

Bureau of Mines Report of Investigations/1972

**The Methane Migration and Storage
Characteristics of the Pittsburgh,
Pocahontas No. 3, and Oklahoma
Hartshorne Coalbeds**



UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 7667

**The Methane Migration and Storage
Characteristics of the Pittsburgh,
Pocahontas No. 3, and Oklahoma
Hartshorne Coalbeds**

By Fred N. Kissell

Pittsburgh Mining and Safety Research Center, Pittsburgh, Pa.



UNITED STATES DEPARTMENT OF THE INTERIOR
Rogers C. B. Morton, Secretary

BUREAU OF MINES
Elburt F. Osborn, Director

This publication has been cataloged as follows:

Kissell, Fred N

The methane migration and storage characteristics of the Pittsburgh, Pocahontas No. 3, and Oklahoma Hartshorne coalbeds. [Washington] U.S. Dept. of the Interior, Bureau of Mines [1972]

22 p. illus., tables. (U.S. Bureau of Mines. Report of investigations 7667)

Includes bibliography.

1. Methane. I. Title. (Series)

TN23.U7 no. 7667 622.06173

U.S. Dept. of the Int. Library

CONTENTS

	<u>Page</u>
Abstract.....	1
Introduction.....	1
Acknowledgments.....	1
Gas pressure and flow measurements.....	2
Analysis of pressure curves.....	2
The crushed zone.....	9
Calculation of permeability.....	9
Increase in permeability with time.....	10
Possible reasons for permeability increase.....	13
Permeability of different coalbeds and effect of overburden.....	14
Anisotropy in permeability.....	15
Other variations in permeability.....	17
Conclusions.....	18
References.....	20
Appendix.--Applying the unsteady-state Darcy equation to experimental pressure gradient curves.....	21

ILLUSTRATIONS

1. Pressure curves from the Pittsburgh coalbed, Federal No. 2 mine, holes 1 and 2.....	3
2. Pressure curves from the Pittsburgh coalbed, Federal No. 2 mine, holes 3, 4, and 5.....	3
3. Pressure curves from the Hartshorne coalbed, Howe No. 1 mine, holes 2 and 3.....	4
4. Pressure curves from the Hartshorne coalbed, Howe No. 1 mine, holes 4 and 5.....	4
5. Pressure curves from the Hartshorne coalbed, Howe No. 1 mine, holes 8 and 9.....	5
6. Pressure curves from the Hartshorne coalbed, Howe No. 1 mine, holes 10 and 11.....	6
7. Pressure curves for the Pocahontas No. 3 coalbed, Kepler mine, holes 1 and 4.....	7
8. Federal No. 2 mine, steady-state flow from 6-foot increments of open hole.....	13
9. A mine entry in a coalbed with pronounced face cleat and butt cleat development.....	16

TABLES

1. Coalbed permeability data.....	8
2. Methane flow data.....	12

THE METHANE MIGRATION AND STORAGE CHARACTERISTICS OF THE PITTSBURGH, POCAHONTAS NO. 3, AND OKLAHOMA HARTSHORNE COALBEDS

by

Fred N. Kissell¹

ABSTRACT

Methane flows and pressures were measured in mines in the Pittsburgh, Hartshorne, and Pocahontas No. 3 coalbeds. From the data, the permeability of each of these coalbeds was computed. It was found to depend strongly on the type of coal and on the amount of water in the coalbed, and it was found to increase with time. All of the coalbeds had a high-permeability zone adjacent to the face or rib, and the Pittsburgh bed exhibited directional anisotropy. Surprisingly, little or no overburden effect was observed.

INTRODUCTION

The Bureau of Mines has been engaged in a program of drilling deep horizontal holes into coalbeds from the working areas of coal mines (3-4).² These holes are sealed with inflatable packers, and the pressure of the gas that seeps into the hole from the coal is measured. These pressures, in conjunction with other data from the mine and the laboratory, can provide information about the gas flow characteristics of the coalbed (7).

In this report, gas pressure and flow measurements from horizontal holes in the Pittsburgh, Hartshorne, and Pocahontas No. 3 coalbeds are used to calculate the coalbed permeability and methane sorption capacity. These measurements show that the permeability of a coalbed depends greatly on the nature of the coal, exhibits spatial variations and anisotropy, and exhibits a remarkable increase with time, possibly owing to loss of water from the coalbed.

ACKNOWLEDGMENTS

Grateful acknowledgment is made to these Bureau of Mines people who have contributed data and helpful advice: J. H. Perkins, T. C. Ruppel, Albert Sainato, and C. H. Elder. Also, G. R. Haworth of the Central Research Division, Continental Oil Co., has submitted helpful comments regarding permeability anisotropy and its effect on rib emission rates.

¹Physical research scientist.

²Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

GAS PRESSURE AND FLOW MEASUREMENTS

Typically in this study, a horizontal hole was drilled into and perpendicular with the solid rib of a return airway a short distance outby the working face.³ After drilling, this hole was sealed with packers; the equilibrium pressure to be measured was achieved in a day or less. Two methods of measurement used were as follows: (1) The hole was drilled in increments, and the pressure at the back of the hole was measured at each increment; (2) the hole was drilled to completion, the packers inserted, and pressures measured simultaneously at points between the packers. The same results were obtained using either method. The gas pressure curves shown in figures 1-7 were obtained from either method.

Flows from some holes were measured by allowing the gas to bleed to the atmosphere after pressure measurement. Generally, a steady-state flow was obtained in less than 1 day. Flows were obtained in one of two ways: (1) By opening the pressure line leading to the back of the hole and measuring the steady flow rate of methane seepage into the last few feet of open hole; and (2) by inserting a single packer near the collar of the hole and measuring the rate of methane seepage into the entire hole.

ANALYSIS OF PRESSURE CURVES

The curves of figures 1-7 were used to calculate the permeability of the coalbed in the location where the horizontal hole was drilled. To do this, it was assumed that methane flow out of the coalbed follows the unsteady-state Darcy equation for gas flow. It also was assumed that the coalbed is a homogeneous, semi-infinite slab, the end of the slab being the coal face. Before mining, the slab is at uniform bed pressure, P_{seam} ; at the time of mining, the pressure at the end of the slab (face) is reduced to atmospheric. Finally, it was assumed that the desorption from the pore structure of the coal to the coalbed fractures is fast compared with the time required for the gas to flow through the fractures from deep within the slab to the face or rib (7).

The Darcy equation is

$$\frac{\partial^2 P^2}{\partial x^2} = \frac{\eta S}{KP} \frac{\partial P^2}{\partial t}.$$

Here P is the gas pressure (atmospheres), x is the distance into the coalbed from the working face (centimeters), η is the viscosity of methane (centipoises), K is the permeability of the coal (darcy), S is the sorption capacity of the coal $\left[\frac{\text{volume adsorbed per atmosphere}}{\text{volume of coal}} \right]$, and t is time (seconds).

³All the mines studied were being worked by the advancing room-and-pillar system of mining in the sections where measurements were made.

