The Effects of Cleat Orientation and Confining Pressure on Cleat Porosity, Permeability and Relative Permeability in Coal

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Abstract

Many previously reported measurements of gas-water relative permeability in coal have been performed with fluid flow perpendicular to the bedding planes. The cleat structure of coal suggests that permeability in coal should be anisotropic and dependent on net confining pressure. Nothing has been previously reported concerning the anisotropy of gas-water relative permeability in coal or its dependence on confining pressure. Laboratory measurements of cleat porosity, permeability and gas-water relative permeability as a function of cleat orientation and confining pressure on Fruitland formation coal collected from the La Plata mine in the San Juan basin of New Mexico have been performed with the following results.

There is no effect of cleat orientation on gas-water relative permeability in well-cleated La Plata coal cores. Relative permeability measurements on well-cleated coal samples can be performed using vertical cores (fluid flow perpendicular to the bedding planes).

As expected, permeability is largest parallel to the bedding planes in the face cleat direction. At 1,000 psig confining pressure, permeability parallel to the bedding planes in the face cleat direction is 0.6-1.7 md and in the butt cleat direction, 0.3-1.0 md. These compare with 0.007 md measured perpendicular to the bedding planes. The permeability measurements parallel to the bedding planes are comparable to those observed in coal seams and used in simulation studies. In general, laboratory permeability measurements made perpendicular to the bedding planes in coal are much lower than the values used in simulation studies.

Confining pressure (i.e., stress) has an effect on cleat porosity, permeability and relative permeability. Increasing confining pressure from 450 psig to 1,000 psig with an injection pressure of 370 psig and a 70 psig pressure drop lowers the permeability by a factor of approximately 5 in all cleat orientations. The cleat porosity is lowered by approximately a factor of 1.7. Increasing confining pressure increases the ratio of the gas relative permeability to the water relative permeability.

Introduction

Determination of coal rock properties (cleat porosity, permeability and gas-water relative permeability) is necessary for prediction of methane and water production rates in coalbed methane operations. Porosity in coal consists of matrix porosity wherein the methane is adsorbed on the coal surface and cleat (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. When the reservoir pressure is lowered, net confining pressure increases.

Previous measurements of rock properties have been made in coal cores with fluid flow perpendicular to the bedding planes. In the standard procedure for such measurements in conventional reservoir cores, fluid flow is parallel to the bedding planes and horizontal core plugs are generally used. However, because of the very low (less than 1%) cleat porosity of coal, accurate measurements cannot be made on horizontal core plugs taken from a 3.5-in. diameter coal core (due to the very low produced water volumes).

The cleat structure suggests permeability in coal should be anisotropic. The face cleat is, by definition, better developed than the butt cleat. The less well developed butt cleat is perpendicular to the face cleat. Both face and butt cleat are perpendicular to the bedding planes. Permeability should be greatest parallel to the face cleat. Vertical permeability can be almost non-existent if the cleat structure does not extend through the bedding planes. The fractured nature of coal also suggests the permeability should decrease as net confining pressure increases, closing the fractures in which fluid flow occurs. Neither the permeability anisotropy nor the dependence of permeability on confining pressure as a function of flow orientation has been previously demonstrated experimentally. Likewise, nothing has previously been reported concerning the anisotropy of relative permeability or its dependence on confining pressure.

To determine the effects of cleat orientation and confining pressure on coal rock properties (cleat porosity, permeability and relative permeability), blocks of coal were collected at the La Plata mine in the San Juan basin. The coal was taken from Seam No. 1 in the Sundance pit and is from the Fruitland formation which produces coalbed methane in the San Juan Basin. Three aligned cores (approximately 3.5-in. diameter and 4-in. long) were taken from the blocks of coal. The La Plata coal used is well cleated and cleat orientation is easily determined visually. The alignments of the cores are: (1) perpendicular to the bedding planes, (2) parallel to the bedding planes and parallel to the face cleat, and (3) parallel to the bedding planes and parallel to the butt cleat. The cores were prepared and permeabilities, cleat porosities and relative permeabilities were determined using previously reported procedures.[1] Confining pressure was varied during the testing of each of the three cores. The results are discussed below.

