Reservoir Engineering in Coal Seams: Part 1—The Physical Process of Gas Storage and Movement in Coal Seams

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Summary. This is the first of two papers concerning the movement of gas in coal seams. It deals directly with the physical behavior of the coal seam as a reservoir. Coal seams show considerable differences in behavior from normal porous gas reservoirs in both the mode of gas storage and permeability characteristics. Most of the storage of gas in coal is by sorption into the coal structure, while the coal permeability is cleat- (fracture-) or joint-controlled and may vary over a wide range during production. This permeability fluctuation is not solely a phase relative permeability effect, but is rather a result of the opposing effects of effective stress increase with fluid pressure reduction and shrinkage of the coal. Reducing fluid pressure tends to close the cleats, reducing permeability, while shrinkage tends to open them.

Introduction

The two papers in this series evolved out of 3½ years of work (1979-82) on the problems of outbursting in Australian underground coal mines. This phenomenon involves the expulsion of gas and coal from the working face with resultant danger to the mining crew. Because energy release studies showed the outbursts to be primarily gas-driven,[1] efforts concentrated on studying gas drainage to alleviate the problem. Because underground mining methods were being used, most of the experimental work was conducted horizontally in-seam rather than from surface-drilled holes.

The mines studied are situated in the Bowen basin area, which extends from central to north Queensland, Australia. The seams with high gas contents are Permian age (260 million years) and bituminous, with rank determined by vitrinite reflectance lying between 1.00 and 1.30. The working depths were typically 380 m [1,247 ft] for Leichhardt Colliery, Blackwater; 135 m [443 ft] for Moura No. 4 mine, Moura; and 250 to 350 m [820 to 1,148 ft] for Bowen No. 2 Colliery, Collinsville. The first two mines contained a seam gas consisting predominantly of methane, while the Bowen No. 2 seam gas was mostly CO_2 of igneous origin.[2] In all three mines, seam thickness was about 6 m [20 ft], with seam slope lying between horizontal and 10° [0.17 rad] above horizontal.

Observations of flow and pressure variations in the seam caused by drainage into boreholes or mine openings showed that conventional oil and gas analysis approaches to describe the reservoir were inappropriate, particularly with respect to the apparent large increases in permeability with drainage. Attempts at simulation with a conventional simulator incorporating phase relative permeability effects could not explain large flow increases measured during drainage. Conversely, some Japanese coal mines[3] showed the opposite effect with apparently "self-sealing" coals.

The theory presented in this paper helps to explain the variations of permeability in coal associated with drainage.

Gas Storage in Coal

Gas is stored primarily by sorption into the coal. This typically accounts for 98% of the gas within a coal seam, depending on the pressure at which the gas is sorbed. In addition, gas is stored in the pore or cleat space either free or in solution. As Fig. 1, a typical sorption isotherm, shows, the amount of gas sorbed per unit increase in pressure decreases with increasing sorption pressure. Because gas drainage is often conducted under vacuum, the sorption isotherm has been extended below atmospheric pressure. Such tests for sorption may be conducted volumetrically[4] or indirectly by weighing pressurized coal samples at a measured equilibrium pressure.[5]

Because seams are often water-saturated, in some cases it is possible that the water pressure exceeds the pressure at which all gas becomes sorbed into coal solids or into solution gas. This is the coal-seam equivalent of the bubble-point of an oil/gas system and is referred to in this paper as the equivalent sorption pressure.

Darcy Flow and Diffusional Movement

A number of references indicate that the movement of gas in coal is caused by Darcy flow down a pressure gradient or diffusion along a concentration gradient.[6,7] The literature provides no clear answers as to which type of behavior is taking place or which type of transport governs the rate of gas production. One concept is that diffusive flow from the solids between cleats and Darcy flow along the cleat structure take place. This view, however, is not