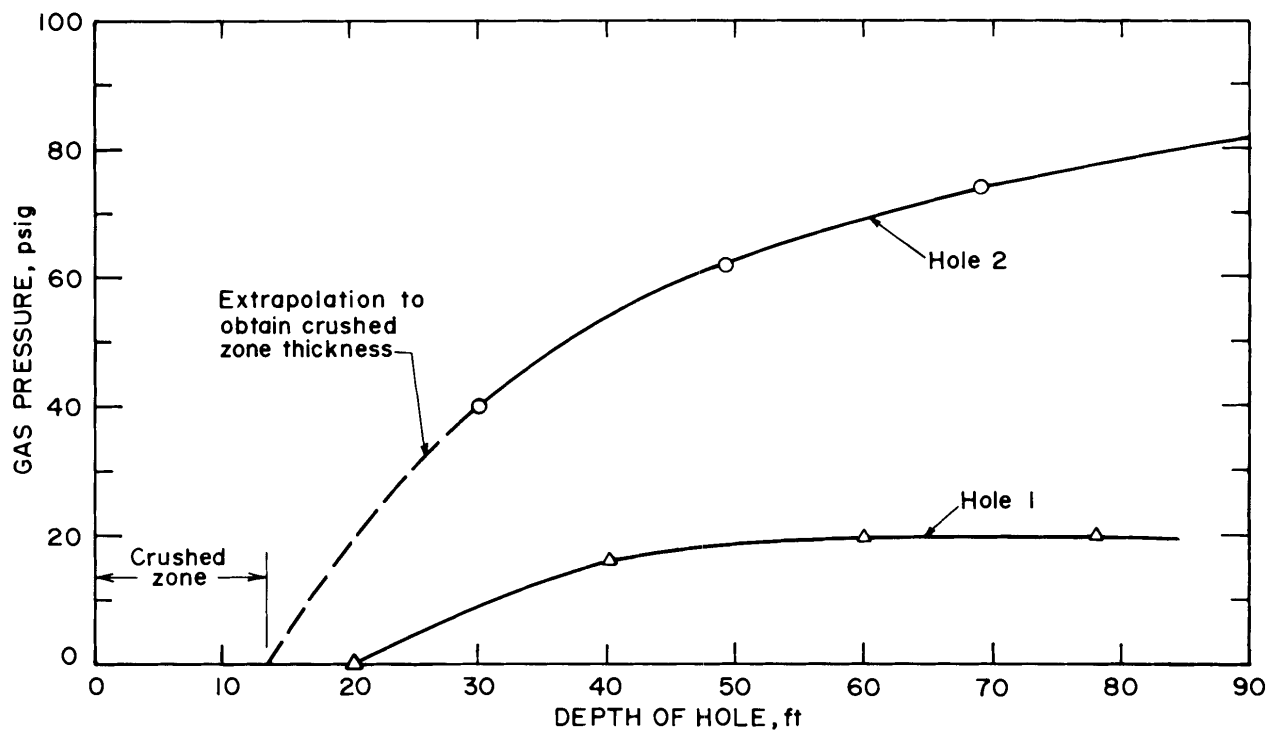


FIGURE 1. - Pressure Curves From the Pittsburgh Coalbed, Federal No. 2 Mine, Holes 1 and 2.

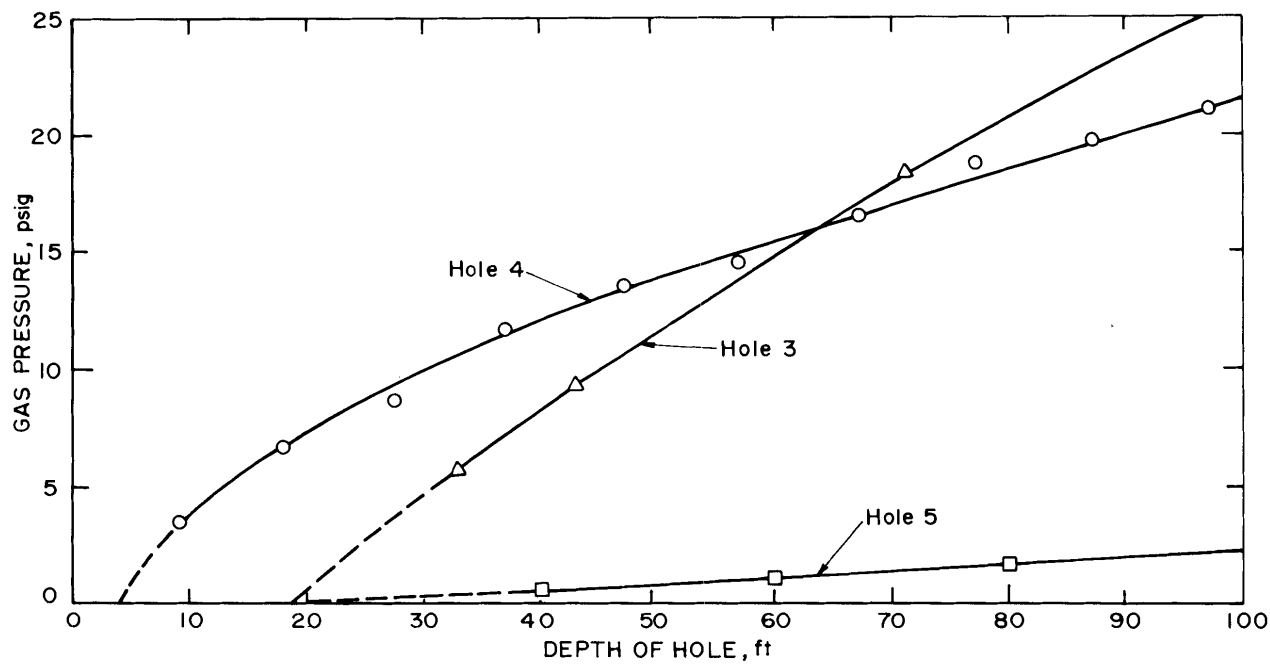


FIGURE 2. - Pressure Curves From the Pittsburgh Coalbed, Federal No. 2 Mine, Holes 3, 4, and 5.

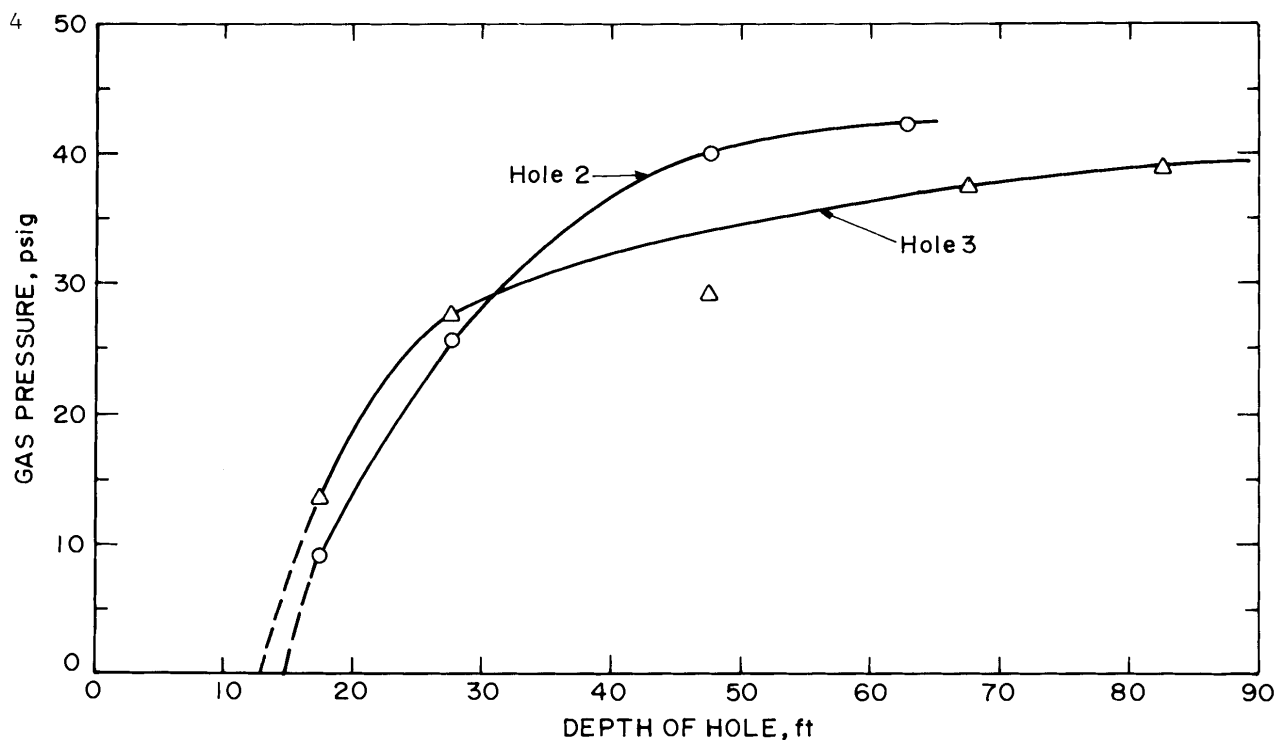


FIGURE 3. - Pressure Curves From the Hartshorne Coalbed, Howe No. 1 Mine, Holes 2 and 3.