Absolute Permeability

Absolute permeabilities to water for the three La Plata cores with different cleat orientations are in Table 1. As noted previously,[1] absolute permeability to water in coal cores decreases with continued injection of water. The permeability results shown in Table 1 are, therefore, the highest and lowest values observed under the stated conditions. Injection pressure was approximately 370 psig with a 70 psig pressure drop across the length of each core. During the permeability measurements several diagnostic techniques were employed to determine the cause of the permeability decline and to stabilize it. These included: (1) Use of 0.2 m NaCl and 0.2 m KCl solutions rather than distilled water. In La Plata coal which has low ash content (7% on a dry basis) use of 0.2 m NaCl and 0.2 m KCl had little effect compared to distilled water. (2) Injection fluids were boiled to eliminate bacterial growth and carefully filtered. This had no effect. (3) Flow in the cores was reversed. Reversal of flow increased the permeability temporarily but did not stabilize the overall decrease. (4) Cores were removed and refaced. Refacing cores increased the permeability temporarily but did not stabilize the overall decrease. (5) Injection was stopped while confining pressure was maintained for approximately one month. In this case the permeability did not decline during the period injection was stopped, confirming that fluid flow, not continued relaxation of the coal core under confining pressure,[1] is involved in the permeability decline.

Just as in conventional rocks, there are probably a number of causes for permeability decline in coal cores, any one of which can be the dominant factor in a particular core depending on mineral content (ash content) and friability. The flow reversal results indicate fines migration plays a role in coal permeability decline. Fines may be generated in facing a coal core.

Even with the complications of permeability reduction, it is apparent in Table 1 that permeability in coal is a function of flow orientation as expected from the fractured nature (cleat system) of coal. The permeability is greatest with fluid flow parallel to the bedding planes and parallel to the face cleat orientation. Permeability is lowest perpendicular to the bedding planes. The permeability parallel to the butt cleat is about half that in the face cleat direction. La Plata coal has a well developed butt cleat compared to most coal, so this ratio cannot be extended to other coals. Previous laboratory measurements of permeability in coal cores made with flow perpendicular to the bedding planes have always been much lower than the values calculated from reservoir pressure transient analysis and those required for history matching in reservoir simulation studies. The values for permeability measurements made parallel to the face and butt cleat directions are comparable to the values calculated from reservoir pressure transient analyses and those required for history matching. Permeability measurements in coal should be made parallel to the bedding plane, just as in conventional reservoir rock.

When confining pressure is increased from 450 psig to 1,000 psig, permeability decreases by a factor of around 5 in each of the flow directions, i.e.,

$k_{1000}/k_{450} \simeq 1/5$. Such a decline in permeability is expected as the cleats (fractures) are closed with increasing confining pressure.

Cleat Porosity

Cleat porosities (mobile water porosities) measured as previously reported,[1] are also included in Table 1. The range given is the lowest and highest measurements for replicate tests. As the cleat system is closed with increasing confining pressure, the cleat porosity decreases by a factor of around 1.7, i.e., $\phi_{1000}/\phi_{450} \simeq 1/1.7$. The experimental data were analyzed as a factorial experiment with three discrete levels of flow direction and two levels of confining pressure to determine the effects of these variables on permeability and cleat porosity. Because of the decline in permeability mentioned above, the last permeability and porosity measurements at the first confining pressure were paired with permeability and porosity measurements at the new confining pressure when confining pressure was varied. Confining pressure was both increased and decreased in the course of data collection. If the data of Table 1, which are the ranges of permeability and porosity, are analyzed one obtains $k_{1000}/k_{450} \simeq 1/4.5$ and $\phi_{1000}/\phi_{450} \simeq 1/1.6$.

The decrease in permeability and porosity in La Plata coal with increasing confining pressure are in agreement with the expression of Jones[2] for fracture systems in conventional rocks:

$$\frac{\phi}{\phi_i} = \left(\frac{k}{k_i}\right)^{1/3}$$

where ϕ and k are the porosity and permeability of the fractured system at a higher confining pressure,

and ϕ_i and k_i are the porosity and permeability at the initial confining pressure.

For La Plata coal

$$\frac{1}{1.7} \simeq \left(\frac{1}{5}\right)^{1/3}$$

Warpinsky[3] has studied gas phase permeability in fractured media and has concluded that no theory is directly quantitatively applicable for gas flow in fractures under changing stress. Based on Warpinsky's findings, the expression given above for La Plata coal cannot therefore necessarily be extended to other coals. To quantify stress-related permeability, empirical measurements should be made on the coal of interest.

Gas-Water Relative Permeability

Previous unsteady-state gas-water relative permeability measurements in coal were only reproducible to within ± 5 saturation percent at $k_{rw} = k_{rg}$ for a given coal core.[1] As will be shown below, improved reproducibility was necessary to reduce uncertainty in simulation studies and to permit the determination of the effects of such variables as cleat orientation or confining pressure.

