Shrinkage of coal matrix with release of gas and its impact on permeability of coal

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Adsorption/desorption isotherms were established for powdered coal samples. Gas pressure-permeability relationships for cylindrical specimens of coal, under triaxial stress conditions, were also determined. Gas pressure-volumetric strain relationships were established using strain gauges on the same specimens. The results indicate that the permeability of coal to methane increases with decreasing gas pressure, in spite of increased effective stress. The primary reason for this increase in permeability is the shrinking of the coal matrix, which is associated with desorption, thus enlarging the gas flow paths. The volume of the coal matrix shrinks by ≈0.4% when the gas pressure falls from 6.9 MPa to atmospheric pressure. The results suggest that higher flow rates can be expected as a consequence of the shrinkage, and the associated enhanced permeability, over the life of methane-producing wells in coalbeds.

(Keywords: coal; gas; permeability)

Over the last few years, tremendous efforts have been made to develop unconventional sources of energy, to supplement the domestic sources of conventional oil and gas in the United States. One such resource is coalbed methane, with gas-in-place estimated[1] at $\approx 4.0 \times 10^{12}$ ft^3. When compared with the 16×10^{12} ft^3 of natural gas annually consumed in the US, this is of great significance. Although the number of wells producing gas from coal basins in Alabama, Colorado, and New Mexico has increased dramatically, and is expected to reach 2000 by 1990, coalbed methane has remained a relatively unexploited resource. Despite success with the existing wells, uncertainties in production present barriers to effective, economic, recovery of gas[2].

One of the main problems faced during simulation and modelling of long-term gas production from coalbeds is the variation in permeability of coal over the life of the producing well. Permeability is influenced by several factors, including *in situ* stress conditions, disturbance associated with drilling, water content of the coalbed, and gas pressure. Most of these factors change continuously, making the process of gas flow difficult to model. Knowledge of conventional gas reservoir modelling is of little value in the case of coalbed methane reservoirs, due to the unique mechanism of gas storage in coalbeds and the unusual flow behaviour of gas in coal.

To study the variations in permeability and flow rates, and to explain these variations, an experimental investigation was carried out using samples from gassy coal seams in the US. This paper discusses the background that led to this study and the experimental work carried out, and presents a theory to explain the flow behaviour of methane in coalbeds.

BACKGROUND

Gas storage in coal

Gas is stored primarily by adsorption into pores and microfractures of coal. This usually accounts for 98% of the gas within a coal seam, the rest being stored as free gas[3]. *Figure 1* is a pictorial representation of the methane molecules inside a coal pore. The volume of gas adsorbed is a function of the gas pressure, and the relationship between the two is known as the adsorption isotherm. *Figure 2a* shows typical adsorption isotherms for coal and methane, and *Figure 2b* compares the adsorbed gas storage in coal with the compressed gas storage in a sandstone reservoir. The sandstone reservoir releases its gas uniformly, as indicated by the straight line. In contrast, gas in the coal reservoir is released in a highly nonlinear manner and the major fraction of adsorbed gas is released at low pressures. To recover a large percentage of gas in coalbeds, the reservoir pressure must be reduced significantly. Since most coals are water saturated, this is usually done by removal of water over long periods of time.

Mechanism of gas flow in coalbeds

Once the pressure in the coalbed is reduced, coal becomes less capable of retaining methane in adsorbed

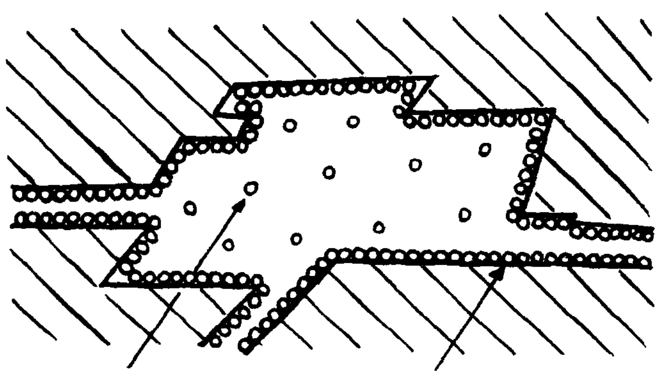

Figure 1 Pictorial representation of methane molecules inside a coal pore[4]

