Reservoir Engineering in Coal Seams: Part 2—Observations of Gas Movement in Coal Seams

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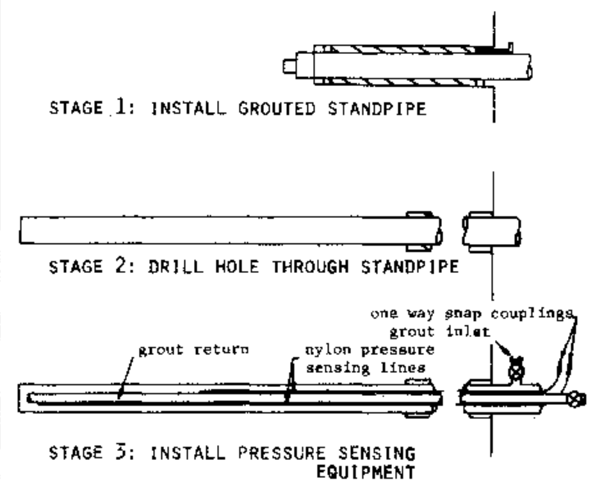
Summary. This paper, the second of two concerning the movement of gas in coal seams, covers observations of seam fluid pressures and flows in mines in northern and central Queensland, Australia. Techniques based primarily on underground measurement rather than measurements from surface boreholes were used to gain information on the seams. The techniques used for in-seam studies are described because they differ substantially from conventional oil and gas surface borehole techniques. The paper demonstrates the importance of cleats and joints in the control of fluid movement and records flow increases consistent with increasing permeability with production.

Methods

Pressure Measurement. Pressure measurement was conducted in seam by two basic techniques. In the first, a hole approximately 50 mm [2 in.] in diameter was drilled in seam and then the drill rods were withdrawn after a predetermined length, typically when 10 to 80 m [33 to 262 ft], had been reached. Following this, a 1- to 2-m [3.3- to 6.6-ft] -long packer was installed as quickly as possible on the end of the conduit string, leaving 2 to 10 m [6.6 to 33 ft] of open hole ahead of the packer. The packer was inflated with water through a synthetic braid hydraulic hose. Packer inflation pressure typically was raised to that required to expand the packer to borehole size plus 1½ times the fluid pressure being measured. Occasionally, this packer pressure may have led to some problems because it may have approached or exceeded total in-seam stress and therefore tended to open the cleats (fractures) within the seam, thus promoting leakage around the packer. The pressure within the zone at the end of the packer was measured through a 4.8-mm [0.19-in.] -OD nylon tube leading to the borehole collar and connected to either a pressure gauge or a chart recorder. The coal permeability was normally sufficiently low that no significant leakage occurred around the packer into the borehole, and reasonably reliable pressure measurements could be obtained.

By repeating the procedure outlined above, it was possible to gain an understanding of the pressure distribution that existed within the coal along the line of a borehole. Up to five tests at 10-m [33-ft] intervals could be conducted in a 7-hour shift with this technique. Attempts were made to extend the use of packers to permanent pressure measurement. A single packer was considered inadequate to measure the overall pressure distribution along a borehole, and therefore multiple packer assemblies were constructed containing pressure measurement ports between the packers as described by Lama *et al.*[1] These were expensive and difficult to maintain. In addition, they were invariably lost through borehole collapse if installed for longer than 2 weeks. On one occasion, accidental deflation of the packers led to a dangerous ejection of the unit from the borehole. For these reasons, the packer system was replaced by a system of grouted-in pressure sensor points that were developed specifically for long-term in-seam pressure measurement. These sensors have been installed successfully against pressures of 3.82 MPa [554 psi] and gas flows of up to 1900 m^3/d [67,098 ft^3/D]. Some of them have been monitored continually for 3 years.