Figure 1 demonstrates the ± 5 saturation percent 95% confidence limits for unsteady-state gas-water relative permeability for a San Juan basin coal core (Core B, Reference 1) based on two replicate measurements. The solid k_{rw} and k_{rg} curves marked Base Case are for a single actual measurement. The shaded area is the 95% confidence interval. The k_{rw} and k_{rg} curves which meet at the four intersections (labeled 1 through 4 in Figure 1) were used as limits to test the sensitivity of coalbed methane simulation results to relative permeability.

The simulation work was performed using the simulator described by Seidle and Arri.[4] A single-layer reservoir with an average thickness of 60 ft was used in all cases. A permeability of 7 md with no anisotropy and a cleat porosity of 0.5% were used. In this idealized case, cleat porosity was initially water saturated, matrix porosity was fully gas saturated, and no flow boundary conditions were used.

Figure 2 presents results from the Base Case and Cases 1 and 2; i.e., the crossover point ($k_{rw} = k_{rg}$) is shifted between 35% and 45% gas saturation and the relative permeability at which $k_{rw} = k_{rg}$ is roughly 18%. The water production rate for Case 1 is slightly lower than for Case 2; the gas production rate is significantly higher for Case 1 than for Case 2. A shift in the crossover point toward Case 1 represents a more water-wet system.

Figure 3 presents results from the Base Case and Cases 3 and 4; i.e., the crossover point remains at 40% gas saturation, but $k_{rw} = k_{rg}$ is is shifted between 13% and 23%. The water production rates are essentially the same after the first 12 months; Case 3 has a significantly greater gas production rate. The results of the simulation studies indicate that prediction of gas production rates from coalbed methane is very sensitive to relative permeability and that reproducibility to within ± 5 saturation percent for measured relative permeability curves is not adequate.

Gas-water ratios during coalbed methane production indicate that relative permeability measurements at low gas saturation are necessary for prediction of gas and water rates. Therefore, the following modifications were made to the apparatus and procedure of Reference 1 to improve the reproducibility and to extend the range of useful data to lower gas saturations:

1. Prior to gas breakthrough, the total production from an unsteady-state measurement is water. However, the total (water + gas) production prior to gas breakthrough was measured as the displacement of gas by water with mass flow meters. Prior to gas breakthrough, the total flow rate in a coal relative permeability measurement was too low (approximately 5 sccm) to be measured with the required accuracy by the lowest flow meters (range 0-200 sccm) being used in the measurements of Reference 1. (The initial total flow rates in a coal relative permeability experiment are much lower than those in a

relative permeability measurement in conventional rock because of the very low absolute permeability of coal.) Since only water is produced prior to gas breakthrough, the water production data which are accurate were substituted for the total production data prior to gas breakthrough. This correction is on the order of 10 cc out of 100 cc or around 10%. After gas breakthrough, gas rates increase so that those measurements with the mass flow meters are correct.

Figure 4 contains the data of Figure 9 in Reference 1 corrected with the procedure described above. Cores A, B, and C are Fruitland coal from the San Juan Basin and are 3.5-in. diameter. Core C is La Plata coal. Core D is from the Blue Creek Seam in the Warrior Basin and is 2-in. diameter. Additional details are in Reference 1.

2. The apparatus of Reference 1 was modified (Figure 5) by adding a mass flow meter with a 0-50 sccm range. All the mass flow meters were calibrated with overlapping ranges. A ballast vessel was incorporated downstream and total flow rate was measured at the downstream pressure (i.e., the backpressure regulator was located after the ballast vessel and the mass flow meters) to eliminate flow rate fluctuations due to the backpressure regulator. These modifications eliminated the need to correct the data as above.

Figure 6 contains the results of typical replicate measurements of gas-water relative permeability in a La Plata coal core with flow parallel to the bedding planes and parallel to the face cleat. The measurements were performed after the apparatus modifications were made. The reproducibility after the modifications, based on pooled variance from numerous pairs of replicate measurements, is ± 2 saturation percent for the saturation at which $k_{rw} = k_{rg}$. This is approximately the same reproducibility observed in unsteady-state gas-water relative permeability measurements in conventional reservoir cores. The improved reproducibility reduces the uncertainty in simulation studies and permits the determination of the effects of cleat orientation and confining pressure on gas-water relative permeability in coal.

Figures 7 and 8 contain the results of gas-water relative permeability measurements performed on the La Plata cores in each of the three cleat orientations. Gas saturation in Figures 7 and 8 is based on mobile water saturation.[1] Helium was used as the injection gas, so the system is water-wet. The difference in the experimental procedure for the data sets represented in Figures 7 and 8 is the confining pressure. At each confining pressure, the same results were obtained. Within experimental error, there is no effect of cleat orientation on gas-water relative permeability in La Plata coal. The cleat structure in the La Plata coal cores employed in this study is continuous through the bedding planes. The conclusion concerning the effect of cleat orientation on relative permeability obtained on La Plata coal cannot be extended to coal with barriers to vertical flow, i.e., cleat structure staggered at bedding planes or shale barriers. Coal with staggered cleat structure or shale barriers generally has such low permeability that relative permeability tests cannot be performed in a vertical core (perpendicular to the bedding planes). From the La Plata results, however, it is safe to assume that for any coal sample with vertical permeability large enough to permit a relative permeability test to be performed and no barriers to vertical flow, representative relative permeability measurements can be performed on cores taken perpendicular to the bedding planes, as has been done in previous work.

