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**An In-Situ Diffusion Parameter  
for the Pittsburgh and Pocahontas  
No. 3 Coalbeds**



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No. 3 Coalbeds**

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# AN IN-SITU DIFFUSION PARAMETER FOR THE PITTSBURGH AND POCAHONTAS NO. 3 COALBEDS

by

Fred N. Kissell<sup>1</sup> and R. J. Bielicki<sup>2</sup>

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## ABSTRACT

In this report the importance of diffusion in controlling the emission of methane in mines is examined. An in-situ diffusion parameter is defined and calculated for a hypothetical unfractured lump of coal in the Pittsburgh and Pocahontas No. 3 coalbeds. The values obtained are similar to those obtained with lump coal in laboratory experiments.

## INTRODUCTION

The flow of methane gas in coalbeds has been a topic of Bureau of Mines research for many years. Methane, produced as a byproduct of the coalification process, is stored in the coal, frequently in considerable quantities. The gas is released where the coalbed is mined, and under some conditions, may present considerable danger to those working in the mine.

Unfractured "solid" coal has a very low permeability; however, bituminous coalbeds in place are highly fractured. The quantity of methane entering a typically gassy coal mine is far greater than could be imagined from any unfractured coalbed, and it is clear that virtually all of the gas entering the mine has come through fractures both in the coal and in the adjacent strata.

Not very much is known about the nature of these fractures, but for coal two facts have been definitely established:

1. The density of fractures varies with the coal rank; friable, low-volatile coals tend to be much more highly fractured.

2. The fractures in a given coal are not of uniform size or spacing. It has been shown by mercury-intrusion studies that there are fractures of all sizes from less than 100 A to several microns in width (15).<sup>3</sup>

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<sup>2</sup>Physical science technician.

<sup>3</sup>Underlined numbers in parentheses refer to items in the list of references at the end of this report.

Because of these fractures, it has been assumed that the gas flow from the coal into the mine is a two-step process (7). In the first step, gas flows from lumps of unfractured, solid coal into the fractures that surround and define these lumps. The lumps may be deep within the coalbed, or they may be close to the mine working. In the second step, gas flows through the fractures to the mine.

In a consecutive process of this sort, if one of these steps is considerably slower than the other, the overall gas flow rate is determined by the speed of the slow step. This is an obvious simplification to make in analyzing the problem, and both extremes have been taken. For instance, Airey (1) has assumed that the coalbed is a collection of desorbing lumps, and that resistance to flow encountered in the fractures is negligible. This means the first step is the slow one. On the other hand, Kissell (13) has calculated some coalbed permeability values by assuming the second step was the slow one. It does not follow that one approach is correct and the other is not. Coalbeds are sufficiently different from one another that it is entirely plausible that either may be reasonable depending on the properties of the coalbed being tested. Further, it follows that there may be many coalbeds that are intermediate in nature; that is, where both steps must be taken into account. In fact, experimental evidence now suggests that many coalbeds may be in this category, and it is clear that any thorough treatment must take both steps into account.

Cervik (4) has suggested that in the first step, flow from the solid lumps takes place by diffusion and that in the second step, flow in the fractures follows Darcy's law (laminar flow). Evidence does definitely suggest the latter is true; calculated fracture widths and Reynolds numbers indicate that gas flow in the fractures is indeed laminar. It is less certain that the gas diffuses from the solid lumps; however, there is evidence for this in Sevenster's (14) laboratory work on powdered coal and coal lumps. The determining factor will be the ratio of passage width to the mean free path of the gas molecule. However, in the absence of further information, a two-step process based on diffusion and laminar flow appears to be a good starting point for further analysis.

#### IN-SITU DIFFUSION PARAMETER

Kissell (13) has obtained some values for coalbed permeability by considering coalbed gas pressures and the rate at which methane flows into the mine. These values represent the permeability of the fractures through which the flow is laminar. Although the diffusion parameter  $\frac{D}{a^2}$  of coal powders and lumps has been measured in the laboratory, no estimate of an in-situ diffusion parameter of solid coal underground has ever been made. This means that it has been impossible to estimate accurately the rate of the first flow step compared with the second.

This report presents a method of obtaining an in-situ diffusion parameter. Although the results are not highly accurate, nevertheless they provide a

reasonable correlation with laboratory diffusion parameters and also some insight into how gas migrates in coalbeds.