To install such a grouted-in sensor, the procedure shown in Fig. 1 is followed. This initially requires drilling a hole for a standpipe (wellhead) approximately 130 mm [5.1 in.] in diameter to approximately 10 m [33 ft] in length. Within this, a 50-mm [2-in.] pipe is grouted and the hole is drilled on to 60 to 80 m [197 to 262 ft] at 50-mm [2-in.] diameter after the grout has set. Then 20-mm [0.8-in.] PVC conduit is installed up the borehole with 4.8-mm [0.2-in.] -OD nylon pressure-sensing lines strapped to it with their inner ends at pressure-sensing locations. Each end of nylon tube is wrapped with cloth to act as a filter. Once the sensor is fully installed, a faucet T, end cap, and valves are fitted to the standpipe to permit grouting. Before this, the borehole is flushed with water to remove loose coal particles. Natural gas flow can then be used to flush water from the hole. Just before grouting, the nylon lines are filled with water through one-way quick connections to prevent the ingress of grout within the lines. Grouting is accomplished up the annulus and back down the conduit return using a cement grout of 0.5 water/cement ratio containing calcium chloride and a post-initial-set expansion agent to promote a quick set and to ensure a tight seal. The grouting is completed at sufficient pressure to compress any gas bubbles to a small size. After grouting, a small amount of water is added to the nylon sensing lines to ensure no grout ingress. After initial grout set, an additional liter of water is injected into each line to fracture the grout and create an opening to the seam.



STAGE 1: INSTALL GROUTED STANDPIPE

STAGE 2: DRILL HOLE THROUGH STANDPIPE

STAGE 3: INSTALL PRESSURE SENSING EQUIPMENT

STAGE 4: FLUSH BOREHOLE

STAGE 5: FILL NYLON LINES WITH WATER

STAGE 6: GROUT BOREHOLE UNDER PRESSURE

STAGE 7: ADD 0.2 LITRES OF WATER TO NYLON LINES

STAGE 8: WHEN GROUT SET TO CORRECT CONSISTENCY FRACTURE GROUT THROUGH NYLON LINES WITH ONE LITRE OF WATER

STAGE 9: ALLOW GROUT TO HARDEN AND CONNECT TO PRESSURE GAUGES

Fig. 1—General sequence of installing a grouted-in pressure sensor.

Once the grout has set, these lines can be connected to pressure gauges or to a chart recorder.

Flow Measurement. Flow measurement involves both gas and water and ideally should be conducted so that the flow contribution from each part of a borehole's length is measured. This can be done, but not on a continual basis because of the large effort required. It is more usual, therefore, to measure flows from the entire borehole length on a daily basis and to carry out incremental flow tests to measure flow per unit length less frequently—e.g., monthly. It is possible to estimate the flow from each section of borehole by distributing the total borehole flow on the basis of the distributions measured in the incremental flow tests.

To measure total flow, a standpipe is grouted into the collar of each borehole; flow passes through this into a vertical pipe of sufficient diameter that the flow velocity is low and the water drains down into a collector tank, while the gas passes upward and through an orifice plate flowmeter.

For incremental flow testing, an inflatable packer is installed at the end of a conduit string to the base of the borehole and expanded. Flow is then ducted through the string and can be measured by an orifice plate flowmeter and water separator. If the packer is withdrawn incrementally and flow tests are conducted stage by stage, it is possible to derive a cumulative flow curve, the slope of which is the flow per unit length in the hole.

Combined Pressure and Flow Testing. Fig. 2 shows the equipment used to conduct buildup tests similar to those used in conventional reservoir engineering, where flow is permitted and then shut off, allowing pressure to build up. The buildup test has a slightly different form, because the borehole is flowing while it is drilled. To overcome this, the hole is shut in first and pressure allowed to build up. A flow period at atmospheric pressure follows with an additional buildup period. Typically, each flow or buildup period would last 1 to 2 days.