Increasing confining pressure decreases the flow of gas (relative permeability to gas) less than it does flow of water (relative permeability to water) in all cleat directions. (Compare Figure 7 (450 psig confining pressure) with Figure 8 (1000 psig) confining pressure.) This is a significant but lesser effect than the effect of increased confining pressure on absolute water permeability. This observed effect of confining pressure on the relative permeability ratio k_{rg}/k_{rw} is predicted from percolation theory in a water-wet fracture system when the fracture aperture variance decreases.[5] It is preferable to measure relative permeabilities at reservoir confining pressure.

Conclusions

1. Reproducibility in unsteady-state gas-water relative permeability measurements in coal has been improved. The improved reproducibility reduces the uncertainty in simulation studies and permits the determination of the effects of cleat orientation and confining pressure on relative permeability in coal.

2. There is no effect of cleat orientation on gas-water relative permeability in well-cleated La Plata coal cores. Relative permeability measurements on well-cleated coal samples can be performed on vertical cores as has been done in previous work.

3. Permeability is largest in the face cleat direction. The permeability measurements parallel to the bedding planes are comparable to those calculated from reservoir pressure transient analysis and required for history matching of coalbed methane production. In general, laboratory permeability measurements made perpendicular to the bedding planes in coal are much lower than the values used in simulation studies.

4. Confining pressure (i.e., stress) has an effect on cleat porosity, permeability and relative permeability. The decreases in cleat porosity and permeability in La Plata coal with increasing confining pressure follow the expression of Jones[2] for fracture systems in conventional rocks. Increasing confining pressure decreases the flow of gas (relative permeability to gas) less than it does the flow of water (relative permeability to water). This is a minor effect.

References

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2. Jones, F. O., "A Laboratory Study of the Effects of Confining Pressure on Fracture Flow and Storage Capacity in Carbonate Rocks," JPT, (January 1975), pp. 21-27. (The exponent in Equation 6 in this reference should be 1/3, not 1/2 as printed.)

3. Warpinski, N. R., Teufel, L. W. and Graf, D. C., "Effect of Stress and Pressure on Gas Flow Through Natural Fractures," SPE Paper 22666 presented at the SPE Annual Technical Conference and Exhibition, Dallas, TX, October 6-9, 1991, *p.* Ω 105.

4. Seidle, J. P. and Arri, L. E., "Use of Conventional Reservoir Models for Coalbed Methane Simulation," CIM/SPE Paper 90-118 presented at the CIM/SPE Joint International Technical Meeting, Calgary, June 10-13, 1990, p. 118-1.

5. Mendoza, C. A., Ph.D. Thesis, in preparation, University of Waterloo.

Table 1. The Effect of Cleat Orientation and Confining Pressure on Cleat Porosity and Permeability

	Confining Pressure (psig)			
	450		1000	
Flow Direction	Absolute Water Permeability (md)	Cleat Porosity %	Absolute Water Permeability (md)	Cleat Porosity %
Perpendicular to bedding planes	0.8-0.04	0.53-0.59	0.007	0.28-0.32
Parallel to face cleat	6.0-3.0	0.37-0.39	1.7-0.6	0.19-0.27
Parallel to butt cleat	4.8-1.6	0.50	1.0-0.3	0.34-0.37