#### RESIDUAL GAS--CALCULATION OF IN-SITU DIFFUSION PARAMETER

The Bureau of Mines has been engaged in a program of measuring methane pressures in coalbeds. These pressures are measured by drilling a horizontal hole into the working face or a rib and sealing the hole with inflatable packers (8-9). A pressure curve for a hole 160 ft deep is shown in figure 1. Not only is the pressure at the back of the hole measured, but pressures at intermediate distances also are obtained. These pressures represent the pressure of gas in the fractures. If the first flow step (the diffusion step) is fast compared with the second step (the fracture flow step), these pressures also represent the amount of gas in the coal at any given depth. However, if the two steps have a comparable rate or if the first step is slower, the amount

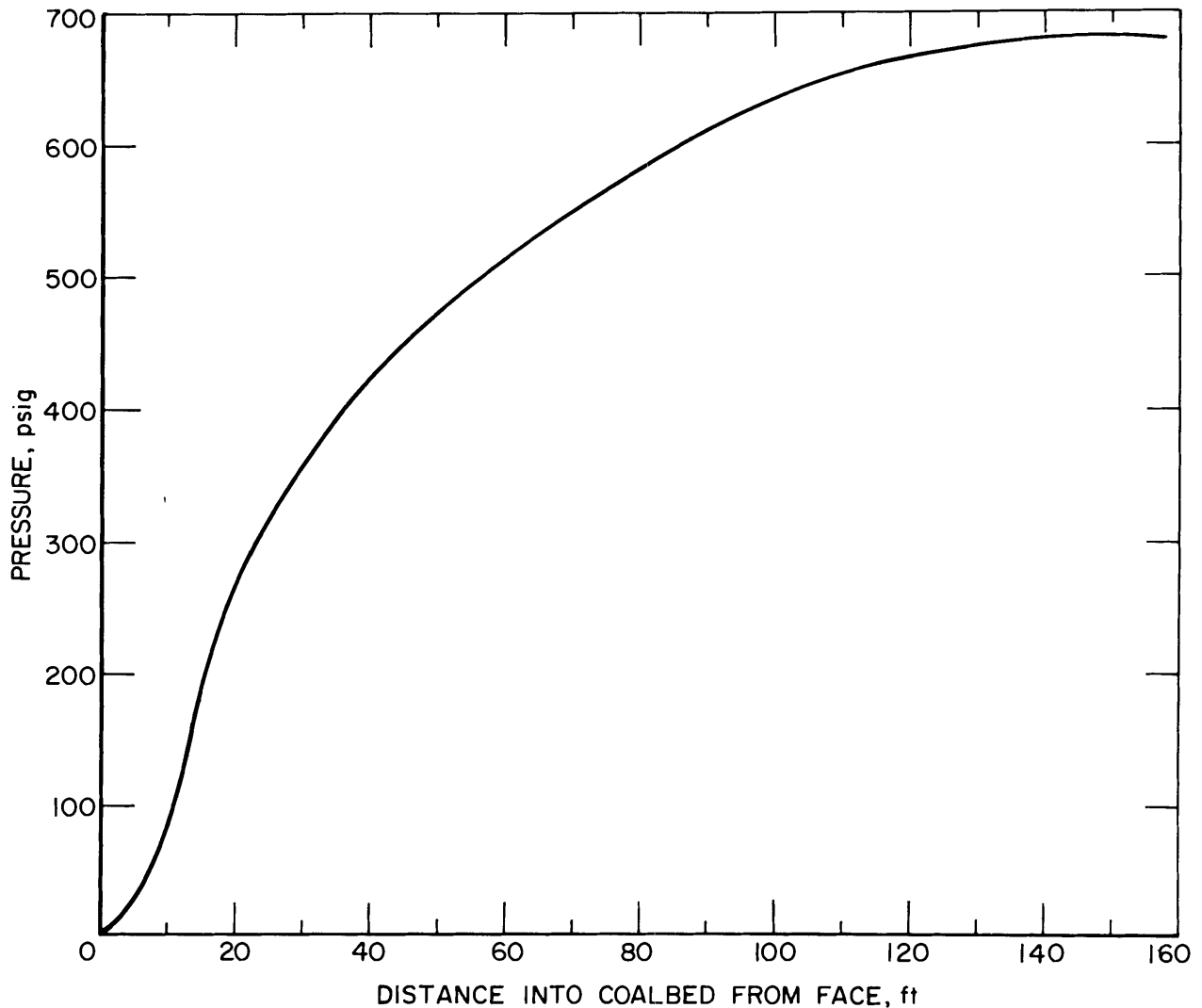


FIGURE 1. - A Pressure Curve in Pocahontas No. 3 Coalbed.

of gas in the coal actually will exceed the amount indicated by the fracture pressure.