Gas Content Measurement. The usual method for measuring gas content in a coal seam is by coring the seam, retrieving the core as fast as possible, and permitting it to desorb in a canister. The gas evolved may then be collected and the desorption rate measured. This general procedure is described by McCulloch and Diamond.[2] Two aspects of this type of gas content determination should be described further. The first is the necessity of an estimate of the initial gas content lost before the core is in the canister. Normally, a plot of total evolved gas

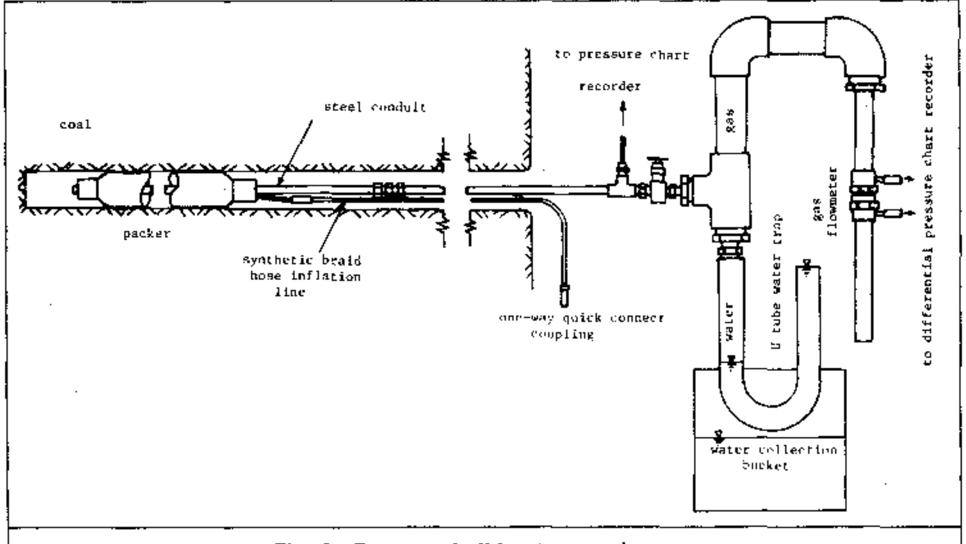


Fig. 2—Pressure buildup test equipment.

vs. the square root of time since the start of gas evolution is made. This is supposed to be a straight line, and it is extrapolated back to zero time to find the total gas evolved. The definition of zero time requires some care, though, because the core will desorb gas at various rates, depending on water pressure within the borehole. In an in-seam hole, the core is expected to begin desorption immediately on drilling, while in a hole drilled from surface, the desorption will occur at various rates as the core rises in the borehole. The second aspect is that some workers have found it necessary to grind the coal to promote final gas loss within a reasonable time. However, this does not appear to be necessary for all coals.

Observations

Pressure Distributions Around Mine Openings. During the studies conducted in the underground mines of Queensland, pressure distributions were measured from mine openings with packers and grouted-in sensors. An example is shown in Fig. 3, a plan view of a section of Leichhardt Colliery mined in 1975 with pressure measurements made in boreholes drilled in 1981. Virgin seam pressure is 3.8 MPa [551 psi]. This case illustrates the importance of anisotropy caused by the cleat system. As can be seen, a high pressure gradient exists perpendicular to the cleat where no drainage can occur downcleat into the mine roadways. Where drainage can take place along the cleat into the roadway, the pressure gradient is low. This is reinforced by the cumulative incremental flow measurements made in Borehole C (across-cleat) and Borehole D (along cleat) and shown in Fig. 4. Borehole C shows substantial inflow along its entire length, with a major inflow at 31 m [102 ft] in length, presumably associated with some joint. Borehole D shows negligible inflow except where it traverses a differential compaction fault of 0.2-m [0.7-ft] throw. Some flow occurs in virtually all sections of Borehole C.