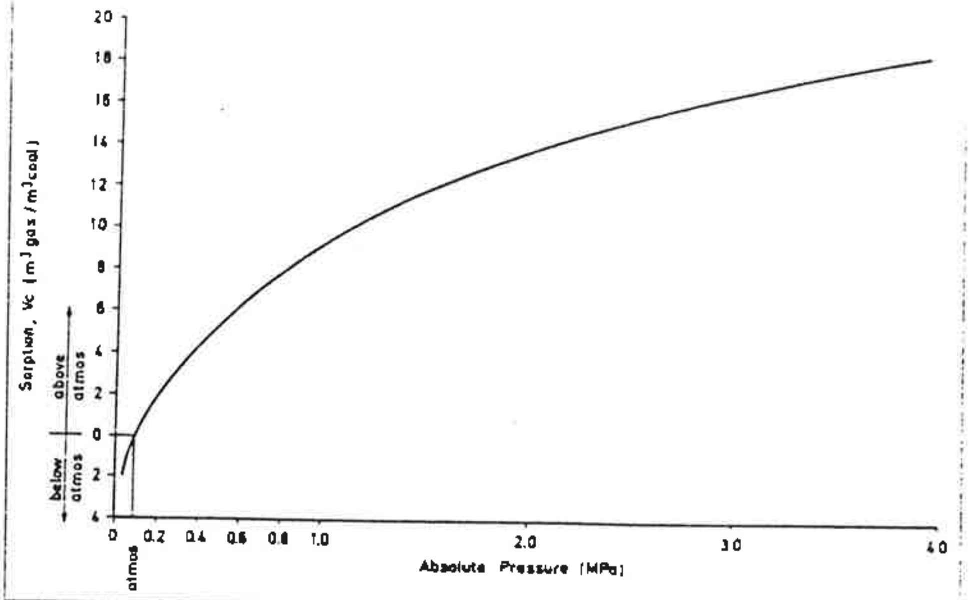

Fig. 1—Example of sorption isotherm. Gemini seam, Leichhardt Colliery, isotherm at 33.5°C, gas mixture of 95% CH_4 and 5% CO_2.

universal: Hemela* stated that tests on core showed diffusive behavior, while Tabor *et al.*[8] measured core permeability changes with different saturations, suggesting Darcy behavior, and Somerton *et al.*[9] measured Darcy behavior.

Observation of Australian coals indicates that the most important mode of fluid transport is Darcy flow in the cleats. The reasons for this are the close spacing of the cleats (typically 20 to 150 mm [0.8 to 5.9 in.]), the fact that most flow was measured as occurring along the cleats, the generally low bulk permeability of the coal (1.5 md), and the ready desorption of core in gas-content tests. The last involves taking coal core from borehole, placing it in a container, and measuring the gas evolved as described.[10] Such core desorbed relatively quickly without a residual gas content. Such a residual gas content may be released from some U.S. coals only if the coal core is ground. The days or weeks taken for desorption of core drilled to approximately the same diameter as the cleat spacing is a short time interval compared with the months or years necessary for a coal block between boreholes to degas, which supports the hypothesis that Darcy flow is the rate-governing part of the drainage process for Australian coals. Other coal seams with a less fractured structure and with slower desorption from solid may show a rate that is controlled by diffusive movement. Because some of the blocky coals tend to be more porous in nature, however, the flow may shift back to being Darcian with gas movement through the pore structure, as in a more conventional reservoir.

As described in Part 2 of this paper, the permeability can be strongly directional-controlled by predominant cleat sets. This also lends weight to the concept that Darcian flow is of prime importance in the movement of gas within the coal.

Taking quantitative account of diffusive movement within a seam is difficult because the structure of the seam could be considered to approximate a series of solid blocks between cleats. Because cleat spacing varies over a wide range—from a few millimeters to tens of meters—and the nature of the cleats varies significantly, it is virtually impossible to assign a mean cleat spacing and permeability into which the solid blocks could be considered to diffuse.

Variations in Coal Permeability

The permeability of the cleat structure within the coal may vary in two basic ways. The first is by phase relative permeability effects, whereby the degree of saturation will affect the gas and water relative permeabilities of the reservoir. This effect is well-known in the oil and gas industry. The second and probably more important way by which the permeability may vary is by a change in the effective stress within the seams. The effective stress is the total stress minus the seam fluid pressure. The effective stress tends to close the cleats and to reduce permeability within the coal. Although not proven conclusively by field and laboratory tests, it is very likely that the permeability is related particularly to the effective normal stress across the cleats because these appear to conduct most seam fluids. The effective normal stress referred to is the total stress normal to the cleat minus the fluid pressure within the cleat. If this is the case, then permeability variations brought about by variations in fluid pressures will be anisotropic, depending on the nature, frequency, and direction of the cleats. Such opening and closing of the cleats is also likely to change the phase relative permeabilities and capillary pressures within the coal.