Fortunately, a simple method exists for testing which is true. The pressure curve shown in figure 1 indicates that the pressure in the fractures within a few feet of the working face is virtually zero. If diffusion is fast when compared with the fracture flow, the amount of gas in a sample collected at the working face (the "residual gas")<sup>4</sup> also will be virtually zero.

One example in which the residual gas was close to zero was in a mine in the Pocahontas No. 3 coalbed (12). At this mine, the residual gas amounted to about 1 cm<sup>3</sup>/g, whereas the original gas concentration before mining was estimated to be 13 cm<sup>3</sup>/g. (All gas volumes have been corrected to standard temperature and pressure.) It is clear for this coalbed that the diffusion step is fast compared with the fracture flow step. However, at a mine in the Pittsburgh coalbed, the residual gas was approximately 4 cm<sup>3</sup>/g, whereas the original gas concentration was 6 to 7 cm<sup>3</sup>/g. For the Pittsburgh coalbed, it appears that the speed of the diffusion step is comparable with or less than that of the fracture flow step, and thus consideration of the in-situ diffusion parameter is especially important.

The residual gas measurements present a unique way of estimating a diffusion parameter. To accomplish this, a hypothetical lump of coal in the coalbed can be considered. If no mine opening is nearby, the quantity of gas in the lump is in equilibrium with the gas pressure in the fractures surrounding the lump. The quantity-pressure relationship will be given by the equilibrium adsorption isotherm, which is the curve relating the quantity of gas adsorbed in the coal to the surrounding pressure at constant temperature and under equilibrium conditions. Isotherm curves for Pittsburgh and Pocahontas No. 3 coals are shown in figure 2. As a mine working approaches the hypothetical lump, gas will seep into the mine, and the pressure in the fractures surrounding the lump will decrease, causing desorption of gas from the lump. Eventually, the mine working face will reach the hypothetical lump, which then may be collected for the residual gas measurement. Two aspects of this sequence are important:

1. A "pressure history" of the hypothetical lump may be deduced from the rate of advance of mining, a related pressure curve such as that in figure 1, and an estimate of the original gas content.

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<sup>4</sup>To obtain the residual gas, a sample of coal is collected at a working face that has been continuously active and which penetrates into a virgin area of the coalbed. The coal is immediately enclosed in a container, and the quantity of gas given off over the next several weeks is measured. Then, the coal is crushed to at least 200 mesh, and the gas given off in the crushing is measured. The gas given off by the coal while in the container plus that from the crushed sample is the residual gas.

Both steps are performed at 1 atm pressure. After crushing, the coal still will retain some methane unless the atmospheric pressure is reduced to zero. This retained gas is not included in the "residual gas."



5 cm<sup>3</sup>/g is adsorbed (fig. 2). If the density of coal is assumed to be 1.3, this corresponds to  $2.9 \times 10^{-4}$  moles/cm<sup>3</sup> of coal. At the face, the absolute pressure is 1 atm, and  $0.44 \times 10^{-4}$  moles/cm<sup>3</sup> of coal is adsorbed. It follows that in the 2-week period the surface concentration of the lump is reduced by  $2.46 \times 10^{-4}$  moles/cm<sup>3</sup> of coal.

A typical value for residual gas in Pittsburgh coal is about 4 cm<sup>3</sup>/g. This means that only about 20 pct of the original gas is lost from the coal, or  $0.20 \times 2.9 \times 10^{-4}$  moles/cm<sup>3</sup> =  $0.58 \times 10^{-4}$  moles/cm<sup>3</sup>.