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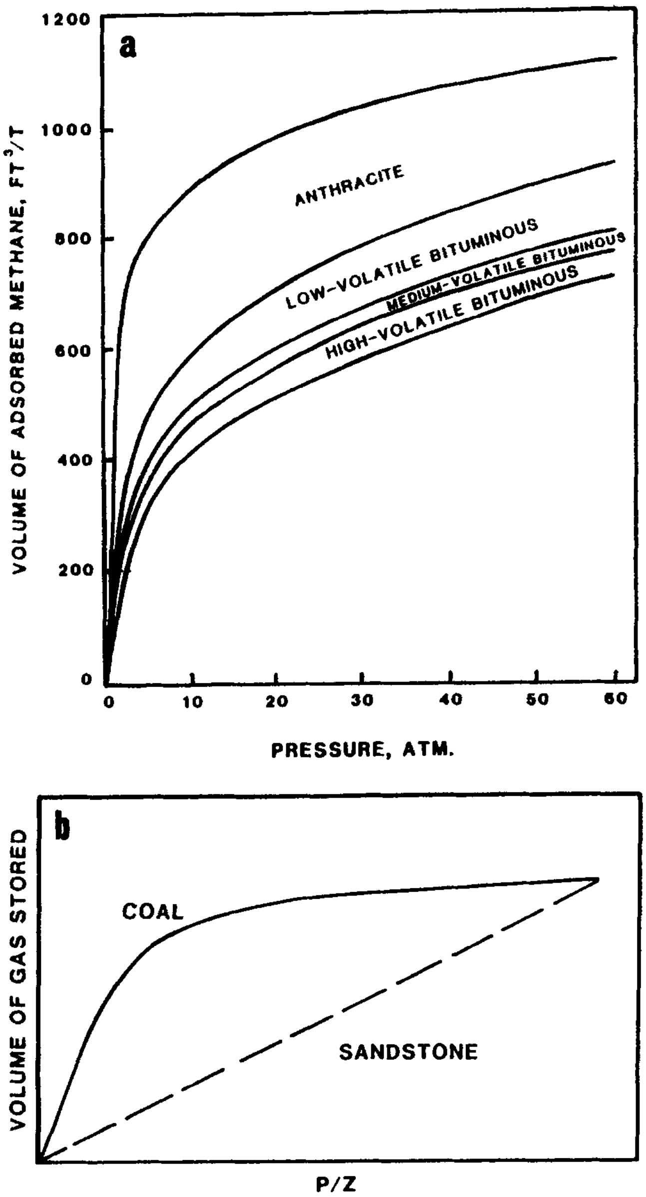

Figure 2 a, Variation of methane adsorption isotherm with coal rank at 0°C[5]; b, comparison of gas storage for coal with an equivalent capacity sandstone[5]

form. The gas molecules start detaching themselves from the surface of the pores and microfractures and the process of desorption is initiated, making more gas available for flow towards the well. The rate of flow is primarily dependent on the diffusion characteristics and the permeability of coal. *Figure 3* shows the three distinct processes involved in the transport of coalbed methane, starting with desorption from the internal coal surfaces. Gas then diffuses through the matrix and micropores towards the cleats/fractures. Once in the natural fracture network, the flow of gas is eased significantly and follows Darcy's Law[7].

Most numerical and computer models developed recently are based on these physical phenomena. The most commonly used model is shown in *Figure 4*, where *S* is the fracture spacing. A coalbed is shown to be made up of small blocks, or units, separated by fractures. The spacing of the fractures determines how far the gas has to diffuse before reaching the fracture, and the dimensions

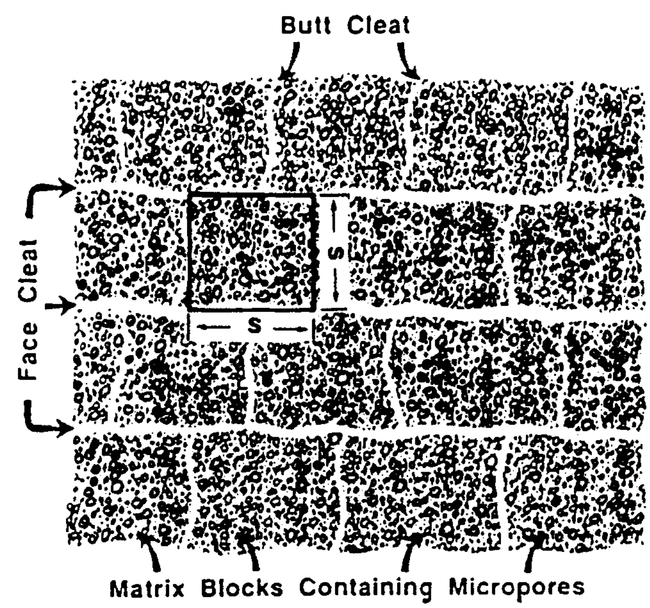

Figure 4 Illustration of coal fracture system and diffusion[8]