The importance of effective stress is emphasized in this paper because of its large range (caused by seam drainage) compared with total stress and the large variations in permeability that may be brought about by changes in effective stress.

Relation Between Effective Stress and Permeability. The effect of such a variation in permeability of coal core with confining stress was presented by Somerton *et al.*[9]

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*Personal communication, M.L. Hemela, Broken Hill Proprietary Co. Ltd., Oil and Gas Div., Melbourne, Australia, May 12, 1982.

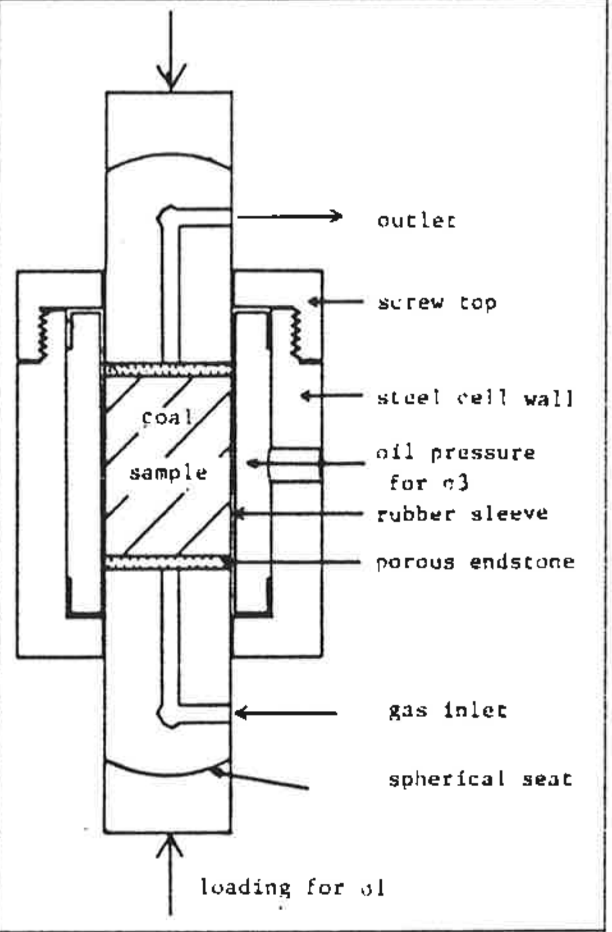

Fig. 2—Test apparatus based on Hoek cell used to carry out coal core permeability tests under stress.

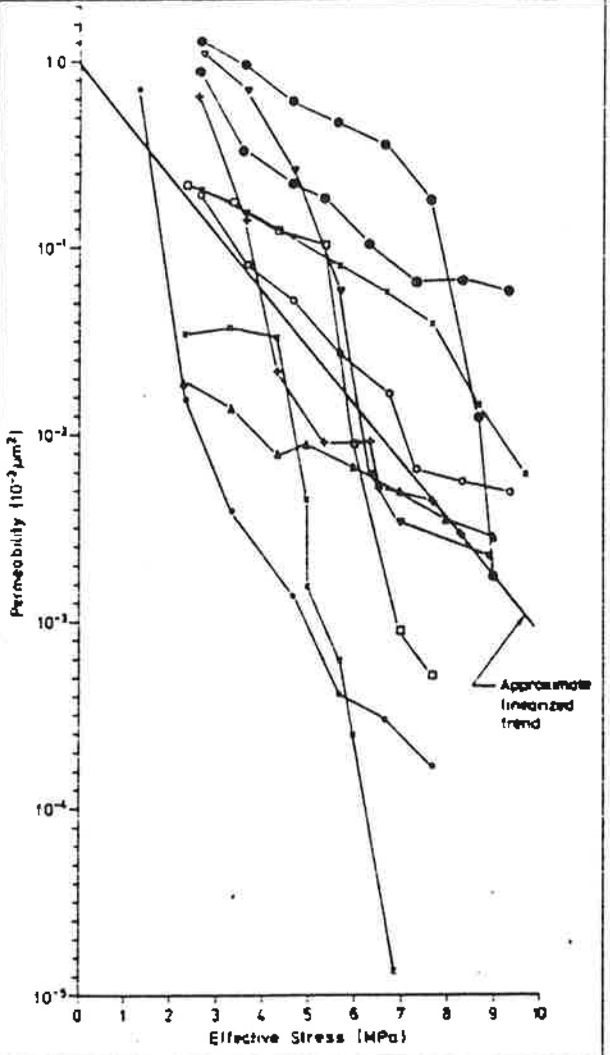

Fig. 3—Permeability vs. effective stress using CH_4 for core samples taken from the Gemini seam, Leichhardt Colliery.