Crank (5) gives solutions to the diffusion equation for various shapes under different boundary conditions. For a sphere whose surface concentration varies linearly with time [ $\phi(t) = kt$ ] the solution is

$$\frac{M_t}{\frac{4}{3}\pi a^3 k} = \left( t - \frac{a^2}{15D} \right) + \frac{6a^2}{\pi^4 D} \sum_{n=1}^{\infty} \frac{1}{n^4} e^{-\frac{D n^2 \pi^2 t}{a^2}},$$

where  $\frac{D}{a^2}$  = the diffusion parameter  $\left( \frac{1}{\text{sec}} \right)$ ,

$a$  = sphere radius (cm),

$D$  = diffusion coefficient  $\left( \frac{\text{cm}^2}{\text{sec}} \right)$ ,

$t$  = time (sec),

$M_t$  = amount sorbed or desorbed (moles) at time  $t$ ,

$$\frac{M_t}{\frac{4}{3}\pi a^3} = \frac{\text{amount sorbed or desorbed}}{\text{unit volume}} \left( \frac{\text{moles}}{\text{cm}^3} \right),$$

and  $k = \text{const} = \frac{\phi(t)}{t} \left( \frac{\text{moles}}{\text{cm}^3 \text{ sec}} \right)$ .

If it is assumed that the hypothetical lump is a sphere of radius  $a$ , that this sphere has a surface concentration that varies linearly at the rate of  $\frac{2.46 \times 10^{-4} \frac{\text{moles}}{\text{cm}^3}}{2 \text{ weeks}}$  or  $k = 2.03 \times 10^{-10} \frac{\text{moles}}{\text{cm}^3 \cdot \text{sec}}$ , and that the amount desorbed is  $0.58 \times 10^{-4}$  moles/cm<sup>3</sup>, then  $\frac{D}{a^2} = 1.3 \times 10^{-8}$ . Note that this quantity is  $D/a^2$ , not  $D$ . This is not surprising, for the size of the hypothetical lump is just as important as the diffusion coefficient, and where in-situ coal is concerned, a  $D$  alone would be meaningless, simply because the lump size is unknown. It should be pointed out that both the residual gas and the pressure curve will vary somewhat from location to location in the mine, depending on the rate of advance and other factors (12-13). However, the diffusion parameter is not very sensitive to minor changes in any of these.

2. The difference between the original gas content and the residual gas is the amount of gas lost from the hypothetical lump.

This information may be inserted into a standard solution for the diffusion equation to obtain a diffusion parameter for the hypothetical lump.

#### Calculation for Pittsburgh Coalbed

In a mine in the Pittsburgh coalbed that was the subject of a previous study (13), the pressure in the undisturbed coalbed was assumed to be 120 psia. The gradient of a typical pressure curve in this coalbed was about 60 psi per 100 ft, and a typical advance in the section under study was about 100 ft per week. The elapsed time for the lump to "reach" the face from the undisturbed

coalbed was 2 weeks. Thus, for 2 weeks the pressure in the fractures surrounding the hypothetical lump fell at a rate of 60 psi per week. This is the pressure history of the hypothetical lump.