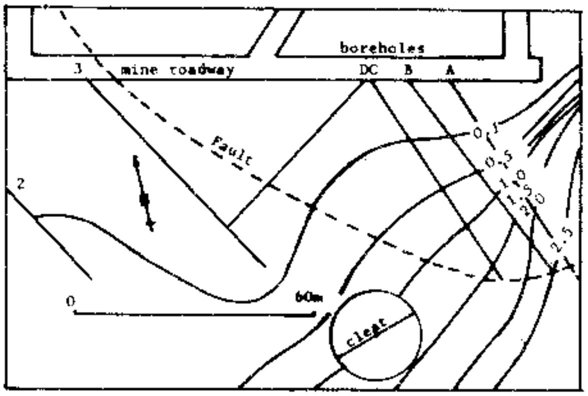


Fig. 3—Plan view of east track road drainage trial at Leichhardt Colliery.

Other examples of pressure distribution around openings typically tended to show a low-pressure-gradient zone initially, followed by a steep rise and flattening out of the pressure distribution to virgin seam pressure. The low-pressure distribution near the mine roadways often extends into solid coal substantially beyond the region where the stress redistribution caused by mining has any influence. This suggests an increasing permeability with drainage.

Drainage into Boreholes. To measure the effectiveness of a series of parallel boreholes drilled from a mine roadway into solid coal, a four-hole drainage pattern was used, as shown in Fig. 5. For a trial, two sets of drainage patterns were generally drilled, one across and one along the direction of the major cleat set. The outer two boreholes acted as cutoffs to flow laterally in seam. The inner two were expected to have a drainage behavior similar to that

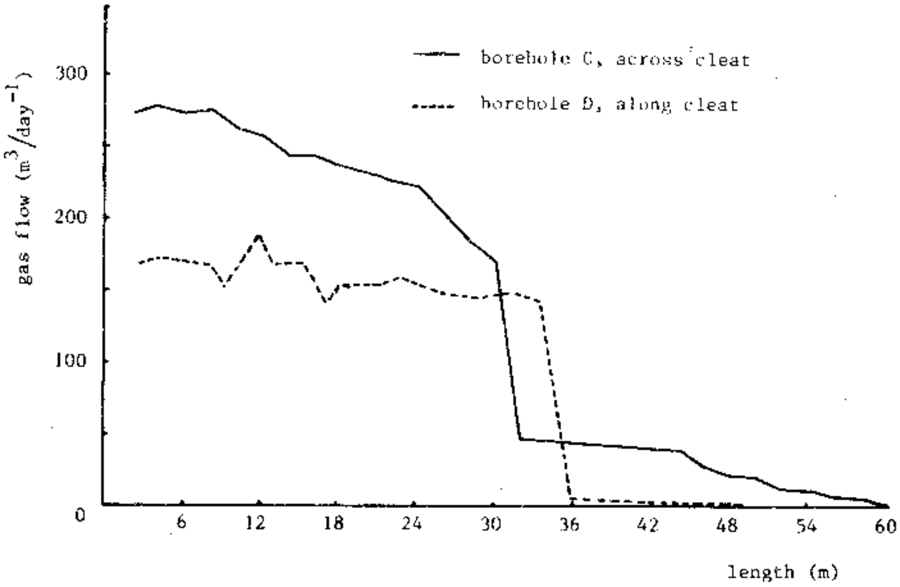


Fig. 4—Cumulative incremental flows fom Boreholes C and D on the east track road, Leichhardt Colliery.

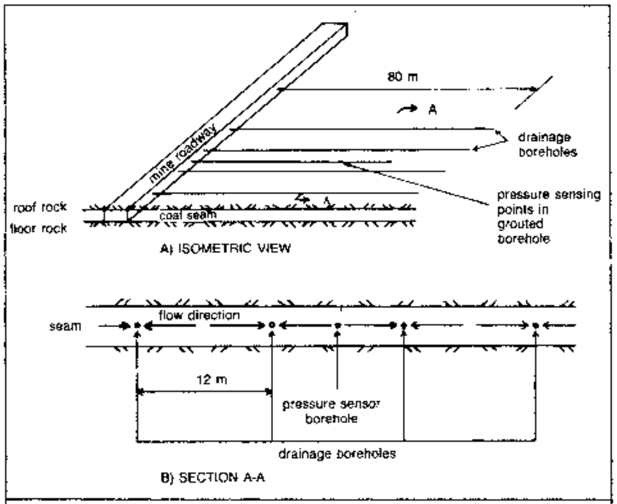


Fig. 5—Isometric view of four-hole drainage trial.