Work at the Australian Coal Industry Research Laboratories confirmed their findings and showed that the relationship existing between effective stress and permeability for core taken from Leichhardt Colliery is approximately as shown in Eq. 1.

$$k = 1.013 \times 10^{-0.31\sigma}, \quad \ldots\ldots\ldots\ldots (1)$$

where k is the dry permeability in md and σ is the effective triaxial confining stress in MPa. This suggests a 10-fold reduction in permeability with a 3-MPa [435-psi] increase in effective confining stress.

Note that the term "effective triaxial confining stress" is used here rather than "effective normal stress across cleats." The reason is that the core was tested for permeability in a triaxial Hoek cell,[11] and specific cleats generally could not be isolated within the 50-mm [2-in.]-diameter cores. In addition, it was impossible to identify how the gas traveled through the specimen. Fig. 2 shows the test apparatus, and Fig. 3 shows test results from which this relation was established. The test procedure involved confining a core sample under a number of isotropic stress levels in the cell and passing methane through the sample at a steady pressure until the flow came to equilibrium. Because gas pressure varied across the specimen, the average of the two end gas pressures was used in the calculation of the effective stress. Eq. 2 was used to calculate core permeability.

$$k = (1.013 \times 10^{13}) \frac{2qp_o L\mu}{A(p_i^2 - p_o^2)}. \quad \ldots\ldots\ldots\ldots (2)$$

As can be seen in Fig. 3, different core samples gave widely differing permeabilities. This is normal for coal samples taken from different plies in the seam and emphasizes the need for field testing that includes the whole seam.

Three factors influence the effective stress: initial stress, fluid pressure changes, and the shrinkage/expansion characteristic of the coal matrix, which is related to the equivalent sorption pressure in the seam.

Initial Stress in Seam. The initial stress in the seam is difficult to estimate because it is directional and not easily measured from surface or underground because of the weak and jointed nature of the coal. Total overburden stress is not of primary interest, because it will remain unaltered by drainage, provided that this is carried out over a wide area. Rather, the horizontal stresses are more important because they act across the subvertical cleats that conduct gas. Some idea of the stress pattern possibly may be gained from stress measurement in the rock surrounding the seam. This may be carried out either by overcoring from underground workings[12] or by hydrofracture.[13] This stress may be approximately separated into two components. The first is caused by gravitational effects—i.e., an overburden stress and the associated lateral stress developed under conditions of no lateral strain and given in Eq. 3.[14]

$$\sigma_h = \frac{\nu}{1-\nu}\sigma_v. \quad \ldots\ldots (3)$$

The second component is the tectonically induced horizontal stresses that, apart from redistribution through creep, should theoretically be proportional to the moduli of the rocks, provided that horizontal strains are approximately equal, as could be expected in extensive sedimentary deposits.

Fluid Pressures. Initial fluid pressures may be measured by conducting packer tests or by installing grouted sensors in seam as described in Part 2 of this paper.

Fluid pressure changes in the seam typically are brought about in the short term by drainage works or by the creation of mine openings. In geological time, the fluid pressures are probably controlled by the overburden thickness and the hydrostatic pressure associated with fluctuating groundwater levels.

As already mentioned, the water pressure in the seam is not necessarily related to the equivalent sorption pressure. In some cases, significant lowering of water pressure may have to take place before the equivalent sorption pressure is reached and sorbed gas is released. Such fluid pressure reductions will be associated with an increase in effective stress.

Equivalent Sorption Pressure. Equivalent sorption pressure needs to be measured because it is related to the state of coal matrix expansion and contraction. The most usual method would be to obtain core and desorb it fully so that an estimate of gas content can be obtained that may then be related to effective sorption pressure through the sorption isotherm for the coal. A more direct but as yet untried method would be to isolate the seam with packers and to lower the water pressure within the drillstring until gas is released. This method would require the solution pressure of the gas in the borehole fluid to be equal to the equivalent sorption pressure in the coal. This may not be the case if there has been inadequate time for equilibrium to become established.