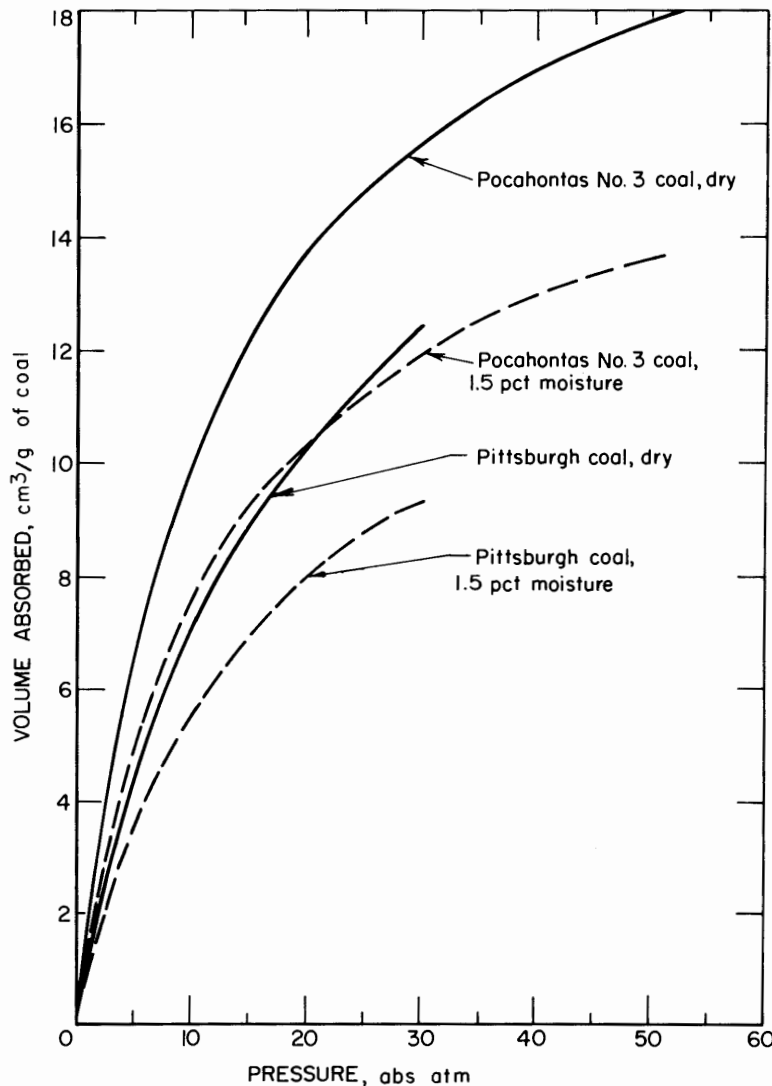


FIGURE 2. - Equilibrium Adsorption Isotherms for Pittsburgh and Pocahontas No. 3 Coals.

Next, from this pressure history the variation in the surface concentration of the hypothetical lump may be calculated if it can be assumed that the surface concentration is in equilibrium with the fracture pressures.

Through a personal communication with T. C. Ruppel<sup>5</sup> equilibrium adsorption isotherms have been obtained for dry and moist Pittsburgh and Pocahontas No. 3 coals. In-situ coal always contains moisture, and moist coal adsorbs less gas than dry coal. This moisture effect was first observed by Ettinger (6).

If the coalbed is assumed to contain 1.5 pct moisture at 120 psia,

<sup>5</sup>Research chemist, Pittsburgh Energy Research Center.

### Calculation for Pocahontas No. 3 Coalbed

A pressure curve for a deep mine (12) in the Pocahontas No. 3 coalbed is shown in figure 1. It is much steeper than the curve for the Pittsburgh coalbed, and the original coalbed pressure is reached in about 100 ft. Thus, the pressure around the hypothetical lump drops from 680 psia to 15 psia in just 1 week. If the coals were similar, the residual gas content would be quite high, but the opposite is true. The residual gas is only 1 to 1.5 cm<sup>3</sup>/g, whereas Ruppel's adsorption curve gives 13.1 cm<sup>3</sup>/g for the original coal, assuming 1.5 pct moisture. This means that nearly 90 pct of the original gas is gone, whereas for the Pittsburgh coal it was only 20 pct.

Applying the same analysis used previously,  $k = 11.3 \times 10^{-10}$ , the amount desorbed =  $6.14 \times 10^{-4}$ , and  $\frac{D}{a^2} = 1.05 \times 10^{-6}$ . This is 100 times larger than the  $\frac{D}{a^2}$  for Pittsburgh coal. Whether it is due to a larger D or a smaller a is immaterial, but later findings indicate that it is probably a combination of both.

#### COMPARISON WITH LABORATORY AND OTHER FIELD DATA

Another way to obtain  $D/a^2$  for a lump of coal is to pressurize the lump with methane in the laboratory. After the coal is equilibrated, the pressure is reduced abruptly, and the rate of emission of gas from the coal is measured. From the emission rate,  $D/a^2$  is calculated. The authors have obtained a number of emission curves for different size lumps of both Pittsburgh and Pocahontas coals; these will be published elsewhere. However, a few typical results are given in figure 3.

A simple procedure used by Hofer, Bayer, and Anderson (10) can be used to calculate  $D/a^2$  from these curves. The equation for diffusion from a sphere is applied again except that the boundary conditions are different [constant concentration at  $t = 0$  and surface concentration = 0 for  $t > 0$ ]. A solution valid for short times (2) is

$$\frac{M_t/M_\infty}{t^{1/2}} = \frac{6}{\pi^{1/2}} \frac{D^{1/2}}{a},$$

and  $D/a^2$  is found readily by plotting  $M_t/M_\infty$  against  $t^{1/2}$ . Using this procedure, we obtained  $\frac{D}{a^2} = 1.4 \times 10^{-8}$  for 1/4- to 1/2-in size range Pittsburgh coal and  $\frac{D}{a^2} = 0.5 \times 10^{-6}$  for 1/4- to 1/2-in size range Pocahontas coal.