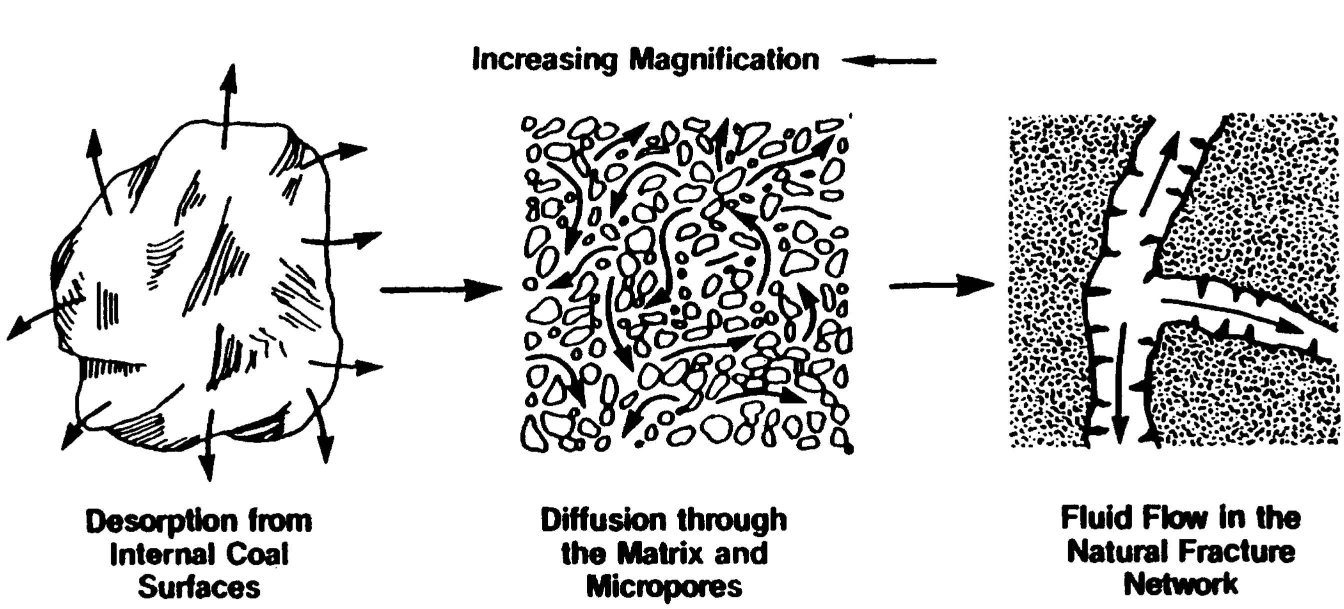

Figure 3 Processes involved in the transport of coalbed methane gas[6]

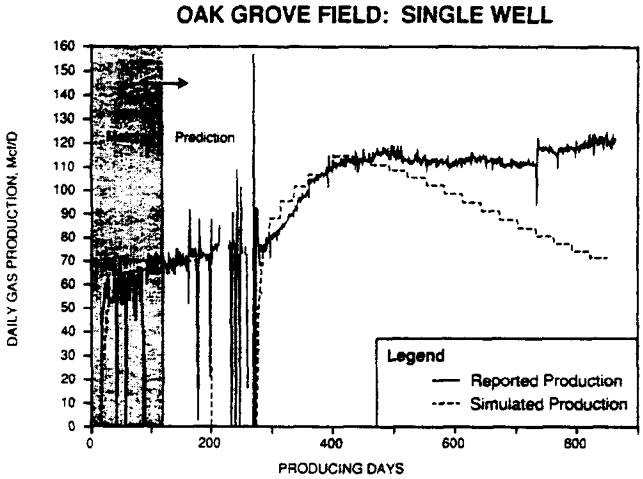

Figure 5 Reported and simulated production of methane[12]

of the fractures decide the quantity of gas that can flow through.