Where the fluid pressure is lowered below the equivalent sorption pressure, gas is desorbed from the coal. This typically results in a shrinkage of the coal matrix,[3,15] leading to a reduction of effective horizontal stress. This could lead to a complete loss of horizontal stress and the further opening of the cleats caused by continued shrinkage of the matrix.

Coal Shrinkage Related to Equivalent Sorption Pressures. Coal has been shown to shrink on desorption of gas and to expand again on resorption. Hargraves[15] conducted a series of tests on coal from Metropolitan Colliery, New South Wales, Australia, that showed an average linear strain of 0.00182 per MPa change in equivalent sorption pressure using CO_2 as the gas. Japanese workers showed a similar but lesser effect using methane on coal from the northern Ishikari coal field in Hokkaido.[3] Their average value was 0.000125 linear strain per MPa, more than an order of magnitude less. The latter low value is significant, particularly in the context of the "self-sealing" coals encountered in this part of Japan.

To incorporate this shrinkage effect into the estimation of effective stress within the coal, it is necessary to examine the elastic relation between stress and strain changes within the coal. If $\Delta\sigma_z$ is the change in vertical stress and $\Delta\sigma_x$ and $\Delta\sigma_y$ are changes in the principal horizontal stresses, then it is possible to write Eq. 4 describing the change in strain, $\Delta\epsilon_x$, in the horizontal x direction by use of elastic theory.

$$\Delta\epsilon_x = \frac{1}{E}(\Delta\sigma_x - \nu\Delta\sigma_y - \nu\Delta\sigma_z), \quad \ldots\ldots (4)$$

where E is Young's modulus of elasticity.

If the changes in horizontal stress are the same and there is no change in vertical stress, then it is possible to write Eq. 5, which relates horizontal stress and strain changes.

$$\Delta\sigma_x = \frac{E}{1-\nu}\Delta\epsilon_x. \quad \ldots\ldots (5)$$

In the case of coal shrinkage, there is no real overall horizontal strain of the coal, provided that the effective stress does not drop below zero, because the coal is confined laterally. Where effective stress does drop below zero, the coal may be expected to shrink away from the cleats, and localized lateral strain of the coal will occur. Until this happens, the stress change in the coal can be described by replacing the strain-change term in Eq. 5 with the free strain-change value that could be expected in coal subject to desorption, Δp_{se} (p_{se} refers to equivalent sorption pressure). This in turn may be related directly to the equivalent sorption pressure change, Δp_{se}, and Eq. 6 can be written to describe the variation in horizontal stress with a change in equivalent sorption pressure.

$$\Delta\sigma_x = \frac{E}{1-\nu}\,\frac{\Delta\epsilon_{se}}{\Delta p_{se}}\Delta p_{se}. \quad \ldots\ldots (6)$$

The effects of fluid pressure increasing effective stress and matrix shrinkage reducing it cause opposing changes in permeability. These changes can be of several orders of magnitude. Where shrinkage is small, permeability may drastically reduce during drainage, while in the case of a high shrinkage, the permeability will increase.

Estimation of Permeability When Effective Stress Is Negative. To examine the range of permeability when effective stress extends into the negative range, it has been assumed that all gas flow takes place in the cleats. The permeability can then be estimated by laminar flow theory for a series of parallel cracks, perpendicular to the direction of flow as described by Snow[16] and shown in Eq. 7.

$$k=(1.013\times10^{9})\frac{b^{3}}{12}s, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where b is the crack width and s is the spacing between cracks.

Thus if we know the permeability as zero effective stress is reached in the cleat, it is possible to estimate the cleat width for a given cleat density ($1/s$). Variations in this width may be calculated with further desorption and fluid pressure reduction. In each case, the shrinkage caused by desorption or the elastic expansion caused by a fluid pressure drop across the intercleat width (s) is added or subtracted, respectively, from the cleat width. For the example below, the contraction of the solid coal between cleats is assumed to take place without constraint perpendicular to the cleat set. This is reasonable because usually a secondary cleat set will intersect the principal set. The elastic strain, $\Delta\epsilon$, of each intercleat block associated with an isotropic change in effective stress caused by a fluid pressure variation Δp can be found from Eq. 8 (which is derived from Eq. 4). It is not known whether this type of elastic strain occurs with a block subject to different gas pressures because the nature of the effective stress in a sorbent medium as opposed to a porous medium is uncertain. In the case where water is the seam fluid, however, this type of relation seems reasonable.

$$\Delta\epsilon=\frac{1}{E}(1-2\nu)\Delta p. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Fortunately, the strain derived from testing samples of coal that are free to move in all directions will be the result of the shrinkage and effective stress terms and can be directly used in calculations where strain is related to varying equivalent sorption pressure.