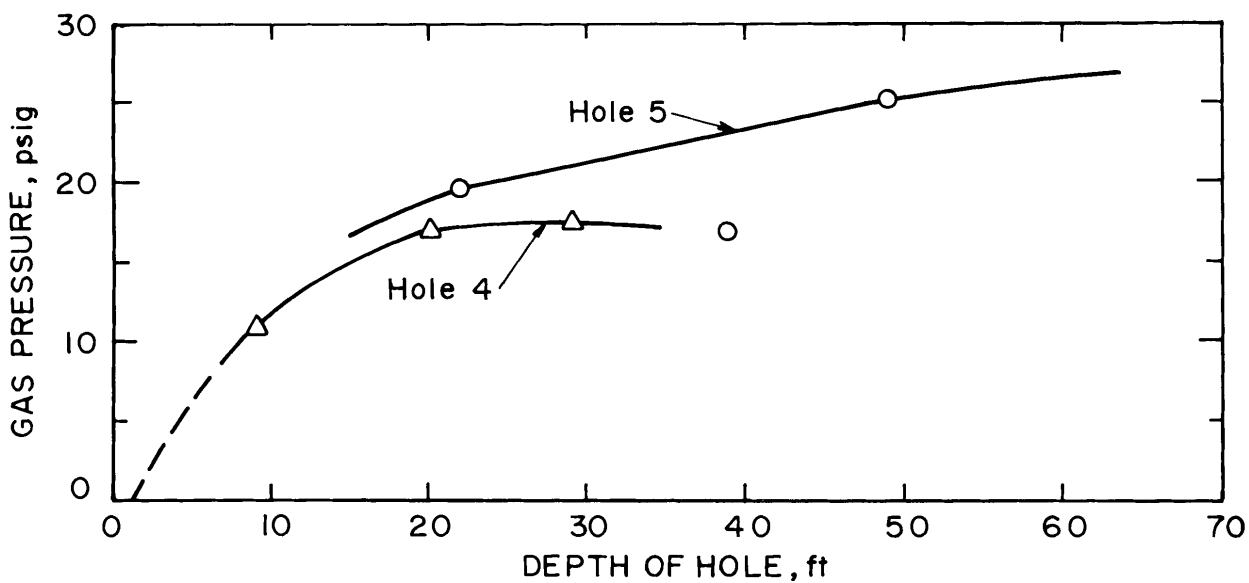


FIGURE 4. - Pressure Curves From the Hartshorne Coalbed, Howe No. 1 Mine, Holes 4 and 5.

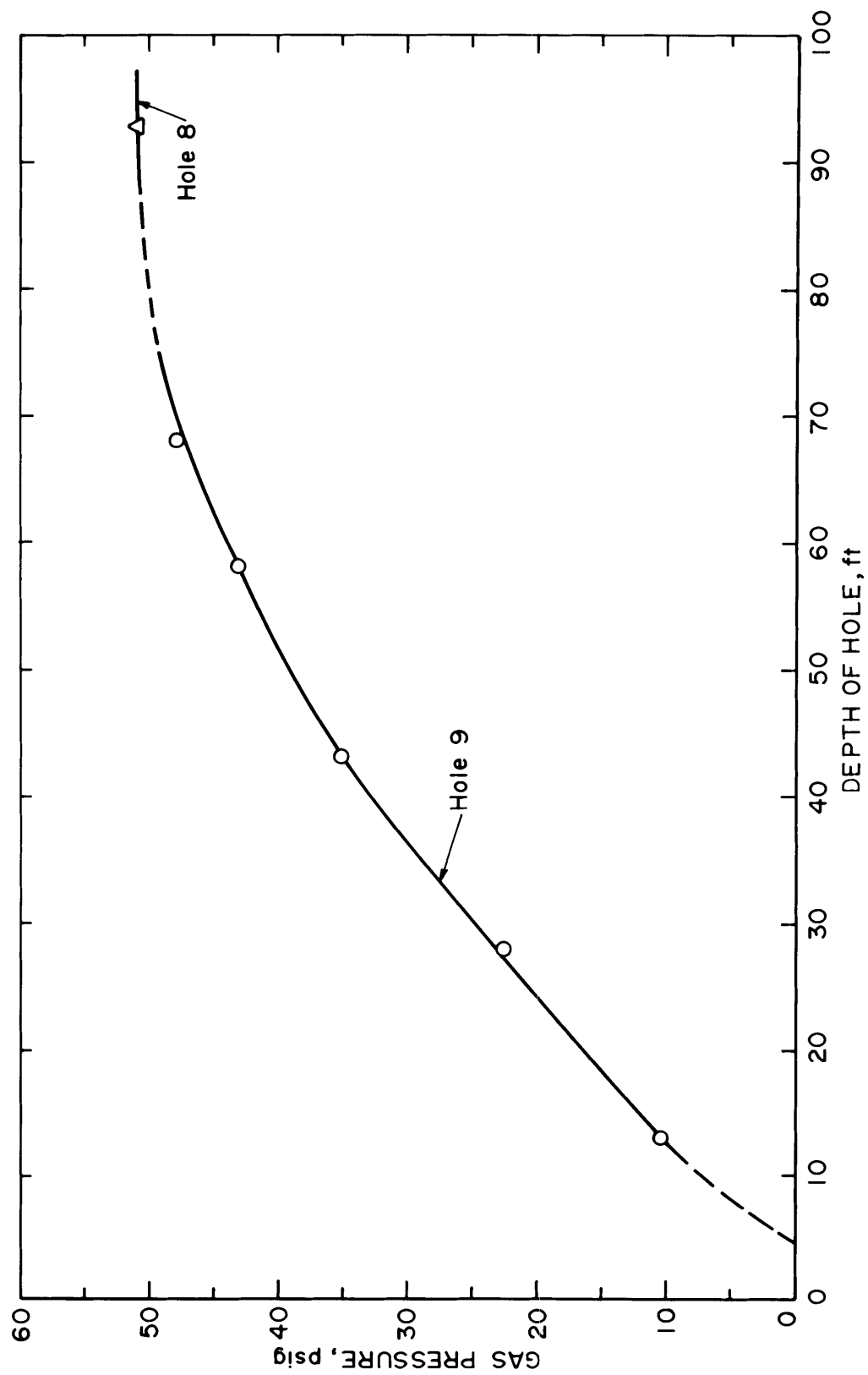


FIGURE 5. - Pressure Curves From the Hartshorne Coalbed, Howe No. 1 Mine, Holes 8 and 9.