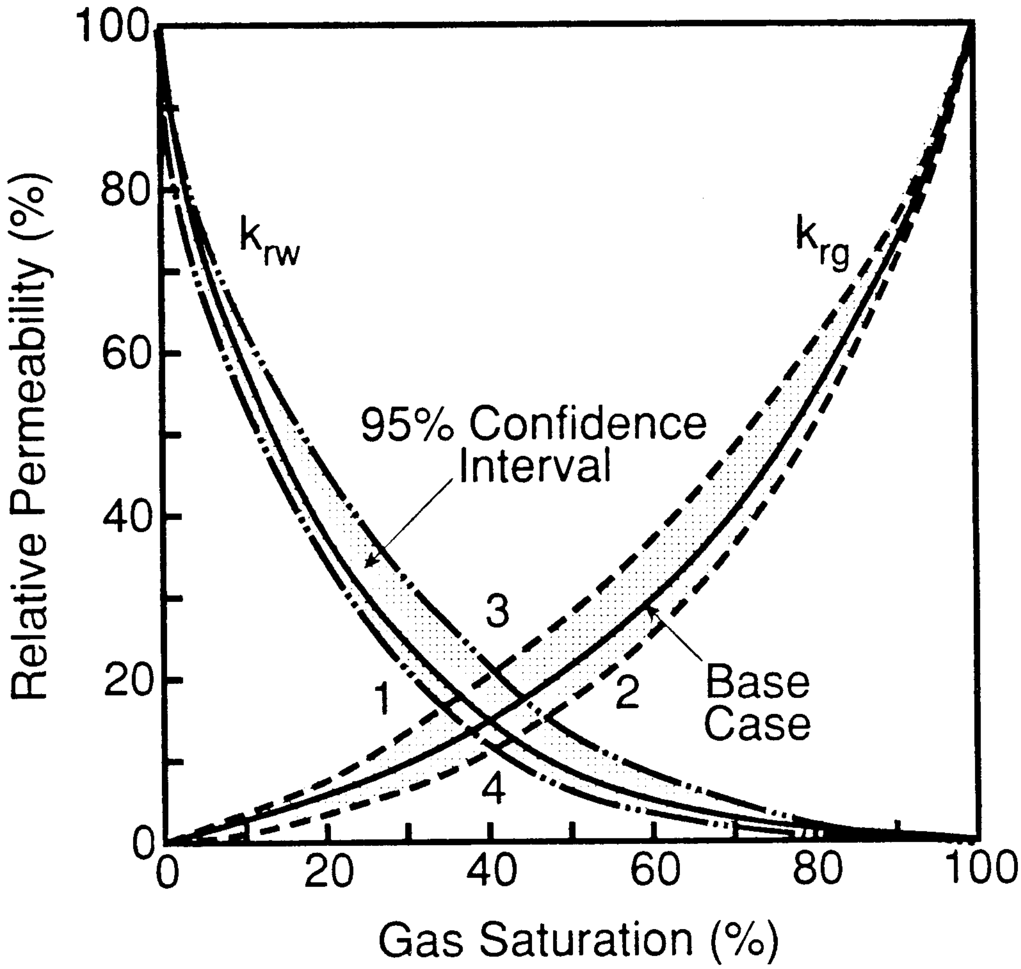

Fig. 1: Ninety-five Percent Confidence Interval for Gas-Water Relative Permeability with ±5 Saturation Percent Reproducibility at $k_{rw} = k_{rg}$. Core B in Reference 1.

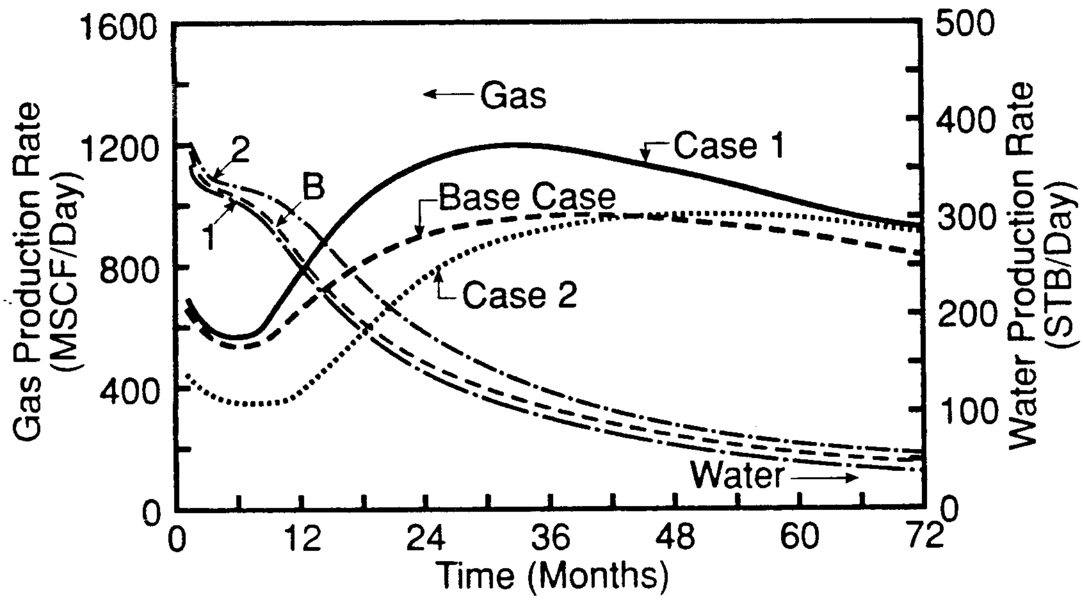

Fig. 2: The Effect of Gas-Water Relative Permeability on Coalbed Methane Computer Simulation Results. Cases 1 and 2 and Base Case from Fig. 1.