It is known that  $D/a^2$  will vary with lump size only if the lump size is smaller than the fissure network of the coal (3). For Pocahontas coal, lumps 1/4 to 1/2 in in size already are larger than the fissure network as measured in the laboratory, and  $D/a^2$  does not change if the lump size is increased beyond this. Such is not the case for Pittsburgh coal;  $D/a^2$  will decrease slightly with an increase in lump size, but  $D/a^2$  still will be approximately  $10^{-8}$ .

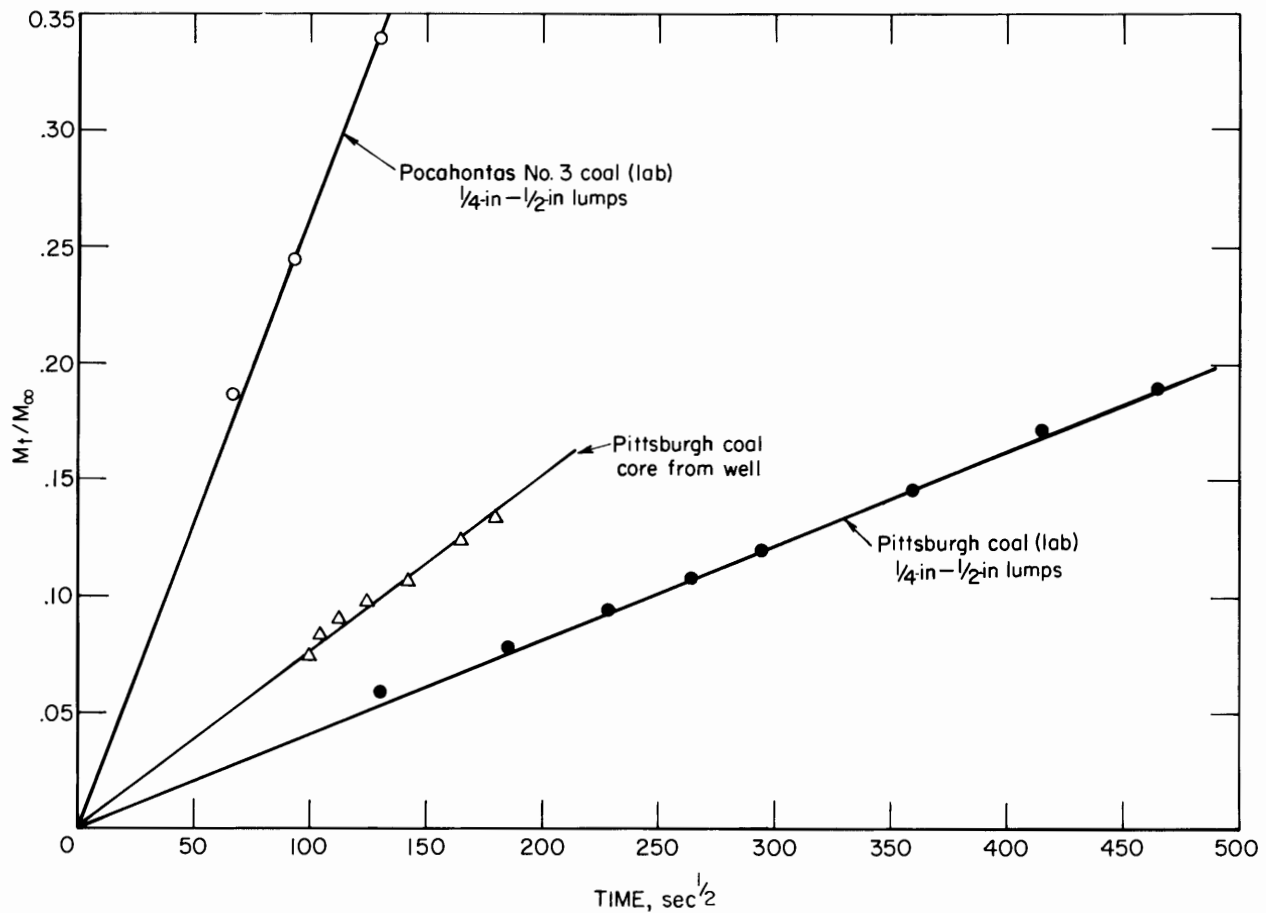


FIGURE 3. - Emission Curves for Pittsburgh and Pocahontas No. 3 Coals.