Note that, while a zero or negative effective horizontal stress may exist in one direction, a positive value may exist in another because of the different initial in-seam stresses. The vertical effective stress will always be positive.

Example of Varying Seam Permeability With Drainage. To illustrate the effects of stress and shrinkage changes on the permeability of the coal to a single fluid, an example is given with assumed but reasonable values for seam properties. Incorporated into this example is a series of different possible shrinkage cases: the greatest was that recorded by Hargraves[15] for Metropolitan Colliery coal, and the smallest was no shrinkage with varying equivalent sorption pressure. The relationship between effective stress and permeability used is that given in Eq. 1. Note that because of shrinkage the actual stress in seam will become anisotropic. This was not the case for the laboratory testing cited in the derivation of Eq. 1.

Seam parameters used for the example are (1) isotropic initial total stress in seam of 6.8 MPa [986 psi], (2) initial seam water pressure of 4.2 MPa [609 psi], (3) initial equivalent sorption pressure of 3.8 MPa [551 psi], (4) absolute seam permeability at zero effective stress of 1.013 md, (5) Young's modulus of elasticity of 2.7 GPa [392×10^{3} psi], (6) Poisson's ratio of 0.32, (7) cleat spacing of 20 mm [0.79 in.], and (8) seam shrinkage coefficients $\Delta\epsilon_{ve}/\Delta p_{ve}$ shown below (in MPa^{-1}).

Case a: −0.00182 Metropolitan coal with CO_2 gas;
Case b: −0.00091;
Case c: −0.000182;
Case d: −0.0000125 northern Ishikari coal with CH_4 gas;
Case e: 0.0.

The calculations for Cases b and d are given in Table 1, and the results for all cases are plotted in Fig. 4. As can be seen from this figure, very substantial variations in permeability take place because of changes in effective stress and the opening of the cleat structure below zero effective stress. Notably, as fluid pressure decreases without desorption, all permeabilities reduce. Then, depending on the shrinkage associated with desorption, the permeability may increase or continue to decrease as fluid pressures continue to drop along with equivalent sorption pressures. Where the effective stress falls to zero and cleat separation can occur, the permeability increases sharply.

Discussion

The concept of permeability variations closely controlled by effective stress—related both to fluid pressure and to shrinkage characteristics of the reservoir material—is substantially different from normal reservoir engineering concepts. Along with these permeability variations described here for a single phase, the other reservoir parameters—such as pore volume, capillary pressure, and phase relative permeability characteristics—can be expected to change. This makes calculating coal seam reservoir performance an extremely nonlinear and difficult problem.

One suggestion to overcome the permeability testing problems associated with sample strain is to stress core and then hold it at a constant circumferential strain during permeability testing. This would partially reflect conditions in seam. This type of test has limitations, however, because the main gas flow is usually parallel to the seam, not vertical to it, and principal stresses are probably different and unable to be modeled with conventional core permeability test apparatus that can provide only a single circumferential stress.

Conclusions

The storage and permeability characteristics of coal seams require that an approach substantially different from that for conventional gas reservoirs be used to assess their performance. Of primary importance is the storage of gas within the coal. Associated with this gas storage within the coal structure is a change in coal volume. Shrinkage of the coal occurs on desorption, leading to a effective stress reduction. This opposes the effective stress increase that would normally be expected with a lowering of fluid pressure. Because permeability is a function of the effective stress, it may increase or decrease with stress changes associated with drainage. Failure to acknowledge and take into account this effect will preclude reliable estimates of coal seam reservoir performance. These estimates are complicated additionally by seam inhomogeneity.

TABLE 1—DERIVATION OF PERMEABILITY CHANGES WITH DRAINAGE. EXAMPLE FROM TEXT.