Variation in permeability

Two distinct consequences are associated with reduction in pressure. The first is the release of gas, and the second is an increase in effective stress, defined as the difference between external stress and gas pressure. This increase in effective stress causes a decrease in the permeability of coal due to closure of flow paths at high stresses[9–11]. The reduction in gas pressure, and the resulting increase in effective stress, associated with flow of gas, should therefore decrease the permeability and result in lower flow rates. However, flow rates in wells are frequently observed to increase with time, indicating an increase in permeability, and often remain steady for long periods of time suggesting an effect counteracting this increase in effective stress. An example of such a situation is shown in *Figure 5*. These variations in permeability cannot be explained using the conventional oil and gas approaches, and are attributed to the desorption phenomenon, unique to the coal/methane system.

Limited research in Australia[3] indicates that desorption of methane results in shrinkage of the coal matrix. This shrinkage widens the fracture openings that are primarily responsible for gas flow in coalbed methane reservoirs, and thus increases the permeability. This increase due to shrinkage is, in fact, more than the decrease in permeability due to increased effective stress, thus resulting in an overall increase in permeability.

To investigate the concept that desorption of gas results in increased permeability, an experimental investigation was carried out, involving measurement of the permeability of coal samples and monitoring of the volume of the coal matrix associated with desorption.

EXPERIMENTAL

Adsorption characteristics

Prior to the experiments involving measurement of permeability and monitoring of the volume of the coal matrix, adsorption/desorption experiments were carried out. They were important to enable the flow of gas due to free gas alone to be distinguished from the flow due to free and desorbing gas. Using the indirect method of gas expansion, an adsorption isotherm was established for the coal sample. The procedure is described in detail in a previous publication[13]. *Figure 6* shows the adsorption isotherm obtained for one sample along with the quantity present as free gas. The graph indicates that the quantity of adsorbed gas is still rising at 6.9 MPa. However, the quantity adsorbed does not increase significantly after $\approx$4.14 MPa. For this particular coal, significant flow of methane can therefore be expected to start only after the pressure drops below 4.14 MPa, and the major part of the gas can be recovered only if the pressure drops below 2.76 MPa. Some flow of gas, of course, occurs during the dewatering phase.

Permeability experiments

The main objective of this experimental study was to establish a relationship between desorption and permeability. Desorption takes place when the gas pressure is reduced, so all the experiments concentrated on studying the flow behaviour with changes in gas pressure, increasing pressure being associated with adsorption and decreasing pressure with desorption.

Permeability experiments were carried out using cylindrical specimens of coal, 3.81 cm in diameter, and $\approx$7.62 cm in length. Coal samples for the major part of the experimental work, including measurement of the adsorption characteristics, were obtained from a gassy coal seam in the Piceance basin in Colorado (Mid Continent Resources, Carbondale). Big chunks of coal were wrapped in plastic to prevent oxidation and shipped to the specimen preparation laboratory. A coring machine with a set of guides was used to prepare the cores. After coring, the specimen ends were ground parallel. The specimens were then dried and stored in a desiccator. Proximate analysis of the coal samples indicated the following composition: moisture, 0.6%; volatile matter, 23.7%; fixed carbon, 71.2%; ash, 5.1%.

The permeability experiments were carried out with the specimen stressed triaxially to simulate the *in situ* conditions. It was therefore necessary to design an experimental rig that permitted simultaneous control and measurement of applied stress, applied gas pressure, and gas flow rate through the specimen. The set-up designed consisted of a triaxial cell, modified to provide gas inlet and exit ports through the upper and lower platens. The cell was connected to a hydraulic pump and gauge to apply the confining stress. A compression testing machine

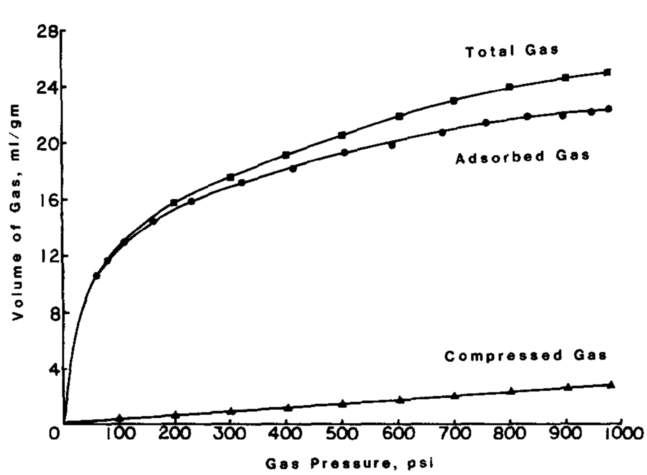

Figure 6 Adsorbed and free gas components of the total coalbed gas content (dry sample, moisture free gas)