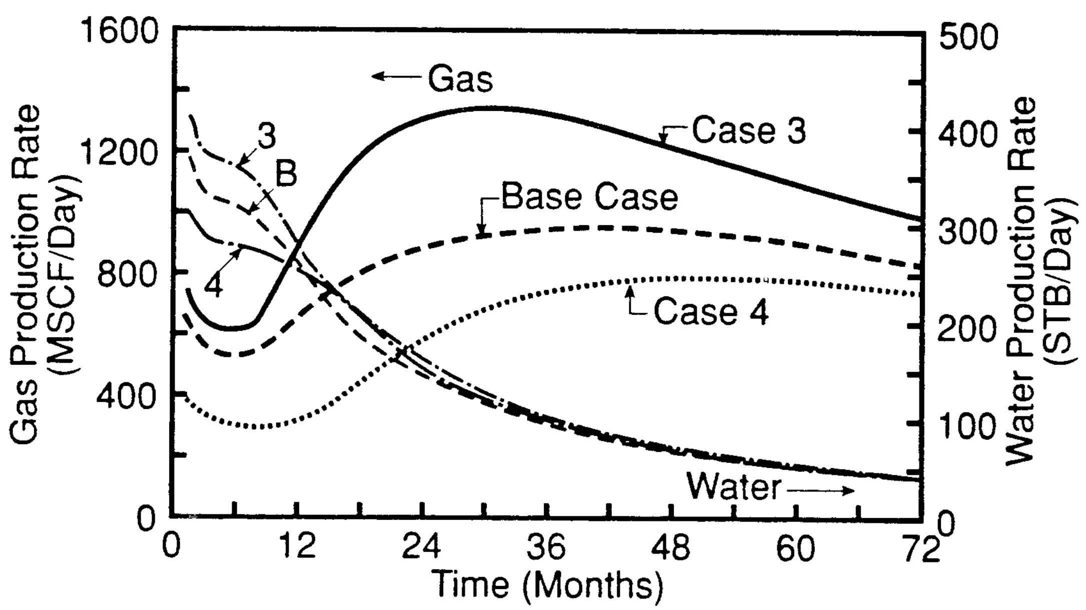

Fig. 3: The Effect of Gas-Water Relative Permeability on Coalbed Methane Computer Simulation Results. Cases 3 and 4 and Base Case from Fig. 1.

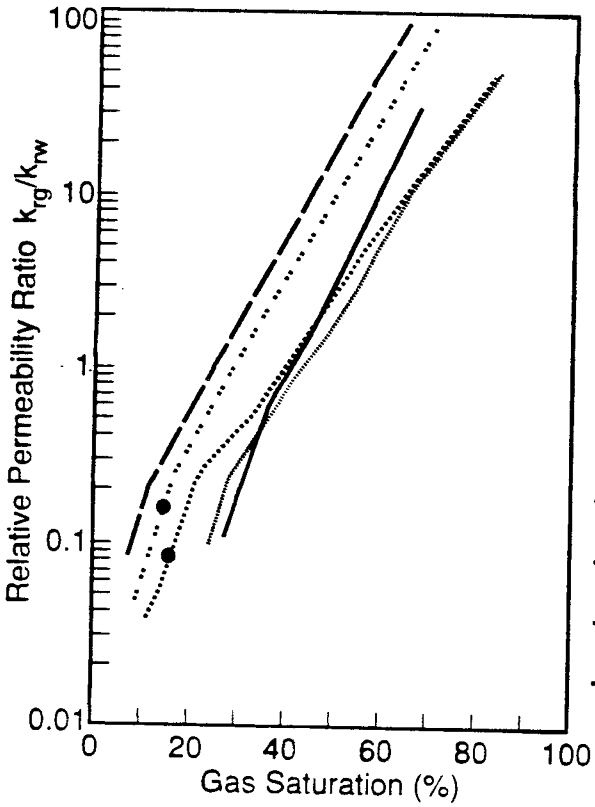

Fig. 4: Corrected Relative Permeability Ratios for Fig. 9 in Reference 1. Additional data is to the left of and below the large solid black circles.

