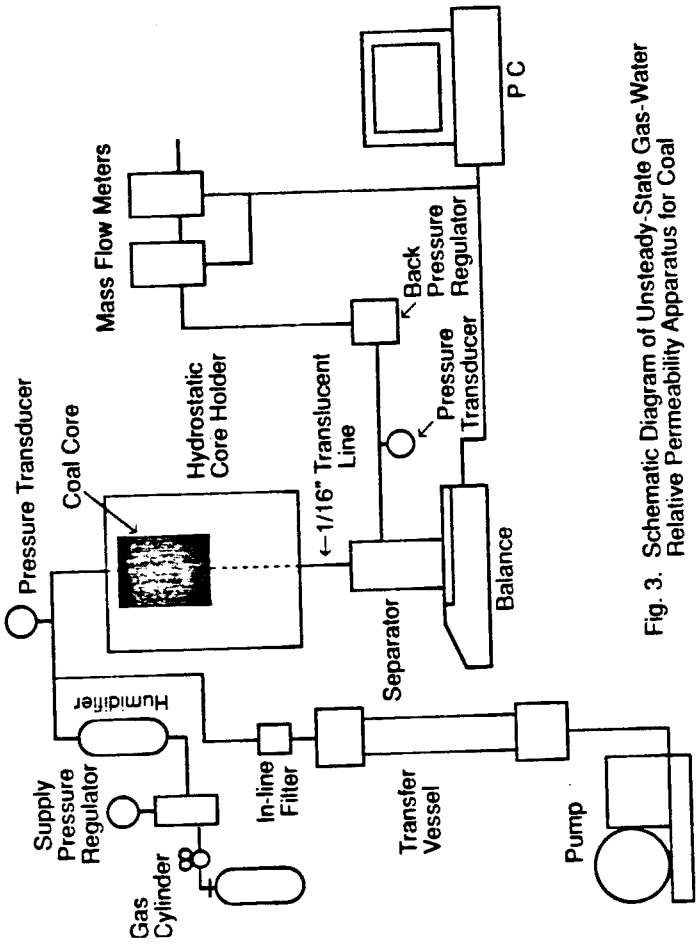

Fig. 3. Schematic Diagram of Unsteady-State Gas-Water Relative Permeability Apparatus for Coal