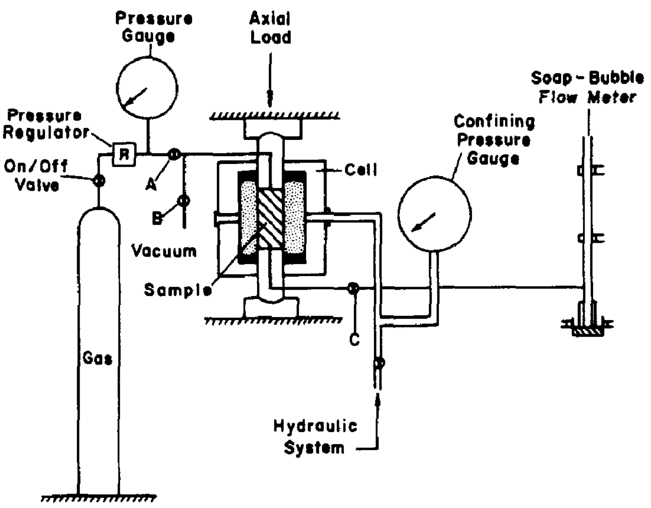

Figure 7 Schematic diagram of apparatus for testing coal permeability

was used to apply the axial load, and soap bubble gas flowmeters were used to measure the gas flow rate. Gas was supplied via a regulator and pressure gauge to the top of the cell, and was led away from the lower end of the specimen to the flowmeter. The experimental set-up is shown in *Figure 7*.

The specimen to be tested was inserted into the cell, and steel perforated discs (to distribute and collect the gas) were fitted to the flat ends of the specimen. Platens were then inserted into the ends of the cell. The upper platen was connected to the gas cylinder and the lower one to the flowmeter. The entire cell assembly was placed in the centre of the testing machine. Both confining and axial stresses were then increased simultaneously until the desired level for the particular experiment was reached. The applied hydrostatic stress was kept constant for the entire experiment. Gas pressure was then increased gradually until the flow rate at the outlet end of the specimen became measurable. This happened at different gas pressures, depending on the stress conditions for a particular experiment. Once the flow of gas started, flow rate was measured continuously until three consecutive measurements were close. Once this was achieved, gas pressure at the inlet was increased by 0.69 MPa and the procedure was repeated. After reaching 6.9 MPa, the gas pressure was decreased in similar steps. The experiment was continued until the flowrate became too low to be measured.

Shrinkage and swelling experiments

The volumetric changes in the coal matrix, associated with changes in gas pressure, were measured independently of the permeability measurements. Determination of permeability involved maintaining a pressure gradient across the specimen, resulting in a change in the volume of the pores, fractures, and microcracks in the specimen. The measured volumetric change would therefore not only be due to a change in the volume of the coal matrix, but also to the volumetric change of the void space. In fact, the latter would be the major component of the total volumetric change. It was, therefore, necessary to measure the volumetric changes without a pressure gradient, i.e. with equal pressure around the specimen on all sides. In the absence of a pressure difference between the pore pressure and the outside pressure, the volume of the voids in the coal specimen would remain unchanged. Measured volumetric change would then be due to changes in the volume of the coal matrix alone.

Using cylindrical specimens identical to the ones used for permeability experiments, and following the standard procedure suggested by the International Society of Rock Mechanics (ISRM), four strain gauges were used on the specimen surface – one each for axial and radial strains, 180° apart. The strain gauge wires were passed between two rubber O-rings, with the space in between completely sealed with rubber cement. The specimen was then placed in the sample container, the wires were connected to a strain indicator and the container was closed. The set-up is shown in *Figure 8*. The zero readings were recorded and the specimen was evacuated for several hours. Using helium, the gas pressure was increased to 0.69 MPa. After the readings on the strain indicator had stabilized, they were recorded. The procedure was repeated for pressure increments of 0.69 MPa until the pressure reached 6.9 MPa. Gas pressure was then decreased in similar steps. At the end of this part of the experiment, the specimen was evacuated and the entire procedure was repeated using methane. After each pressure change the apparatus was left for 8–10 h, since desorption is an extremely slow process and it took a long time for the reading on the strain indicator to stabilize.