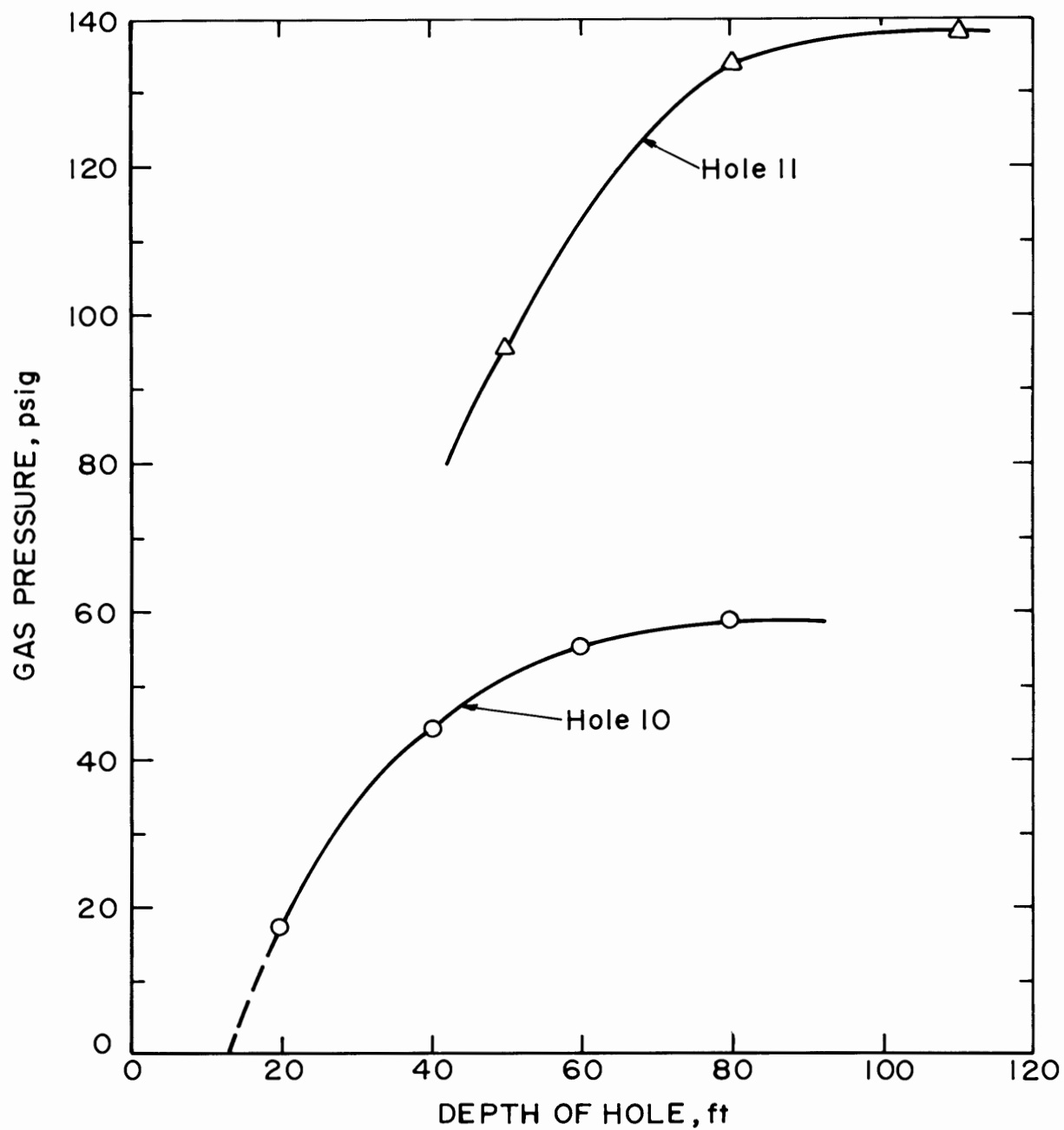


FIGURE 6. - Pressure Curves From the Hartshorne Coalbed, Howe No. 1 Mine, Holes 10 and 11.

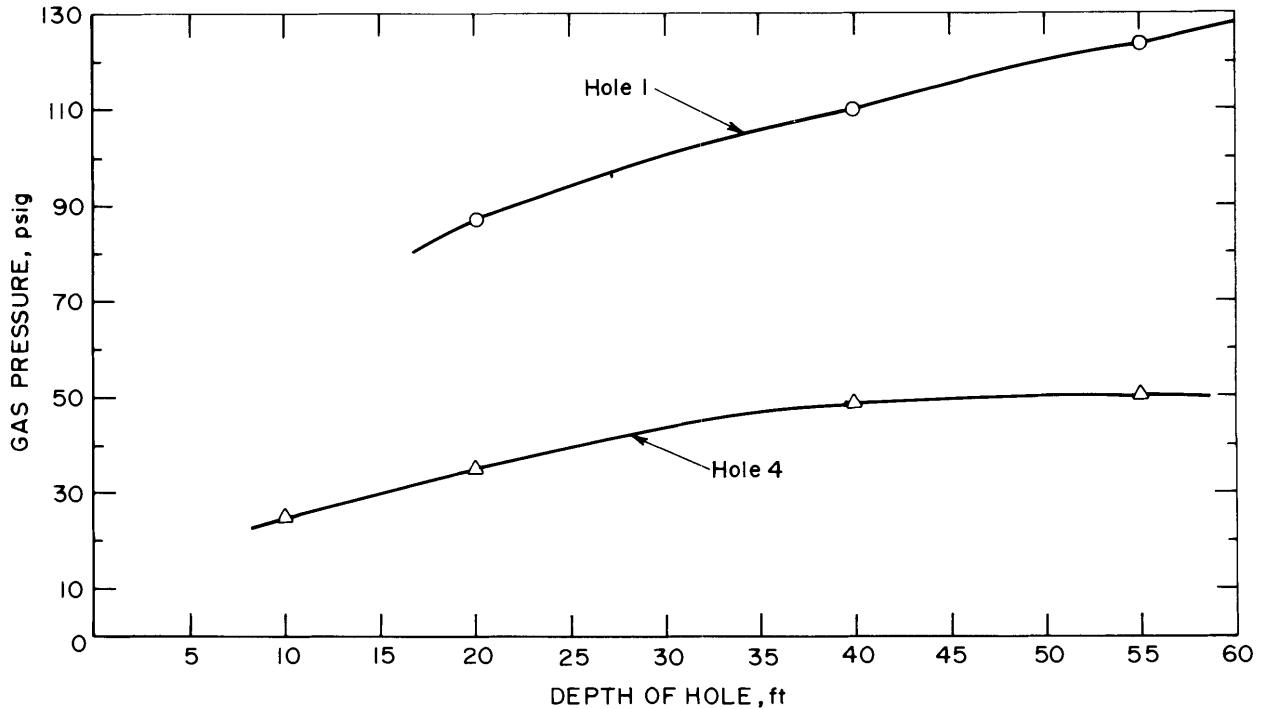


FIGURE 7. - Pressure Curves for the Pocahontas No. 3 Coalbed, Kepler Mine, Holes 1 and 4.

This equation has no exact solution, but an approximate solution is (6)

$$\frac{P^2(x,t) - P_{seam}^2}{P_{atm}^2 - P_{seam}^2} = \operatorname{erfc} \frac{1}{2t_d^{1/2}},$$

where erfc is the complementary error function and $\operatorname{erfc} = 1$ minus the probability integral. Values of the probability integral may be obtained from

standard tables. Here t_d is equal to dimensionless time $= \frac{t_m PK}{\eta x^2 S}$, $P(x,t)$ is

the pressure in the coalbed at point x and time t , P_{seam} is the gas pressure in the undisturbed coalbed, P_{atm} is atmospheric pressure, t_m is the elapsed time since mining, and $\bar{P}$ is the average pressure at x . The ratio K/S or

$\left[\frac{\text{permeability}}{\text{sorption capacity}} \right]$ is obtained by fitting the best theoretical error function curve to the experimentally measured pressure. Table 1 gives the K/S values obtained from each hole, together with K/S values calculated from a number of published pressure curves (2, 7).

TABLE 1. - Coalbed permeability data

Coalbed	Mine and location	Hole No.	Direction	Time since mining, days	Pressure at 50 ft, psig	K/S	Permeability K, md	Crushed zone thickness, ft	Assumed bed pressure, psia	Overburden, ft
Pittsburgh.....	Federal No. 2, Fairview, W. Va.	1	S	75	18	47	7.7	20	120	800
		2	S	18	60	4	.7	14	120	800
		3	W	15	12	500	82.5	19	120	800
		4	N	60	13	200	33	4.5	120	800
		5	N	912	2	1,100	181	20	120	800
Hartshorne.....	Howe No. 1, Heavener, Okla.	2	N	60	40	.15	.08	14.7	57	285
		3	N	91	40	.2	.1	12.5	55	285
		4	S	91	25	1	.5	1.6	55	285
		5	S	91	25	1	.5	-	55	285
		8	E	48	37	1	.5	-	70	285
		9	E	48	37	1	.5	4.9	70	285
		10	E	143	50	2	1	13	155	700
		11	E	40	95	.4	.2	-	155	700
		1	-	15	490	.57	.32	8.6	665	2,000
		2	-	30	180	3.6	2.0	-	665	2,000
		3	-	180	20	500	280	-	665	2,000
Pocahontas No. 3..	Beatrice, Keen Mountain, Va.	1	S	10	120	1	.56	-	155	680
		4	W	120	50	2	1.1	-	155	680

THE CRUSHED ZONE

It has been shown (7) that no simple theoretical curve can be fitted to the experimental pressure curve unless the "crushed zone" is taken into account. The crushed zone is a region of high permeability in the coalbed adjacent to the face and rib and is probably similar to the relaxed zone around a longwall face. Presumably, it forms because coal in this region is unable to withstand the compressive load of the overburden. Partial crushing greatly increases the permeability of the region so that gas emerging from the intact coalbed behind the zone flows easily to the face or rib. The thickness of the crushed zone is calculated by fitting the best theoretical curve to the pressure gradient and extrapolating the theoretical curve to zero gage pressure (7). The distance from the face to this zero pressure point is the crushed zone thickness (fig. 1).

The calculated crushed zone thickness for figures 1-7 are shown in table 1.⁴ A crushed-zone thickness from a previous report also is included (7). These zones ranged in thickness from 1.6 to 20 feet and averaged about 10 feet. Hargraves (5) has published gas pressure data for a number of Australian mines. If the curves from this data are extrapolated to zero gage pressure most of them also yield a crushed zone thickness of about 10 feet.

It might be expected that a rough correlation exists between the thickness of the crushed region and the amount of overburden as shown in table 1, but this does not seem to be the case. In part, this lack of correlation is probably because shallow mines have pillars and supporting members of smaller dimensions. Regardless, a high-permeability zone in the coal adjacent to the face and rib seems to be a feature common to all the mines even though the roof was not being caved.