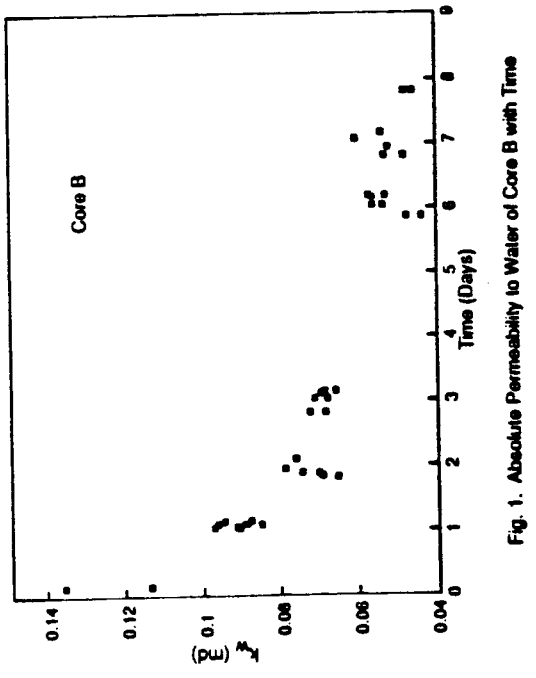

Fig. 1. Absolute Permeability to Water of Core B with Time

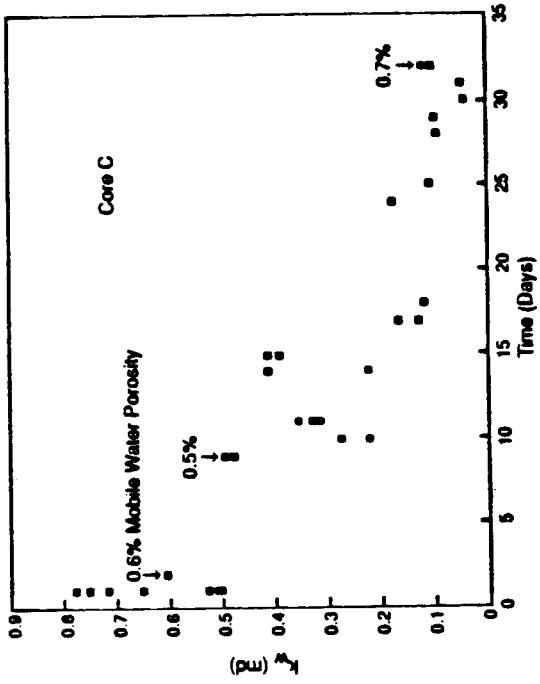

Fig. 2. Absolute Permeability to Water of Core C with Time

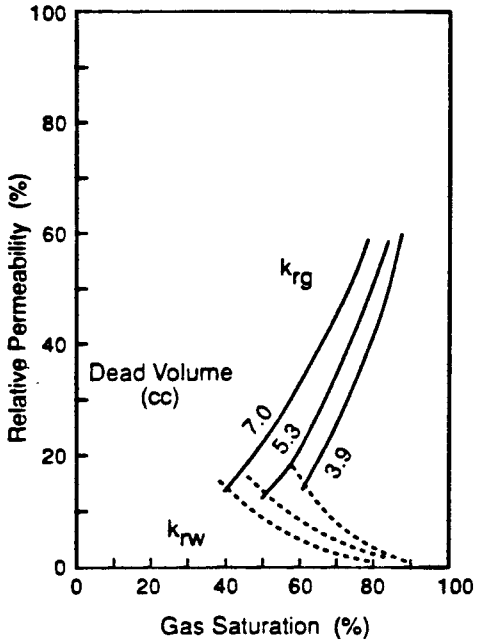

Fig. 4. The Effect of Inaccuracy in the Determination of System Dead Volume on Computed Unsteady-State Gas-Water Relative Permeability in Coal