RESULTS AND DISCUSSION

Permeability variations

Using the measured flow rates of the permeability experiments, the permeability of the coal sample was calculated using Darcy's Law for steady state isothermal flow of fluids through porous media:

$$k=\frac{Q_j \mu \Delta L P_j}{A \Delta P P_m}$$

where k is permeability of the media (m^2); μ is viscosity of the fluid ($Ns\ m^{-2}$); A is area of cross-section of flow (m^2); $\Delta P/\Delta L$ is pressure gradient ($N\ m^{-2}\ m^{-1}$)); Q_j is volumetric flow rate at the outlet ($m^3\ s^{-1}$); P_m is mean gas pressure ($N\ m^{-2}$)$=(P_i+P_j)/2$; P_i is inlet gas pressure ($N\ m^{-2}$); and P_j is outlet gas pressure ($N\ m^{-2}$).

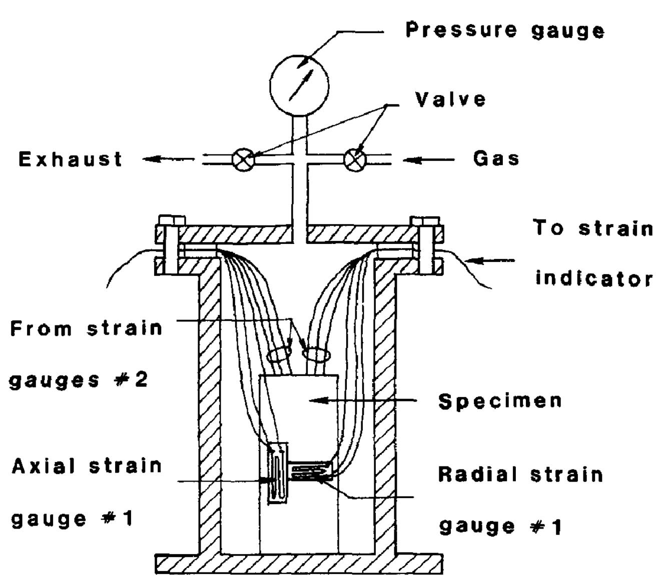

Figure 8 Apparatus to monitor volumetric changes in coal matrix, with variation in gas pressure

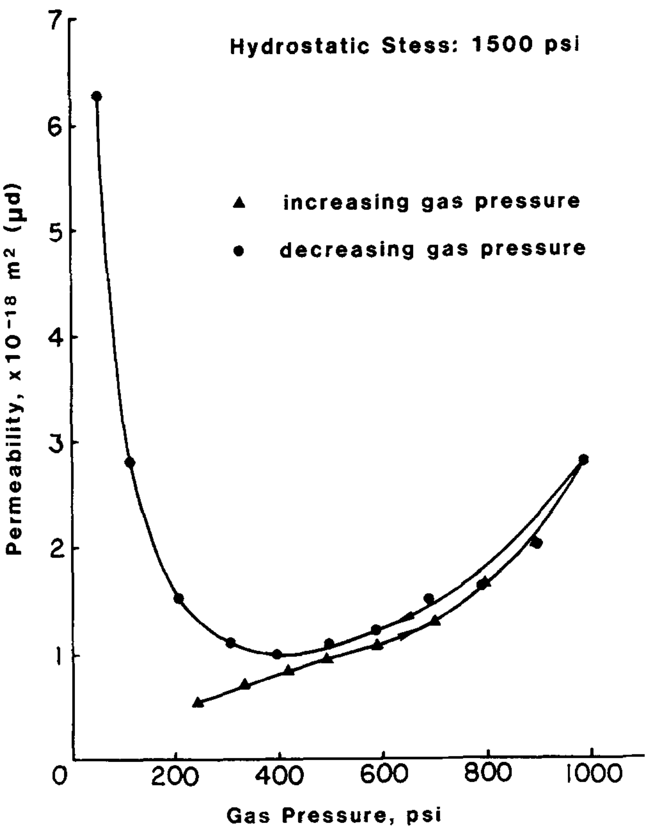

Figure 9 Variation in permeability of coal to methane for one cycle of increasing and decreasing gas pressure (sample from the Piceance basin)