It should be mentioned that pressure curves do not provide the sole evidence for this high-permeability zone. Parsons (11) has measured dilations of pillars in the Pittsburgh coalbed and has found differential dilations up to a depth of 15 feet in pillars.

CALCULATION OF PERMEABILITY

Fitting the theoretical error function curve to the experimental pressure curve only yields the ratio $K/S \left[\frac{\text{permeability}}{\text{sorption capacity}} \right]$. Other methods must be used to obtain K or S independently. K can be estimated if both the pressure data from a hole and the methane flow from the face or rib region surrounding the hole are known (7). First, the pressure curve is fitted to the best theoretical curve, and the crushed zone thickness is obtained. Then, the theoretical curve is differentiated, and the slope at zero gage pressure is calculated. This slope and the face or rib flow are inserted into the steady-state Darcy equation (6-7), and K is obtained.

⁴Some of the pressure curves, such as Howe mine hole 11 in figure 6, do not have points close enough to the face to warrant extrapolation.

For instance, when Federal mine hole No. 4 was drilled into the rib, a careful methane survey was made in the airway adjacent to the rib. Methanometer readings were taken 150 feet upstream and downstream of the hole. Assuming that all of the methane comes from the rib, it was estimated that the average square foot of rib was emitting 7.7 cubic feet of methane per day. A permeability of 33 millidarcys was calculated from this. Table 1 shows 200 millidarcys for K/S of hole 4, and so S is 0.165. This is much lower than the 0.56 reported (7) for the Pocahontas No. 3 coalbed. Some of this decrease is to be expected, for laboratory sorption experiments on dry coal powders conducted at the Bureau of Mines show that the sorption capacity of the Pittsburgh coal is about three-quarters that of the Pocahontas No. 3 coal. However, the main reason that S is low for the Pittsburgh coalbed is that the assumption of fast desorption is not a good one in this case because of the nature of the coal. (See appendix.) Methane emission data have been obtained from ribs in the Howe No. 1 mine (Hartshorne coalbed), but the emission level was too low for accurate evaluation. The Hartshorne coal is similar petrographically to the Pocahontas No. 3 coal, and T. C. Ruppel⁵ has found that the equilibrium adsorption isotherms are about the same. So, the in-situ sorption may be assumed to be about 0.5.

Table 1 gives values of permeability for the rest of the locations, assuming that S is 0.56, 0.165, and 0.5, for the Pocahontas No. 3, Pittsburgh, and Hartshorne coals, respectively. This table shows that permeability varies with the age of the area in which the hole was drilled (the elapsed time since mining at that point ceased), with the type of coal; and in the Federal No. 2 mine, with the direction of the hole.

INCREASE IN PERMEABILITY WITH TIME

The most notable feature in table 1 is a substantial increase in permeability as the age of the region around the horizontal test hole increases. For instance, in the Federal No. 2 mine, holes 1 and 2 were drilled in the same return airway. Hole 1 was 800 feet outby the working face, and the face was at this point 75 days earlier. Hole 2 was about 50 feet outby the face, and the face was at this location 18 days earlier. The permeability of the coalbed at hole 1 is more than 10 times greater than at hole 2. The same effect is illustrated by hole 5 in the Federal mine; by holes 10 and 11 in the Howe mine, by holes 1, 2, and 3 in the Beatrice mine, and by holes 1 and 4 in the Kepler mine. All three coalbeds show the effect.

The reason for this increase in permeability with time is not entirely clear. Several possibilities are considered in the appendix. These include incorrect estimation of bed pressures, problems associated with the assumption that the coalbed at any given location begins to drain when that location is mined, possible incorrect pressures at long times owing to a delay in micropore desorption, and an assumption of constant sorption capacity. However, the variation in permeability appears too large to be accounted for by any of these.

⁵Research chemist, Pittsburgh Energy Research Center.

The borehole gas-flow data shown in table 2 provides evidence that this increase in permeability is real and not the result of the assumptions made in applying the unsteady-state Darcy equation. It is known that as methane seeps out of the coalbed into the mine, the gas pressure in the coalbed falls. If the coalbed permeability were constant, a decrease in gas pressure would lower the rate of emission from the horizontal test holes, but this never happened. For example, Federal hole 5, which was in an area 30 months old, had 4 psig at the back of the hole; whereas hole 4 in an area 2 months old had 21 psig. A constant permeability would indicate a much higher flow from hole 4, but as table 2 shows, the flow rates were about the same. Since the flow rate corrected for pressure and depth⁶ is roughly proportional to permeability, the permeability of the coalbed near hole 5 appears to be considerably larger than that of the coalbed near hole 4. Exactly the same effect is shown for holes 1 and 2 of the Beatrice mine, holes 1 and 4 of the Kepler mine, and it appears also to a much lesser degree at holes 10 and 11 of the Howe mine. Always, an increase in the age of an area caused an increase in permeability.⁷ The result of this effect is that holes drilled into older, low-pressure areas often seem to yield as much gas as holes drilled into freshly mined areas. Gas yield performance is of critical importance in coalbed degasification.

A more critical test, especially with regard to degasification, would be to measure the flow from a single hole over a long time period rather than measure flows from holes in different age areas, as is done in table 2. The Bureau of Mines has recently drilled a 400-foot hole in a freshly mined area of the Federal No. 2 mine. The initial gas flow of 100,000 cubic feet per day continued virtually unabated for 2 months.

At least one other investigator has observed a similar increase in permeability. Stewart (14), in a study of Australian coalbeds, measured incremental flows from a borehole in a manner similar to that used to obtain the data of figure 8. He observed a peak in the flow, whereas in figure 8 the flow increases smoothly with depth. In 30 days this peak moved inward from a depth of 6 feet to about 21 feet. Stewart attributed this change in permeability to "destressing," a reduction in stress with relaxation along cleat and bedding planes. This explanation might be valid for regions close to the face such as Stewart observed. (The crushed zone is probably such a destressed region.) However, hole 2 in the Beatrice mine (which exhibits a vastly increased permeability compared with hole 1) was 250 feet deep, and it seems unlikely that any stress removal would extend to this depth. It is significant that the crushed zone (which has been created by stress effects) is no thicker in older regions (table 1).

⁶Shown in table 2 as $\left[\frac{\text{flow}}{\text{pressure} \times \text{depth}} \right]$, or $\left[\frac{A}{B \times \text{depth}} \right]$, or $\left[\frac{C}{B} \right]$.

⁷Since other factors affect permeability, there appear to be some exceptions, which will be discussed later.

TABLE 2. - Methane flow data

Coalbed	Mine	Hole No.	Time since mining, days	Depth, ft	A Flow from entire hole, cu ft per day	B Pressure at end of hole, psig	C Flow from last foot at end of hole, cu ft per day	$\frac{A}{B \times \text{depth}}$	$\frac{C}{B}$
Pittsburgh.....	Federal No. 2.....	3	15	113	10,000	27	155	3.3	5.7
		4	60	100	17,000	21	833	8.1	39.6
		5	912	100	18,200	4	-	45.5	-
Hartshorne.....	Howe No. 1.....	4	91	30	-	17	10	-	.59
		5	91	39	-	16.5	20	-	1.2
		3	48	93	-	51	3.3	-	.06
		9	48	63	-	48	20	-	.42
		10	143	32	2,220	50	-	.54	-
		11	40	113	6,620	140	588	.42	4.2
Pocahontas No. 3.	Beatrice.....	1	15	100 (avg)	5,000 (avg)	650	-	.08	-
		2	30	100	7,500	360	-	.21	-
Pocahontas No. 3.	Kepler.....	1	10	55	600	124	-	.09	-
		4	120	100	1,250	50	-	.25	-