of a real drainage panel consisting of a series of boreholes drilled parallel to each other from a roadway. In the middle of the four drainage holes was a borehole fitted with a grouted-in pressure sensor. This system enabled the pressure to be monitored as drainage occurred. It was possible to carry out material-balance studies with this technique. Comparison of the gas content of the central block—derived by subtracting the quantity of gas drained from initial gas content measurements—allowed estimation of the quantity of gas left. This could be compared with estimates of gas content derived from pressure-sensor measurements and the sorption isotherm curves. Naturally, some drainage into the roadway would take place, as would drainage from virgin coal into the block. In the central area of the trial, however, a reasonable material-balance estimate usually could be made.

An example of such a material-balance estimate is shown in Fig. 6, which compares the two gas content estimates for an across-cleat drainage panel in the Bowen No. 2 mine. As can be seen, a quite reasonable comparison of the two gas contents exists up to Day 220, when the gas content derived from pressure measurements and sorption isotherms tends to exceed that from a material balance. This indicates the presence of an external source, probably leakage from the surrounding stone and an adjacent seam.

The flow behavior of such holes is interesting because, in all the seams tested, the general pattern is that flow increases for a substantial period after the hole is drilled and then declines. Fig. 7 shows the measured average flow from the central region of inner boreholes in four-hole drainage patterns at the Bowen No. 2 and Moura No. 4 mines. In addition, the flow in Borehole B of the previously mentioned Leichhardt Colliery east track road is shown, though this is only the central borehole of a three-hole pattern into which substantial external leakage occurred. The general trend of increasing flow tends to support an increase in permeabilities with drainage.

Water flows occurred in all cases except those drilled in seams where substantial drainage had already taken place—such as Borehole D on the east track road at Leichhardt Colliery. The water flow could occur over the borehole length, as at Leichhardt Colliery, or be more associated with major joints, as was the case at Moura. In the Moura mine, the gas/water ratio of the central boreholes was initially less than 500 but rose to 6000 after 50 days' production. Outer boreholes tended to dry out less quickly.

Combined Pressure Buildup and Flow Tests. Fig. 8 shows the pressure buildups for the inner 10 m [33 ft] of a 56-mm [2.2-in.] borehole at Moura No. 4 mine. The