Another value of  $D/a^2$  for Pittsburgh coal was obtained recently by field experiment. A vertical well was drilled from the surface into the Pittsburgh coalbed near Amity, Pa., and a 4-in-diam core was brought to the surface. The core was enclosed immediately in a vessel, and the emission rate was measured (fig. 3). Some of the data are missing owing to the amount of time (150 min) required to cut the core and bring it to the surface, but a plot of  $M_t/M_\infty$  against  $t^{1/2}$  still could be made, and  $D/a^2$  was calculated to be  $4.95 \times 10^{-8}$ .

These results may be summarized as follows: For the Pittsburgh coalbed, the in-situ  $D/a^2 = 1.3 \times 10^{-8}$ . Lumps in the laboratory gave  $D/a^2 = 1.4 \times 10^{-8}$ , and a core from a vertical well gave  $D/a^2 = 4.95 \times 10^{-8}$ . For Pocahontas No. 3 coal, the in-situ  $D/a^2 = 1.05 \times 10^{-6}$ , and lumps in the laboratory gave  $D/a^2 = 0.5 \times 10^{-6}$ .

#### COMPUTATION OF IN-SITU FRACTURE SPACING

It is possible to compute an in-situ fracture spacing from the  $D/a^2$  values obtained. E. D. Thimons<sup>6</sup> (personal communication) has obtained values for

<sup>6</sup>Physicist, Pittsburgh Mining and Safety Research Center.

the transient diffusion coefficient  $D$  for Pittsburgh and Pocahontas No. 3 coal in the laboratory by flowing dry methane through small disks of coal. Timons obtained  $1.3 \times 10^{-6}$  for Pittsburgh coal and  $70 \times 10^{-6}$  for Pocahontas No. 3 coal. He also found that if the methane was saturated with water vapor (this is more realistic than using dry methane) the coefficient for Pittsburgh coal was reduced by a factor of 8, and for Pocahontas coal the coefficient was reduced by a factor of 14. This gives more realistic values of  $D = 1.6 \times 10^{-7}$  for Pittsburgh coal and  $D = 5 \times 10^{-6}$  for Pocahontas No. 3 coal. Now if

$\left(\frac{D}{a^2}\right)_{\text{pittsburgh}} \cong 10^{-8}$  and  $\left(\frac{D}{a^2}\right)_{\text{pocahontas}} \cong 10^{-6}$ , then  $2a_{\text{pittsburgh}} = 8$  cm and  $2a_{\text{pocahontas}} = 4.5$  cm, where  $2a$  is the diameter of the hypothetical sphere.

These values seem large, especially since the laboratory lump emissions results discussed previously indicate that the fissure spacing of Pittsburgh coal is closer to 2 cm and that of Pocahontas coal is approximately 1 mm. However, it must be remembered that coal in the laboratory has been treated rather harshly. The confining forces that squeeze the coal underground have been removed, and it has been torn from the coalbed by the mining machine. It has been sieved, evacuated, and dried in the desorption experiment. Just drying a lump of coal will crack it; therefore, it is not surprising that a fissure spacing in the laboratory will be much less than that found underground.

#### USING DIFFUSION PARAMETER TO FIND SLOW STEP

Previously, we pointed out that the flow of gas from a coalbed could be viewed as a two-step process, and that the analysis could be considerably simplified if one step could be considered much slower than the other. In particular, it has been assumed (12-13) that in the Pocahontas No. 3 coalbed the second step (laminar flow) is much slower than the first step (the diffusion from lumps). Since a value for  $D/a^2$  is available now, this hypothesis can be tested.

The easiest way to do this is to compare the time required for the hypothetical lump to lose half the original gas by diffusion with a similar time required for a hypothetical lump some distance back in a homogeneous coalbed. Using the equation valid for short times,

$$\frac{M_t/M_\infty}{t^{1/2}} = \frac{6}{\pi^{1/2}} \frac{D^{1/2}}{a}$$

If  $M_t/M_\infty = 0.5$  and  $D/a^2 = 10^{-6}$ , then  $t = 6$  hr. This should be the time required for the hypothetical lump of Pocahontas No. 3 coal to lose half of its original gas by diffusion from the lump.