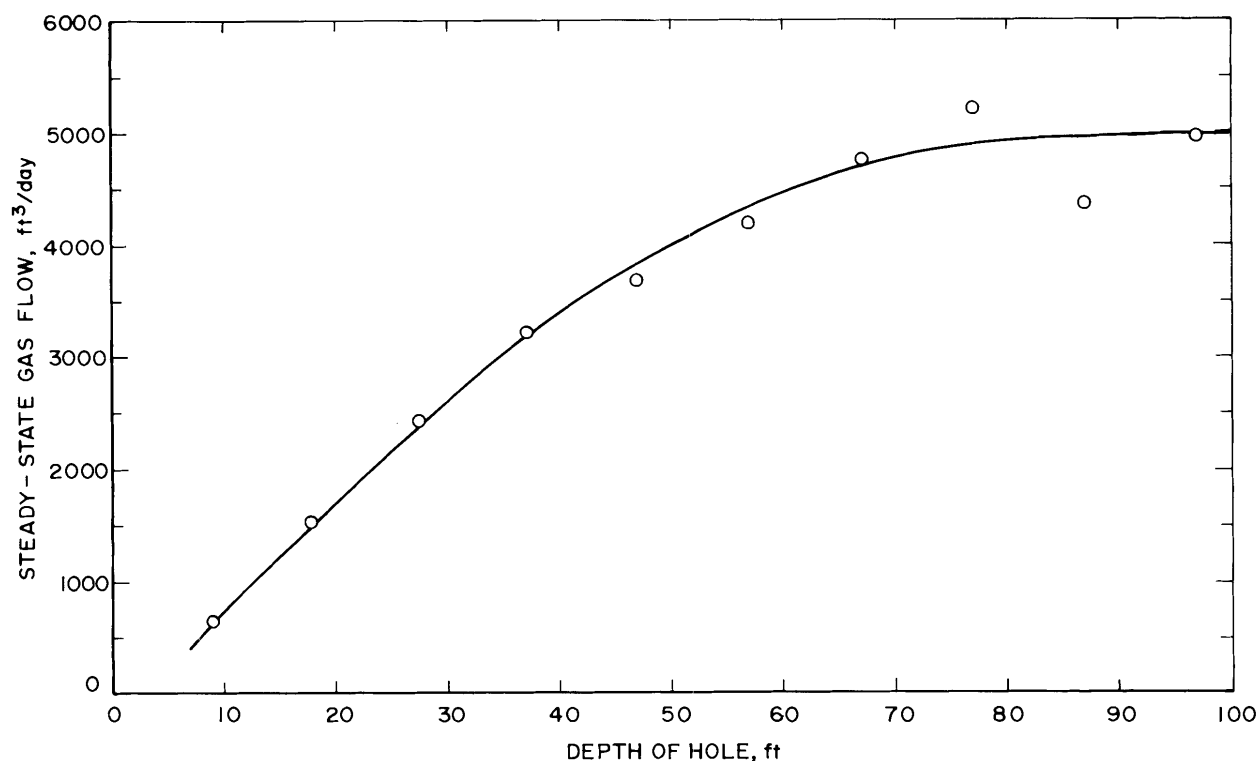


FIGURE 8. - Federal No. 2 Mine, Steady-State Flow From 6-Foot Increments of Open Hole.

POSSIBLE REASONS FOR PERMEABILITY INCREASE

Present evidence suggests that the increase in permeability is due to a loss of water from the coalbed rather than a reduction in stress. Drill crews frequently have noticed that holes drilled into freshly mined faces and ribs emit much more water than those drilled in faces or ribs mined months earlier. From natural gas reservoir studies (6), it is known that the amount of water in the reservoir rock strongly affects the permeability to gas; more water results in less gas permeability. If a freshly mined area of a coalbed contains water, its permeability to gas is relatively low. However, as the water and gas drain into the mine, the water content of the coalbed is reduced, and the gas permeability increases.

Aside from casual observation, the only firm evidence for this as yet is from borehole waterflows. Some borehole gas and waterflow data were obtained by the Bureau of Mines during a recent experiment at the Beatrice mine. In an attempt to drain methane from the coalbed ahead of the working face, several holes were drilled ahead of the face. One of these emitted 7,260 cubic feet of gas per day and 3 gallons of water per hour (per 100 feet of hole) on the second, third, and fourth days after drilling. However, on the sixth day, the waterflow dropped to 2 gallons per hour and the gas flow increased to 7,960 cubic feet per day. This was in a freshly mined area. Later, in the same mine, a 100-foot hole was drilled into an area mined 30 days earlier (shown as Beatrice hole 2 in tables 1 and 2). The waterflow was 0.2 gallon

per hour, but the gas flow was about the same (7,500 cubic feet per day, table 2) as from the hole in the freshly mined area, even though the pressure was about half that of the freshly mined area.

More data on waterflows from boreholes are required to establish how much variation in permeability is caused by loss of water. It is likely that the total quantity of water involved is much less than that of a natural gas reservoir; the fracture porosity of coal has been estimated at less than 1 percent. Most, if not all, of the water reaching the face evaporates as soon as it exudes from the coalbed; this may be why only one of the three mines investigated had puddles of seepage water on the mine floor.

Another factor contributing to the permeability increase may be coal shrinkage. This was first suggested by Briggs (1). Moffat and Weale (10) found that coal expands as methane is adsorbed and shrinks as it is desorbed. If the pressure is reduced from 40 atmospheres to zero, the bulk shrinkage is about 0.1 percent. Rarely does the pressure in coalbeds fall quite this much, but even with lower pressures such an effect may be great enough to open up cracks in the coalbed.

It has been suggested (13) that the adjacent strata will have an effect on the pressure gradient; the notion being that the gas from the coalbed may leak through the adjacent strata to the mine, thus short-circuiting the coalbed. The roof and floor in a mine will converge with time; this is likely to open cracks in the roof and floor strata. Given the way the analysis was done in this report, such an opening of cracks would be interpreted as a permeability increase. However, results from the horizontal boreholes indicate the permeability increase is real; there is no other way to explain the high flow rates from low-pressure holes in older areas.

PERMEABILITY OF DIFFERENT COALBEDS AND EFFECT OF OVERBURDEN

If the time effect is taken into account, it is apparent from table 1 that the Pittsburgh coalbed is much more permeable than either the Hartshorne or Pocahontas No. 3 coalbeds. This difference in permeability also is reflected in the gas-emission rates from the horizontal holes (table 2). The gas-emission rate, corrected for differences in pressure and depth $\left[\frac{\text{flow}}{\text{pressure} \times \text{depth}} \right]$, is much higher for the Pittsburgh coalbed than for the others.

The permeability of coal measured in the laboratory greatly depends on the degree to which the sample is compressed (12), thus an inverse relationship might be expected between coalbed permeability and overburden depth. No such relationship is indicated in table 1. The deepest coalbed, Pocahontas No. 3, has a low permeability, which is expected. However, the permeability of the Hartshorne coalbed, which has the least cover, is just as low. Moreover, holes 10 and 11 in the Howe No. 1 mine were drilled in an area of the mine where the cover was 700 feet thick. No obvious variation in permeability exists between these holes and others in the same mine that were drilled where the overburden was only 285 feet. The only evidence for an overburden effect

in table 1 is the 0.56 millidarcy permeability given for Kepler mine hole 1 which may be compared with 0.32 for Beatrice mine hole 1. The difference in overburden is substantial (680 feet compared with 2,000 feet), but these represent relatively high overburden pressures. Patching (12) has shown that by far the greatest permeability changes take place below compressive stresses of 500 psi.

The nature of the coal may affect permeability more than overburden depth. Both the Pocahontas No. 3 and Hartshorne coals are friable, low-volatile, highly fractured coals, whereas the Pittsburgh coal is hard and blocky with far fewer (but more prominent) fractures. Still another factor may be the amount of water in the coalbed. The only conclusion to be drawn is that permeability appears to be affected by the nature of the coal and other factors more than by overburden depth.

ANISOTROPY IN PERMEABILITY

Permeability can be expected to have directional anisotropy in coalbeds that have pronounced face cleat and butt cleat characteristics. The permeability should be greatest in the direction of the surface of the face, or major, cleat. The face cleat is a continuous joint surface that crosses bedding planes in the coal and extends for many feet. On the other hand, the butt cleat is a short, discontinuous joint surface that often terminates against a face cleat. The surface of the butt cleat often is curved, and the butt cleat occurs less frequently than the face cleat. It follows that regions of the coalbed drained primarily by face cleats will be drained of gas more easily and will, therefore, exhibit lower pressures than those regions drained by butt cleats (given equal drainage times). The permeability values listed in table 1 are simply calculated using the hole pressure (the pressure curve); the lower the hole pressure, the higher the calculated permeability.