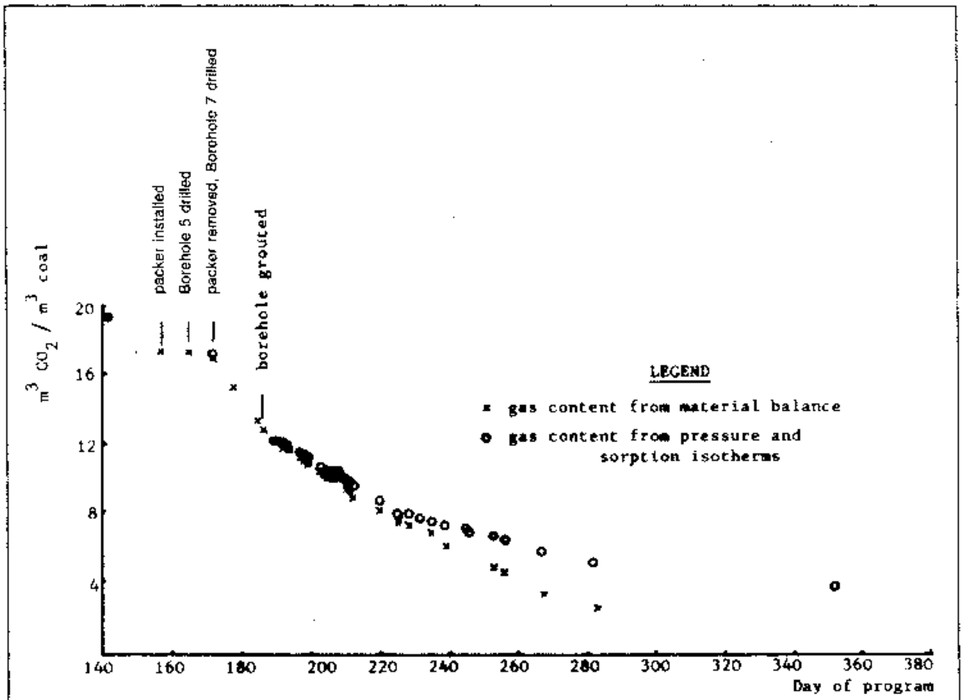


Fig. 6—Gas content comparisons for four-hole drainage pattern at Bowen No. 2 mine.

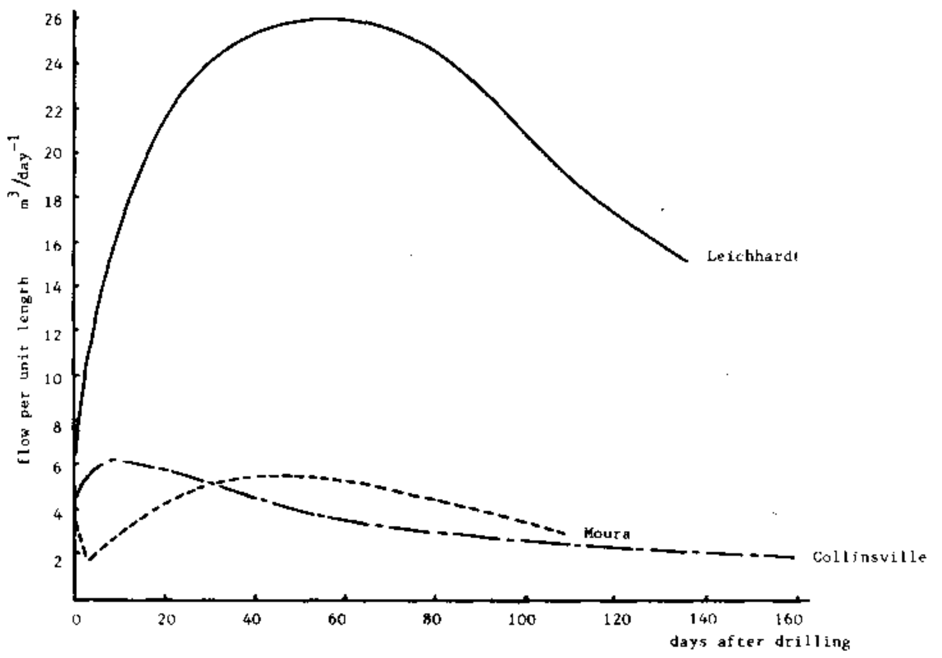


Fig. 7—Measured average flow per unit length for inner boreholes at Leichhardt Colliery, Moura No. 4 mine, and Bowen No. 2 mine.