Absolute Fluid Pressure (MPa)	Equivalent Sorption Pressure (MPa)	Effective Stress (MPa)	Effective Cleat Width (μm)	Permeability (md)
Case b: $\Delta\epsilon_{vc}/\Delta p_{vc} = -0.00091$ MPa^{-1}				
4.2	3.8	2.6	—	0.158
3.8	3.8	3.0	—	0.118
3.5	3.5	2.216	—	0.208
3.0	3.0	0.908	—	0.529
2.653	2.653	0.0	6.21	1.013
2.0	2.0	−2.0	18.1	25.03
1.0	1.0	−1.0	36.3	201.64
0.5	0.5	−0.5	45.4	394.15
Case d: $\Delta\epsilon_{vc}/\Delta p_{vc} = -0.000125$ MPa^{-1}				
4.2	3.8	2.6	—	0.158
3.8	3.8	3.0	—	0.118
3.5	3.5	3.151	—	0.106
3.0	3.0	3.403	—	0.089
2.0	2.0	3.907	—	0.063
1.0	1.0	4.411	—	0.044
0.5	0.5	4.662	—	0.036

Nomenclature

A = area of core cross section, cm^2 [in.^{2}]
b = crack width, mm [in.]
k = permeability, md
L = length of core, m [ft]
p_i = inlet pressure, MPa [psi]
p_o = outlet pressure, MPa [psi]
p_{vc} = equivalent sorption pressure, MPa [psi]
Δp = pressure variation, MPa [psi]
Δp_{vc} = change in equivalent sorption pressure, MPa [psi]
q = flow at outlet pressure, m^3/s [ft^3/sec]
s = spacing between cracks, mm [in.]
V_c = sorption, m^3 gas/m^3 coal [ft^3 gas/ft^3 coal]
$\Delta\epsilon$ = change in strain, m/m [ft/ft]
$\Delta\epsilon_{vc}/\Delta p_{vc}$ = strain in unconfined coal specimen caused by a change in equivalent sorption pressure, MPa^{-1} [psi^{-1}]
$\Delta\epsilon_x$ = change in strain in the horizontal x direction, m/m [ft/ft]
μ = viscosity, Pa·s [cp]
ν = Poisson's ratio
σ = effective triaxial confining stress, MPa [psi]
σ_h = horizontal stress caused by self weight, MPa [psi]
σ_v = vertical stress caused by self weight, MPa [psi]
$\Delta\sigma_x, \Delta\sigma_y$ = changes in the principal horizontal stresses, MPa [psi]

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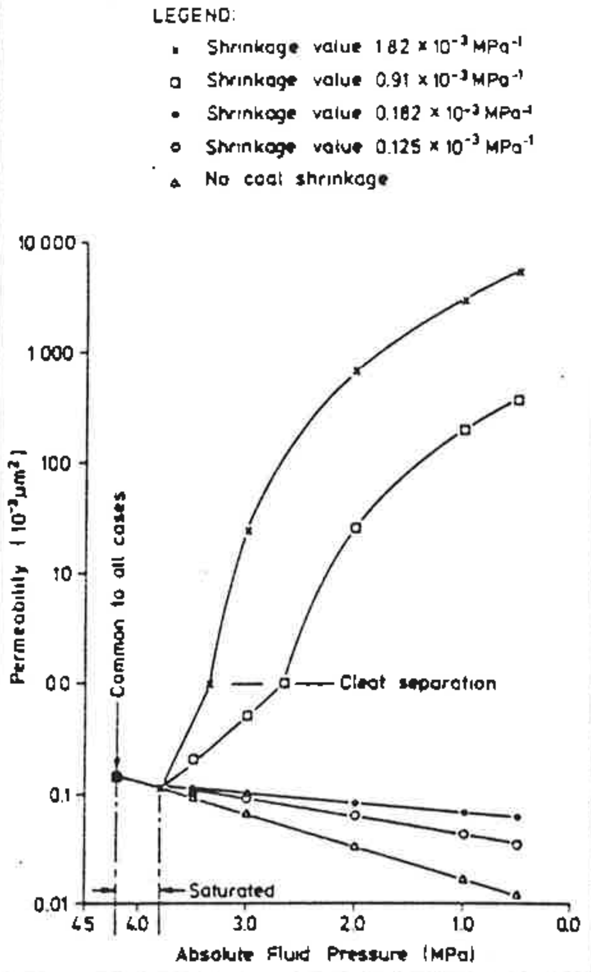

Fig. 4—Changes in single-phase permeability during drainage with various coal shrinkage characteristics. Example from text. (Note: 1 md = 0.987 × 10^{-3} μm^2.)