Of the three coalbeds listed in tables 1 and 2, the Pittsburgh bed is the only one with pronounced face cleat and butt cleat development. The face, or major, cleat direction is roughly east-west, whereas the butt cleats trend⁸ north-south. Hole 3 was the only hole drilled parallel to the face cleat direction into a region drained by the face cleats, and should give the greatest permeability (fig. 9 and table 1). The effect is obscured somewhat by the apparent increase of permeability with time, but it is clear that the relatively high value of 82.5 millidarcys listed for hole 3 is not the result of drilling into an old region.

The gas flow data from Federal mine holes 3 and 4 give additional evidence for a permeability anisotropy. Hole 4 was drilled parallel to the butt cleat direction into a region drained by butt cleats; therefore, the permeability calculated from the pressure curve (33 millidarcys) is lower

⁸Parsons (11) has measured the lateral compressive stresses in strata adjacent to the Pittsburgh coalbed and has found that the major lateral stress is in an east-west direction. Thus the butt cleats are squeezed more tightly, and the permeability difference is even more enhanced.

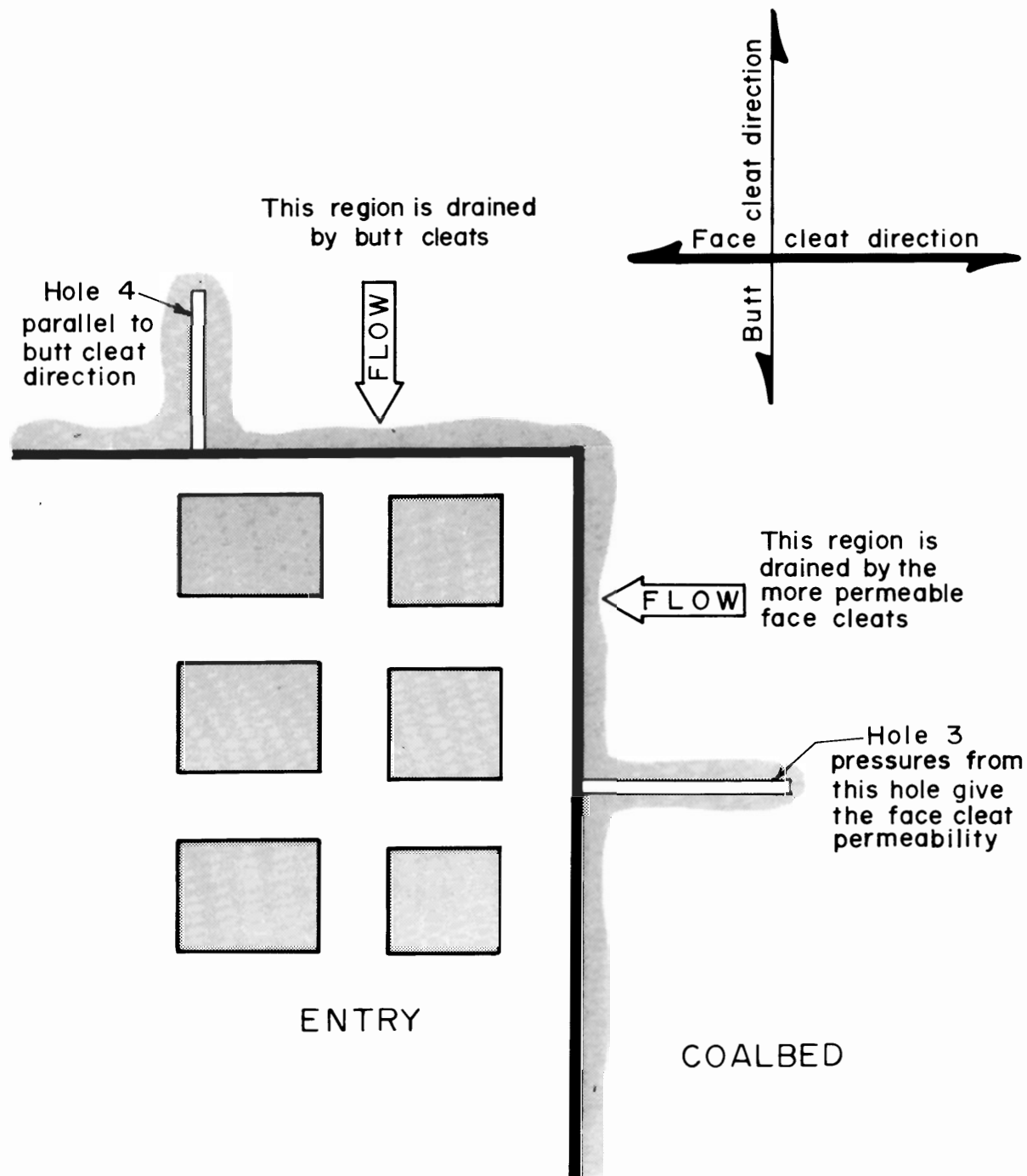


FIGURE 9. - A Mine Entry in a Coalbed With Pronounced Face Cleat and Butt Cleat Development.

than that of hole 3 (82.5 millidarcys)(fig. 9). Despite this lower permeability, the flow of gas corrected for differences in pressure and depth, that is $\left[\frac{\text{flow rate}}{\text{pressure} \times \text{depth}} \right]$, is over twice that of hole 3 (table 2). The

reason for this unusual effect is that the hole pressures are controlled by the permeability parallel to the hole, and therefore the 33 millidarcys from hole 4 is a butt cleat permeability. However, the factor governing the borehole flow rate is the permeability of the cracks the hole intersects, and not the permeability parallel to the hole. Hole 4 intersects the face cleats, whereas hole 3 intersects butt cleats. It follows that hole 4 intersects more permeable cracks than does hole 3, and that the flow from hole 4 should be greater than from hole 3 over and above what would be expected from differences in pressure and depth. Table 2 confirms this.

If holes give different flow rates for different directions, the same might be expected for the mine entries. The Bureau of Mines recently did a careful methane survey in conjunction with a water-infusion experiment in the No. 2 west mains of the Federal No. 2 mine. It was found that in this location the methane emission from the solid rib was far greater than the emission from the working face (the section was idle at the time, so there was no contribution from the advance of the mining machine (7)). This difference in emission rates was not surprising, for the rib intersected the face cleats (as in hole 4), and the face was draining the less permeable butt cleats. The same effect also took place elsewhere in the mine, with face cleats yielding more gas than the butt cleats (other things being equal). It has been implicitly assumed that the rib lines are perfectly parallel with the cleats. This is true in the Federal No. 2 mine. However in many other mines in the Pittsburgh coalbed the rib line and cleat vary by a few degrees.

OTHER VARIATIONS IN PERMEABILITY

It has been suggested (8-9) that in longwall faces a tight abutment zone of abnormally low permeability exists between the crushed zone of high permeability and the intact coalbed. If such an abutment zone existed in mines worked by the advancing room-and-pillar method, a region of the pressure curves shown in figures 1-7 would be steeper than that expected from theory. No distinct evidence of such a steep region can be seen in most of these figures, nor in those publications cited previously (2, 7). There is a possibility that this zone is very narrow and easy to miss; however, at least one hole (Federal mine hole 4, fig. 2) was tested with the pressure points close together so that variations over a small region would not be missed. Flow measurements were taken for each pressure point in the same hole (fig. 8). The flow curve closely parallels the pressure curve shown in figure 2, which indicates that no sharp variations in permeability with distance exist beyond the crushed zone in this case.

The possibility of an abutment zone in room-and-pillar workings cannot be ruled out completely. Theory based on constant permeability beyond the crushed zone would indicate that for inactive areas, the pressure curve should not level off in the first 100 feet. For instance, in Federal mine holes 4 and 5 (fig. 2) the pressure is still climbing at the last measured point. However, in hole 1 (fig. 1) the pressure appears to approach an asymptote, which might be caused by a region of low permeability between 20 and 40 feet. Hole 10 in figure 6 shows the same effect.

Still other variations in permeability may exist for reasons that have not been established. For example, in the Howe mine, holes 2 and 3 gave lower permeabilities than holes 4, 5, 8, and 9. Holes 2 and 3 were in a different location from that of the others, and the coalbed may have been wetter here. It is also possible that an incorrect bed pressure was assumed.

It should be emphasized that the coalbed properties given in this report have a limited applicability, and the properties cannot be expected to predict gas flow into every part of a mine. For example, in the Kepler mine, holes 1 and 4 are 1,900 feet apart (hole 1 is in the east mains and hole 4, in the south mains). The bed pressure of 155 psia was obtained by extrapolating the pressure curve of hole 1, and this was also assumed to be the bed pressure at the location of hole 4. A mile south of the mine a vertical well was drilled into the virgin coalbed. It was packed, and a pressure of 173 psia was measured⁹ and therefore the 155 psia from extrapolation was not too bad.