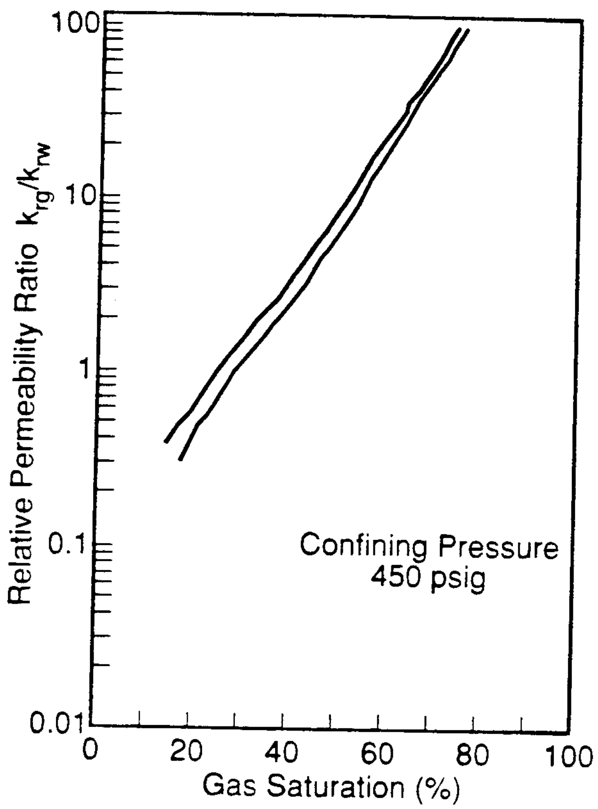

Fig. 6: Typical Replicate Relative Permeability Ratios after Apparatus Modifications.