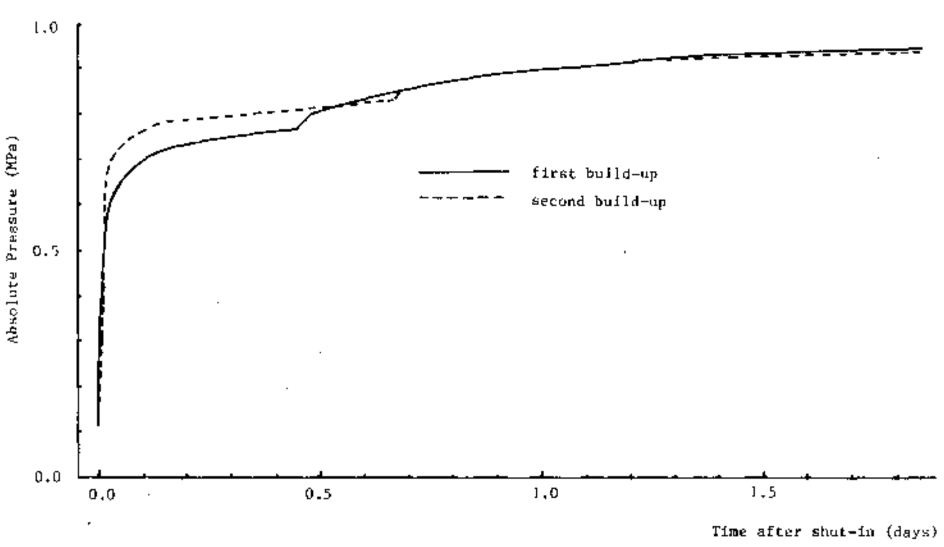


Fig. 8—Pressure buildup plots for borehole at Moura No. 4 mine.

first buildup period of 1.7 days follows 6.5 days of free flow after drilling. The second buildup follows an additional 1.06 days of drainage after the first buildup. As can be seen, the buildup is very steep initially and then flattens out sharply before an additional short rise after about ½ day, and then finally asymptotes to virgin seam pressure. The initial sharp rise is thought to be a result of intercleat coal blocks still desorbing into the cleats near the borehole, as opposed to the gas just being transported along the cleats. The sudden flattening out of the curve is probably associated with the gas pressure within the cleat exceeding the equivalent sorption pressure within the intercleat coal and therefore leading to gas being absorbed back into the coal. The small rise at ½ day after shut-in is thought to be associated with the filling of the borehole with water, thus stiffening the response characteristic of the system. The water flow before shut-in would have led to the borehole's filling with water in about ¼ day, so this hypothesis seems reasonable.

Seam Pressures and Gas Contents. Seam pressures and gas contents often seem to be related to the hydrostatic pressure at the level of the coal seam. In the case of Leichhardt Colliery, the measured seam pressure was 3.82 MPa gauge [554 psig] at 390-m [1,280-ft] depth. At Moura, the seam pressure was 1.1 MPa gauge [160 psig] at 135-m

[443-ft] depth. At German Creek mine in Queensland, seam pressures measured from surface also corresponded to hydrostatic pressure. At Bowen No. 2 mine, pressures appeared to be much lower than hydrostatic pressure, but because most of the methane there has been replaced by igneous CO_2 (which is much more easily transported in seam water), this is not surprising. Harrow Creek mine, also in the Bowen basin, has high water flows through the seam and virtually no gas remains; presumably the gas has been carried away in solution.

The gas contents obtained from core desorptions seem to be closely related to the seam fluid pressure through the sorption isotherm. This allows the hypothesis that as gas is evolved within the coal, it normally is released from sorption as the equivalent sorption pressure builds up and exceeds the hydrostatic head. If high water flows exist, however, it is probable that the seam gas has been removed in solution.

Conclusions

It appears that the cleating of coals is very important in the control of the principal directions of permeability. In addition to the cleats, major joints and faults within the seam act as conduits for seam fluid movement. From observations of the fluid pressure distribution around mine openings and the increase of flow from boreholes that occurs for a long period after drilling, it appears that permeability tends to increase substantially with drainage. Reasonable evidence suggests that gas contents in seams not subject to high water flows may be directly related to hydrostatic pressure through the sorption isotherm. In this instance, the equivalent sorption pressure is hydrostatic pressure.

Acknowledgments

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References

1. Lama, R.D., Marshall, P., and Griffiths, L.: "Methane Drainage Investigations as a Method of Control of Outbursts at West Cliff Colliery," *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) 223-39.
2. McCulloch, C.M. and Diamond, W.P.: "Inexpensive Method Helps Predict Methane Content of Coalbeds," *Coal Age* (June 1976) **81**, No. 6, 102-06.

SI Metric Conversion Factors

ft × 3.048* E−01 = m
ft^3 × 2.831 685 E−02 = m^3
psi × 6.894 757 E+00 = kPa

*Conversion factor is exact.

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