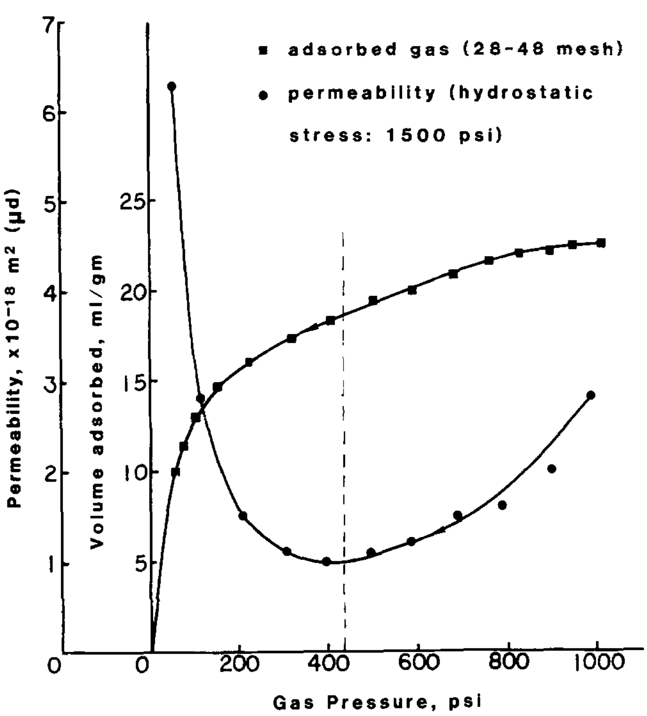

Figure 10 Variation in adsorbed gas and permeability of coal to methane (sample from the Piceance basin)

A complete gas pressure-permeability relationship was thus established. *Figure 9* shows the results for one experiment carried out at 11.72 MPa. For the purposes of this study, only the decreasing gas pressure part of the experiment was important since this is accompanied by desorption, which is significant below 4.14 MPa. Starting at 6.9 MPa, the permeability first decreased with decreasing gas pressure. However, at $\approx$3.1 MPa, the permeability started increasing, and continued to rise sharply until the pressure dropped to 0.34 MPa and the experiment was discontinued. To demonstrate the relationship between desorption and permeability, *Figure 10* shows the variation in permeability for decreasing gas pressure, along with the desorption isotherm. It clearly indicates that once significant desorption starts, the permeability starts increasing.

To further confirm that the observed increase in permeability was due to the desorption characteristics of coal, and not due to a change in the mechanical structure of the specimen as a result of high gas pressure, another experiment was carried out using helium, which is known to be almost non-adsorbing. The results are shown in *Figure 11*. The permeability of coal to helium decreased continuously with reduction in gas pressure, suggesting that the observed increase in permeability of coal to methane is, in fact, due to the desorption process.

Variation in volume of coal matrix

The average of the two measured axial strains was taken as the nett strain in the axial direction. This was repeated for the radial strain. Volumetric changes were thus calculated for each pressure level. *Figure 12* shows the changes in volumetric strain ($\Delta V/V$) with increasing

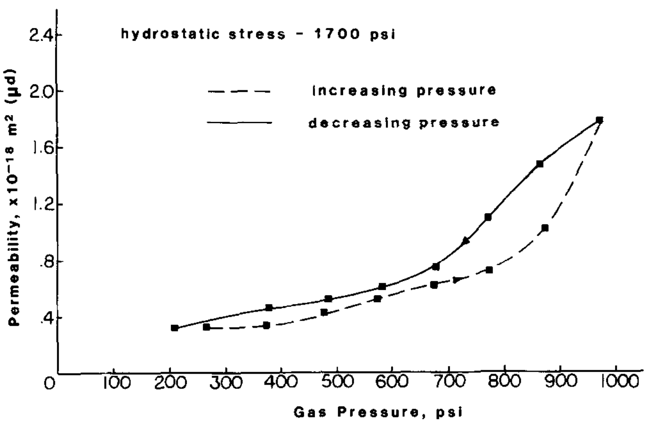

Figure 11 Variation in coal permeability to helium with changes in gas pressure (sample from the Black Warrior basin)

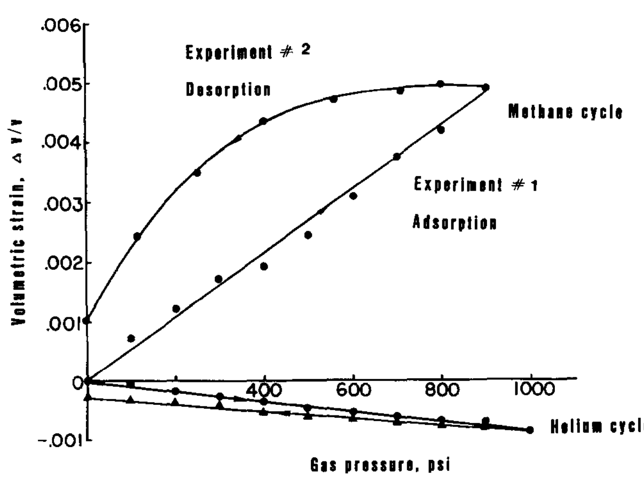

Figure 12 Volumetric strain of coal matrix for two cycles; helium and methane (sample from the Piceance basin)