The foregoing may be compared with a hypothetical lump in a homogeneous coalbed where there is no diffusion step and the flow is entirely laminar and follows the Darcy equation,

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

Here,  $P$  is the gas pressure (atm),  $x$  is the distance into the coalbed from the working face (cm),  $\eta$  is the viscosity of methane (cp),  $K$  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 (sec).

An approximate solution is given by the following equation (12):

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

where  $\operatorname{erfc}$  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  $= \frac{t_m \bar{P} K}{\eta x^2 S}$ ,  $P(x,t)$  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 the working face was mined and gas began to flow, and  $\bar{P}$  is the average pressure at  $x$ . At  $t_m = 0$ , the coalbed is assumed to be at uniform pressure  $P_{seam}$ .

In a previous paper (12), the ratio of the permeability of the coal to the sorption capacity of the coal,  $K/S$ , for the Pocahontas No. 3 coalbed was found to be  $0.57 \times 10^{-3}$  darcy 15 days after mining and  $3.6 \times 10^{-3}$  darcy 30 days after mining. If we use the 30-day value for  $K/S$ ,  $\frac{P(x,t)}{P_{seam}} = 0.5$ ,  $P_{seam} = 46$  atm,  $\bar{P} = 20$  atm, and if we assume the hypothetical lump is 50 ft into the coalbed from the working face, then  $t_m = 523$  hr. It should be noted that the boundary conditions are the same in each case. In other words, at  $t = 0$  the entire hypothetical lump or coalbed is at uniform concentration or pressure. Then, at  $t > 0$  the surface of the lump or working face of the coalbed has "zero" concentration or pressure.

It can be seen that diffusion of half of the gas out of the hypothetical lump requires 6 hr, whereas a lump in a homogeneous coalbed with only laminar flow through cracks will lose half of its gas in 523 hr if that lump is 50 ft from the working face. It is clear that the first step (the diffusion step) is much faster than the second. The low residual gas content of Pocahontas No. 3 coal verifies this.

In Pittsburgh coal, the residual gas content is high, and so it seems the first step may not be the fast one. Repeating the same procedure that was used for Pocahontas No. 3 coal, if  $D/a^2 = 10^{-8}$ , half the gas has diffused from the hypothetical lump in 600 hr. For the lump in the homogeneous coalbed,  $K/S$  is assumed to be  $50 \times 10^{-3}$  darcy (13),  $\bar{P}$  is 5 atm, and then  $t_m = 150$  hr for a lump 50 ft from the working face. Here it may be seen the first step is slightly slower than the second step.

These calculations are very approximate. For example, it may be seen that for the lump in the homogeneous coalbed,  $t_m$  depends on the distance from

the lump to the face. As the lump-to-face distance decreases, then  $t_m$  decreases also. This makes no difference for most of the Pocahontas No. 3 coalbed, but in the Pittsburgh coalbed where the two steps are comparable, consideration of the depth is important. For example, at 100 ft,  $t_m = 600$  hr, and both steps will proceed at the same rate. At distances greater than 100 ft, the first step becomes faster than the second step, which is the opposite of what prevailed at less than 100 ft.

#### CONCLUSIONS

An in-situ diffusion parameter has been calculated for the Pittsburgh and Pocahontas No. 3 coalbeds using typical values for residual gas and typical pressure-depth curves. A two-step process consisting of diffusion and flow through fractures out of the coalbed was assumed. It was found that the diffusion step was much faster in the Pocahontas No. 3 coalbed, whereas the two steps were comparable in the Pittsburgh coalbed.

The quantity obtained was  $D/a^2$ , not  $D$ , for if diffusion is taking place from some hypothetical solid lump within the coalbed, the size of that lump is as important as the diffusion coefficient.

In-situ fracture spacings were computed to be 8 cm and 4.5 cm for the Pittsburgh and Pocahontas No. 3 coalbeds, respectively. These seem large compared with laboratory results, but the breakage of coal that takes place during mining may in part account for this difference. Given the approximate nature of the calculations, these results may be regarded as satisfactory.

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<sup>7</sup>Titles enclosed in parentheses are translations from the language in which the item was originally published.



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