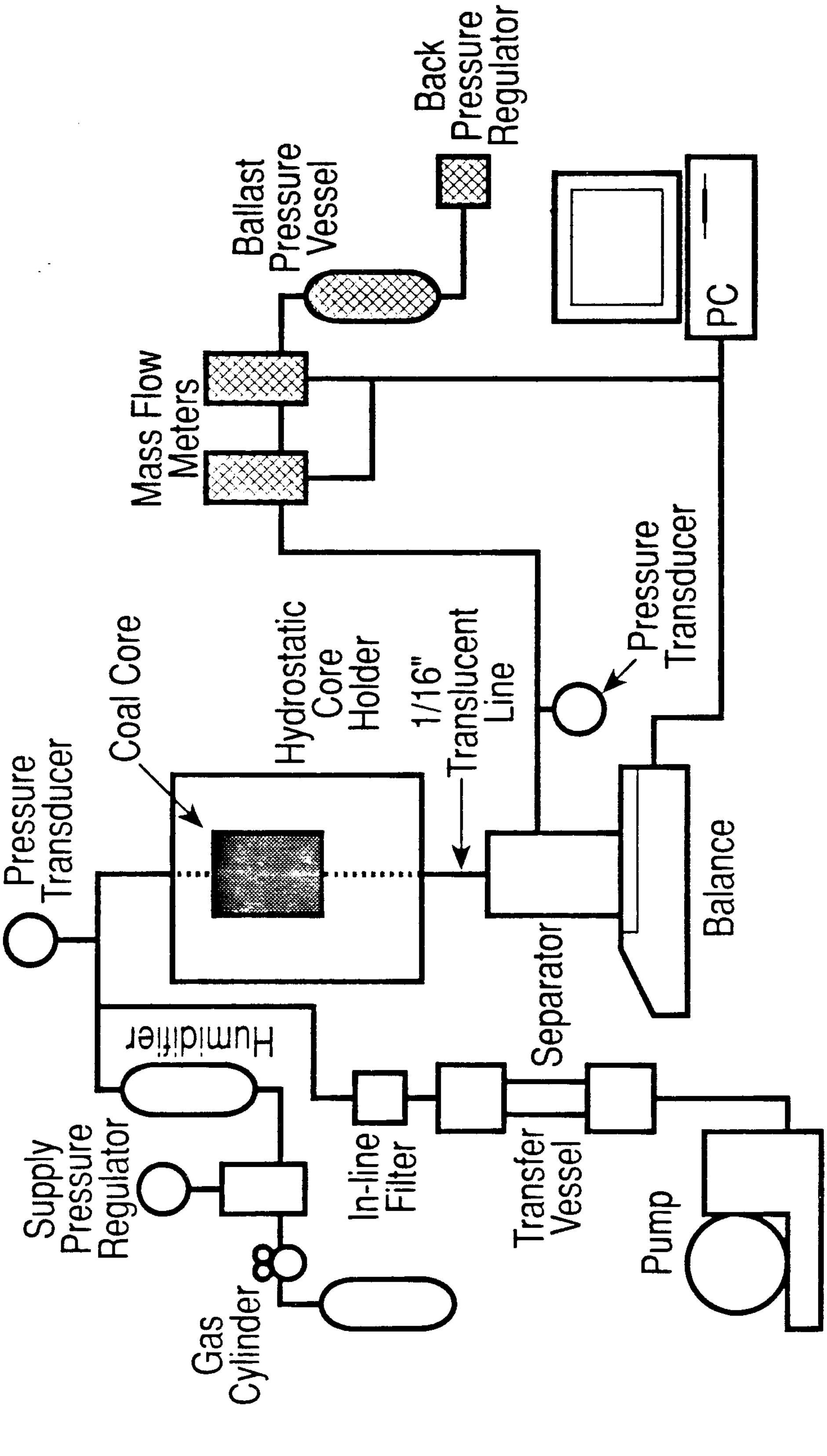

Fig. 5: Schematic Diagram of Modified Unsteady-State Gas-Water Relative Permeability Apparatus for Coal. Modifications are Cross-hatched.

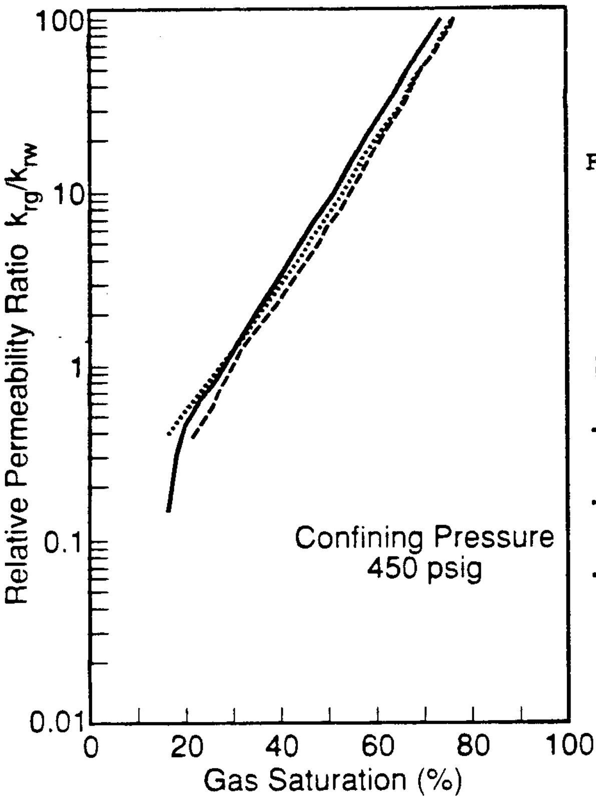

Fig. 7: Relative Permeability Ratios as a Function of Cleat Orientation. La Plata Coal with 450 psig Confining Pressure.

Flow Direction

——— Perpendicular to Bedding Planes
·········· Parallel to Face Cleat
- - - - - Parallel to Butt Cleat

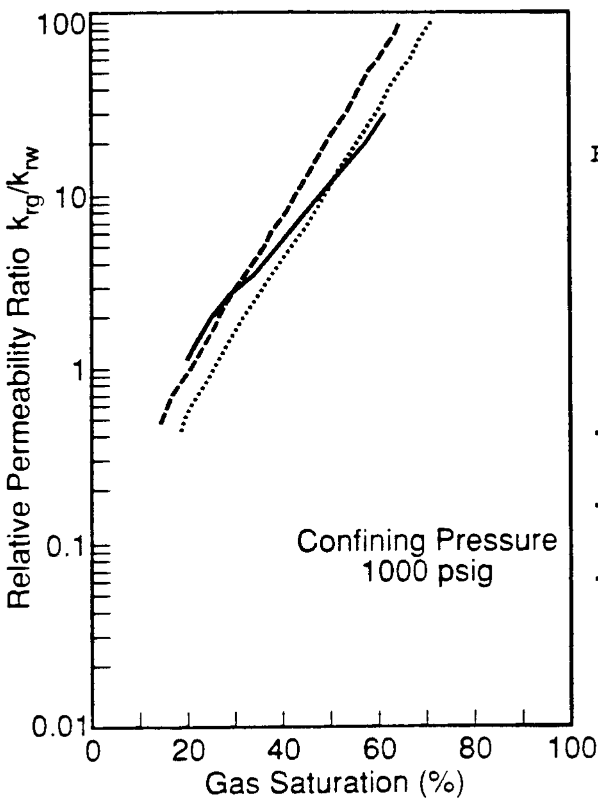

Fig. 8: Relative Permeability Ratios as a Function of Cleat Orientation. La Plata Coal with 1000 psig Confining Pressure.

Flow Direction

——— Perpendicular to Bedding Planes
·········· Parallel to Face Cleat
- - - - - Parallel to Butt Cleat