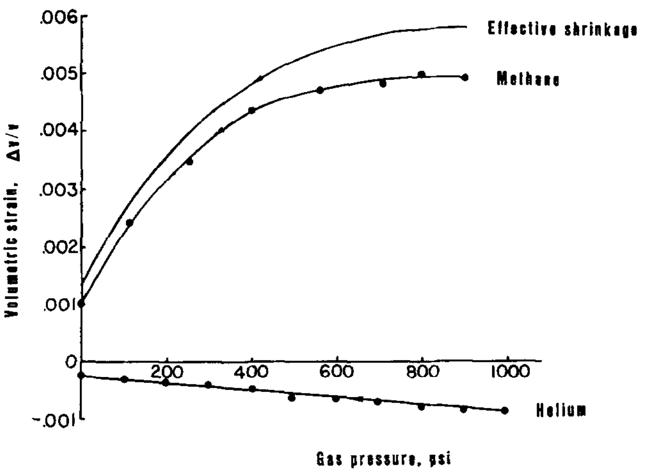

Figure 13 Volumetric strain of coal matrix for decreasing gas pressure and the effective shrinkage due to desorption of methane (sample from the Piceance basin)

and decreasing gas pressure for helium and methane. For helium, the volume of coal matrix decreased with increasing gas pressure. At 6.9 MPa, the volume was reduced by 0.087%. Compressibility of the coal matrix is, therefore, 1.26×10^{-10} per Pa. When the pressure was decreased, the volume did not go back to its original value. In fact, there was a nett decrease in the specimen volume of 0.026%. This can be explained by the fact that coal is not perfectly elastic. When the experiment was repeated using methane, the volume increased linearly with pressure. At 6.9 MPa, the volume of coal matrix increased by $\approx 0.5\%$. This is a clear indication of swelling of the coal matrix, associated with adsorption. When the pressure was reduced, the decrease in the matrix volume was nonlinear. At atmospheric pressure, the volume of the specimen remained 0.1% higher than its original value. Although this could be permanent, it might also be due to the fact that more time is needed for complete desorption. Besides, in nature 100% of the adsorbed gas is never released, thereby leaving a residual gas content.

Figure 13 shows the volumetric strains for decreasing gas pressure only. For helium, the non-absorbing gas, the volume increases linearly. With methane, the volume decreases continuously but nonlinearly. In fact, there is a strong similarity between the shape of this curve and that of a desorption isotherm for the same coal sample. To obtain the effect of desorption alone, the volumetric strain with helium was subtracted from the volumetric strain with methane. The uppermost curve in *Figure 13*, therefore, represents the effect of desorption on the volume of the coal matrix.

CONCLUSIONS

Permeability of coal to a gas is found to decrease with decreasing gas pressure. However, if the gas is an adsorbing gas, the permeability starts increasing once the pressure falls below the point at which significant desorption begins (4.14 MPa). The increase in permeability below this pressure is due to the adsorptivity of methane and not to any change in the internal structure of solid coal. This suggests that the permeability of coalbed methane reservoirs might actually go up significantly over the life of producing wells.

The increase in permeability of coal below the pressure at which significant desorption begins is due to shrinkage of the coal matrix. The blocks of coal between the fractures shrink inwards due to desorption of methane, thus enlarging the fracture width and resulting in higher permeability. The effect of this shrinkage is higher than the counter effect of reduction in permeability due to increased effective stress conditions in a coalbed with producing wells.

Based on the above conclusions, there may be many cases of 'marginally' economical coalbed methane reserves that might, in fact, be economical. Although the flow rates will probably be low initially, results of this study suggest that they might increase significantly later on. This suggests that the quantity of recoverable methane from coalbeds can be much higher than is estimated today.

Based on the work described in this paper, it is felt that the following aspects of the gas flow characteristics of coal should be investigated further:

1. swelling and shrinkage of coal matrix under stressed conditions;
2. effect of the presence of a borehole, by using a large specimen with a hole drilled in the centre;
3. the effect of shrinkage of the coal matrix should be incorporated in the general mathematical models developed to predict permeability and flow rates.

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