References

1. Gray, I.: "The Mechanism of and Energy Release Associated with Outbursts," *Proc.*, Symposium on the Occurrence, Prediction, and Control of Outbursts in Coal Mines, Australasian Inst. of Mining and Metallurgy, Southern Queensland Branch, Brisbane (Sept. 1980) 111-25.
2. Gould, K.W. and Smith, J.W.: "Isotopic Studies of Geochemical Factors in Outbursting," *Proc.*, Symposium on the Occurrence, Prediction and Control of Outbursts in Coal Mines, Australasian Inst. of Mining and Metallurgy, Southern Queensland Branch, Brisbane (Sept. 1980) 85-98.
3. Gray, I.: "Overseas Study of Japanese Methane Gas Drainage Practice and Visits to Coal Research Centres, June-August 1980," Australian Coal Industry Research Laboratories Ltd., Sydney, Report No. P.R. 80-15 (1980).
4. Gray, I. and Truong, D.: "Methods and Equipment Used in Outburst and Gas Drainage Investigations," Australian Coal Industry Research Laboratories Ltd., Sydney, Report No. P.R. 82-9 (1982).
5. Lama, R.D. and Bartosiewicz, H.: "Determination of Gas Content of Coal Seams," *Proc.*, Symposium on Seam Gas Drainage with Particular Reference to the Working Seam, Australasian Inst. of Mining and Metallurgy, Southern Illawarra Branch, Wollongong (May 1982) 36-49.

6. Cervik, J.: "Bureau of Mines Methane Control Program," U.S. Bureau of Mines, Technical Progress Report No. 10 (1969).
7. Hemela, M.L., Chapman, G., and Reichman, J.: "Mathematical Model for Simulation of Seam Gas Drainage," *Proc.*, Symposium on Seam Gas Drainage With Particular Reference to the Working Seam, Australasian Inst. of Mining and Metallurgy, Southern Illawarra Branch, Wollongong (May 1982) 53-59.
8. Tabor, J.J. *et al.*: "Development of Techniques and the Measurement of Relative Permeability and Capillary Relationships in Coal," U.S.B.M., Pittsburgh, OFR 22-74 (1974).
9. Somerton, W.H., Soylemezoglu, I.M., and Dudley, R.C.: "Effect of Stress on the Permeability of Coal," *Intl. J. Rock Mechanics, Mineral Science and Geomechanics Abstracts* (1975) 12, 129-45.
10. McCulloch, C.M. and Diamond, W.P.: "Inexpensive Method Helps Predict Methane Content of Coalbeds," *Coal Age* (June 1976) **81**, No. 6, 102-06.
11. Hoek, E. and Franklin, J.A.: "A Simple Triaxial Cell for Field and Laboratory Testing of Rock," *Trans.*, Instn. of Mining and Metallurgy, London (1968) Sec. A, 77, 13-23.
12. Leeman, E.R.: "The Determination of the Complete State of Stress in Rock in a Single Borehole—Laboratory and Underground Measurements," *Intl. J. Rock Mechanics and Mining Sciences* (1968) **5**, No. 1, 31-56.
13. Enever, J.R. and Woolterton, B.A.: "Demonstration of Hydraulic Fracturing Stress Measurement Techniques," CSIRO Australia, Div. of Geomechanics, Syndal, Lecture Series 59 (1984) 1-57.
14. Hoek, E. and Brown, E.T.: *Underground Excavations in Rock*, Instn. of Mining and Metallurgy, London (1980) 95.
15. Hargraves, A.J.: "Instantaneous Outbursts of Coal and Gas," PhD dissertation, U. of Sydney, Sydney, Australia (1963).
16. Snow, D.T.: "Rock Fracture Spacings, Openings and Porosities," *J. Soil Mechanics and Foundation Engineering Div.*, **94**, No. 1, 73-91.

SI Metric Conversion Factors

°F (°F−32)/1.8 = °C
psi × 6.894 757 E+00 = kPa
psi^{-1} × 1.450 377 E−01 = kPa^{-1}

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