However, in the west mains about 3,000 feet to the northwest of holes 1 and 4, the situation is entirely different. The west mains are much less gassy than the south and east mains, and horizontal holes drilled into ribs give only 10 to 15 psig at the end of the hole. For some reason, the coalbed in the area of the west mains contains less gas than in other areas of the mine. The cause of this is not clear. It may be due to a fault in the area, or to the fact the west mains are close to a region where the overburden is only 310 feet instead of the usual 680 feet. This report has not taken such effects into account.

It must be recognized that a permeability of 0.56 or 1.1 millidarcys, as shown in table 1 for the Kepler mine, probably would not permit such extreme variations in pressure in just 3,000 feet to exist. A permeability of 1 millidarcy is not large, but over geologic time it is enough to insure a relatively constant coalbed pressure over very wide areas. The only conclusion is that the values of permeability shown in table 1 are for coalbeds that have already been influenced by the mining process and that the permeability of the virgin coalbed was much lower.

CONCLUSIONS

The in-situ permeability of three coalbeds has been calculated from field measurements. The findings are as follows:

1. The nature of the coal seems to have a more important effect than overburden pressure on permeability.
2. Where face and butt cleats are prominent, the coalbed is more permeable in the direction of the surface of the face cleat.
3. A high-permeability crushed zone along ribs and faces appears to be a common feature of all mines.

⁹This pressure was measured in conjunction with the BuMines program for coalbed degasification by vertical wells.

4. Beyond the crushed zone there is no evidence for an abutment zone of low permeability.

5. The effect of in-situ water on the permeability to gas is very great. Older regions of a mine from which the water has drained have vastly increased permeabilities. The practical effect of this is to maintain a high borehole flow.

6. The permeabilities given in table 1 are for coalbeds that have already been affected by the mining process. Virgin coalbed permeabilities are probably much lower.

The analysis presented here is preliminary. Its objective is to delineate the major factors that control coalbed gas emission. A better theoretical treatment must await much more comprehensive field data.

REFERENCES

1. Briggs, H. Characteristics of Outbursts of Gas in Mines. Trans. Inst. Min. Eng., v. 72, 1926-27, pp. 323-324.
2. Cervik, Joseph. Behavior of Coal-Gas Reservoirs. BuMines Tech. Prog. Rept. 10, April 1969, 10 pp.
3. Hadden, J. D., and Joseph Cervik. Design and Development of Drill Equipment. BuMines Tech. Prog. Rept. 11, May 1969, 11 pp.
4. Hadden, J. D., and Albert Sainato. Gas Migration Characteristics of Coalbeds. BuMines Tech. Prog. Rept. 12, May 1969, 10 pp.
5. Hargraves, A. J. Seam Gases in Coal Mines. Symp. Univ. of Sydney, Sydney, Australia, March 1966, 200 pp.
6. Katz, D. L. (ed.). Handbook of Natural Gas Engineering. McGraw-Hill Book Co., Inc., New York, 1959, 802 pp.
7. Kissell, Fred N. Methane Migration Characteristics of the Pocahontas No. 3 Coalbed. BuMines Rept. of Inv. 7649, 1972, 19 pp.
8. Lama-Mahajan, Ripu Daman. Outbursts of Gas and Coal. Coll. Eng., v. 45, 1968, p. 103.
9. Metcalf, J. R. The Front Abutment of a Longwall Face. Int. J. Rock Mech. Min. Sci., v. 4, 1967, p. 195.
10. Moffat, D. H., and R. W. Weale. Sorption by Coal of Methane at High Pressures. Fuel, v. 34, 1955, p. 449.
11. Parsons, Robert C., and H. D. Dahl. A Study of the Causes of Roof Instability in the Pittsburgh Coal Seam. 7th Can. Symp. on Rock Mech., Alberta, Canada, Mar. 25-27, 1971.
12. Patching, T. H. Variations in Permeability of Coal. Proc. 3d Rock Mech. Symp., Univ. of Toronto, Jan. 15-16, 1965, Mines Branch, Ottawa, Canada, 1965, 204 pp.
13. Selden, R. F. The Occurrence of Gases in Coals. BuMines Rept. of Inv. 3233, June 1934, 64 pp.
14. Stewart, Ian McC. Diffusional Analysis of Seam Gas Emission in Coal Mines. Canadian Min. and Met. Bull., April 1971, pp. 62-70.

APPENDIX.--APPLYING THE UNSTEADY-STATE DARCY EQUATION TO EXPERIMENTAL PRESSURE CURVES

There are some difficulties involved in applying the Darcy equation to the pressure curves. For the most part the difficulties listed are due to the lack of sufficient experimental data.

1. There is difficulty involved in obtaining a value for P_{seam} , the pressure before mining. A major assumption in the analysis is that the coalbed is a slab at uniform pressure P_{seam} before mining, and that at time zero the face is reduced to atmospheric pressure. This probably is not a bad assumption in coalbeds of low permeability where the pressure curve is very steep and P_{seam} can be measured at the back of a 100-foot borehole drilled into a fresh area. However, in a permeable coalbed such as the Pittsburgh bed, the slab of coal begins to drain and lose gas pressure long before it is mined, and the initial pressure is unknown. The best that can be done under the circumstances for permeable coalbeds is to extrapolate the pressure curve that gives the highest pressures. Hole 2 (fig. 1) was used to obtain P_{seam} for the Pittsburgh coalbed.

2. The desorption of methane from the pore structure of the coal is fast as compared with the Darcy flow to the face or rib through cracks in the coalbed. Thus, the measured pressures from deep within the coalbeds are correct indications of the amount of gas contained in the coal (7); that is, the pressure and the amount are in equilibrium. It follows that the pressures close to zero measured at the face would mean that virtually no gas is left in the coal close to the face.

The Bureau of Mines has collected some coal lumps at an active face in the Federal No. 2 mine and sealed them in a container. The methane given off from the container for the next 2 months was measured. During this time the coal gave off an amount of methane equivalent to 4 cubic centimeters per gram of coal. This amount of methane corresponds to an equilibrium adsorption pressure of about 50 pounds per square inch, absolute. On the other hand, while the sample was in the intact face, it was subjected to only 1 atmosphere of pressure. It appears then that there is more gas in the Pittsburgh coal than the pressure in the fractures would indicate. This would not affect the computed coalbed permeability because permeability is defined in terms of the pressure curve and the observed emission rate. However, it would cause the sorption capacity to be lower than that expected from laboratory sorption experiments, which are done only under equilibrium conditions.

Another way of stating the same thing would be to say the Pocahontas No. 3 coalbed has a good internal equilibrium; that is, deep in the coalbed the amount of adsorbed gas is in equilibrium with the gas pressure in the cracks. It follows that the computed sorption capacity is close to values obtained from equilibrium laboratory measurements. On the other hand, the Pittsburgh coalbed does not have good internal equilibrium. Some gas is retained in the coal as the fracture pressure falls, and the result is a lowered sorption capacity.

3. Another assumption is that the sorption capacity; that is, the $\left[\frac{\text{volume adsorbed per atmosphere}}{\text{volume of coal}} \right]$ is constant. A constant sorption capacity would mean the equilibrium adsorption isotherm is linear, when in fact it is known the methane-coal isotherm is not linear, but follows the Langmuir equation. Dry Pocahontas No. 3 coal adsorbs 10 cubic centimeters per gram of methane at 10 atmospheres pressure. (All volumes are given at standard temperature and pressure.) If a coal density of 1.3 grams per cubic centimeter is assumed, this corresponds to a sorption capacity of 1.3. At 20 atmospheres, 13 cubic centimeters per gram is adsorbed, and this corresponds to a sorption capacity of 0.84. The Hartshorne coal is similar.

Just a few percent moisture in coal considerably decreases the amount adsorbed, therefore it is not surprising that the in-situ sorption capacity for Pocahontas No. 3 coal should be 0.56. In any case, an increase in the sorption capacity, S , as the pressure falls is not likely to explain why the quantity K/S rises with time.

4. A more exact solution to the Darcy equation for unsteady-state gas flow is available (6, p. 421), and, if it is used the calculated permeabilities are somewhat lower. However, the major conclusions about the crushed zone, directional anisotropy, permeability increase, and so forth, are all unchanged.