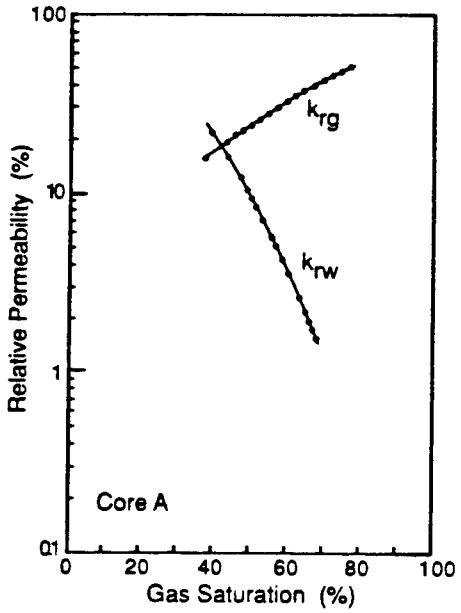

Fig. 5. Gas - Water Relative Permeability for Core A

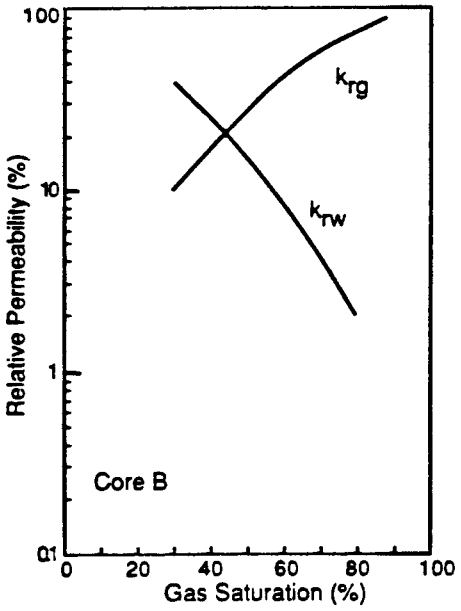

Fig. 6. Gas - Water Relative Permeability for Core B

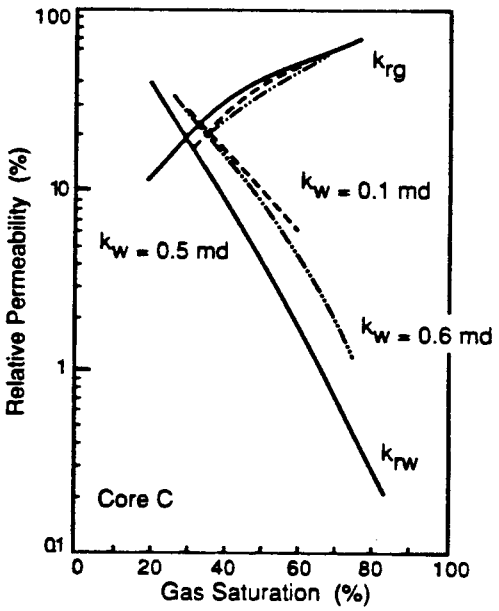

Fig. 7. Gas - Water Relative Permeability for Core C

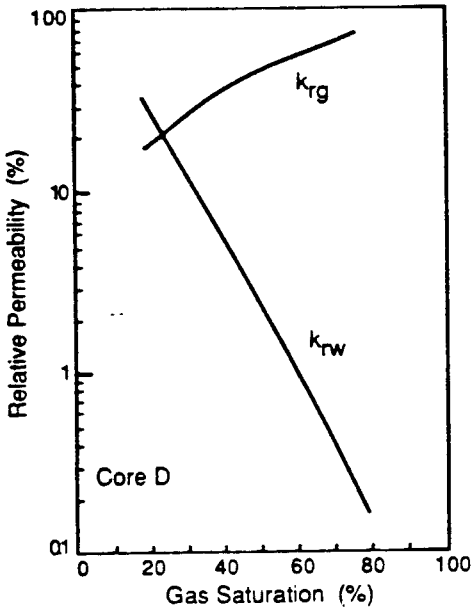

Fig. 8. Gas - Water Relative Permeability for Core D

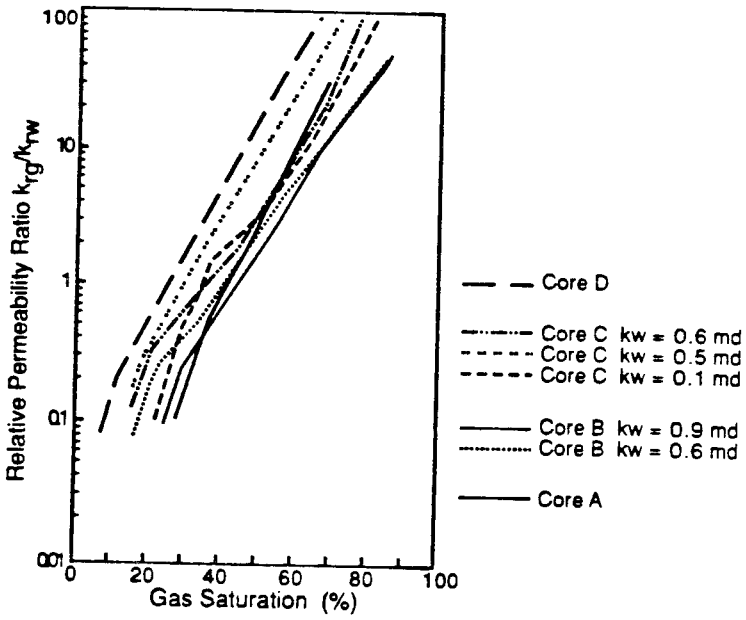

Fig. 9. Comparison of Relative Permeability Ratios for Cores A, B, C and D.

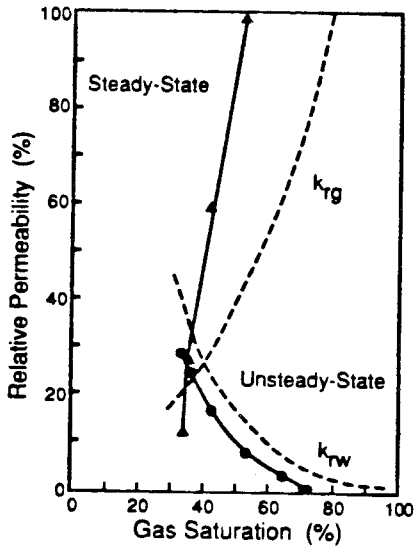

Fig. 10. Comparison of Gas-Water Relative Permeability for Core B Measured by the Unsteady-State and the Steady-State with Sodium Iodide Methods