Report of Investigations 8066

Two-Phase Flow in Coalbeds

By Fred N. Kissell and John C. Edwards
Pittsburgh Mining and Safety Research Center, Pittsburgh, Pa.

UNITED STATES DEPARTMENT OF THE INTERIOR
Stanley K. Hathaway, Secretary

Jack W. Carlson, Assistant Secretary–Energy and Minerals

BUREAU OF MINES
Thomas V. Falkie, Director

This publication has been cataloged as follows:

Kissell, Fred N

Two-phase flow in coalbeds, by Fred N. Kissell and John C. Edwards. [Washington] U.S. Bureau of Mines [1975]

16 p. illus. (U.S. Bureau of Mines. Report of investigations 8066)

Includes bibliography.

1. Methane. 2. Two-phase flow—Simulation methods. I. Edwards, John C., jt. auth. II. U.S. Bureau of Mines. III. Title. (Series)

TN23.U7 no. 8066 622.06173

U.S. Dept. of the Int. Library.

CONTENTS

ILLUSTRATIONS

TWO-PHASE FLOW IN COALBEDS

by

Fred N. Kissell[1] and John C. Edwards[2]

ABSTRACT

Experimental work by the Bureau of Mines indicates that when a coalbed is degassed by boreholes, the flow of methane may actually increase with time. This phenomenon appears to be the result of a relative-permeability effect; that is, the coalbed permeability to the gas increases sharply with decreasing water saturation. This report reviews the background of experimental evidence indicating a relative-permeability effect, and presents the results of a computer simulation of two-phase flow in coal.

INTRODUCTION

A major characteristic of coalbed permeability is that the measured permeability to methane appears to increase with time. This was first reported by Kissell (6),[3] who found that regions of a coalbed adjacent to older areas of a mine were considerably more permeable than regions adjoining freshly mined areas. Several factors could account for this. One is "destressing," the relaxation resulting from the strata movements that accompany mining (13). Another is the coal shrinkage resulting from the loss of methane (8). However, the most probable explanation is a relative-permeability effect in which the flow of methane is controlled in part by the degree of coalbed water saturation; the permeability to methane increases as the water in the coalbed decreases and makes more pore space available to the gas phase. This assumption was based on observation of the variations in gas and water flow from boreholes drilled horizontally into the coal.

This Bureau of Mines report presents the background of experimental evidence for a permeability change caused by loss of water, and discusses the results of a computer simulation of two-phase flow in coalbeds. Although the relative-permeability concept is somewhat novel to flow through coalbeds, it has been employed extensively by the petroleum industry.

---

[1] Physical research scientist.
[2] Physicist.
[3] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

BACKGROUND

Kissell used coalbed gas-pressure curves to estimate gas permeability. Figure 1 shows two curves obtained from a very deep mine in the Pocahontas No. 3 coalbed (5). These pressures were determined by drilling horizontal holes into the working face or rib of a development section. The holes were immediately sealed with inflatable packers so that no gas drained from the coal. The gas pressure in the open spaces between the packers soon reached equilibrium, which was assumed to represent the true gas pressure in the coalbed before drilling. For the calculation, the coalbed was assumed to be a homogeneous slab, to which a simple one-dimensional, unsteady-state form of the Darcy equation was applied. The upper curve in figure 1 was obtained from a hole drilled into a rib that had been mined 15 days before; thus, the rib had been exposed for 15 days prior to drilling and packing. The calculated permeability for this region of the coalbed was 0.57 md. The lower curve was obtained from a hole drilled into a rib that had been exposed for 180 days prior to drilling and packing; the calculated permeability for this region was 280 md.

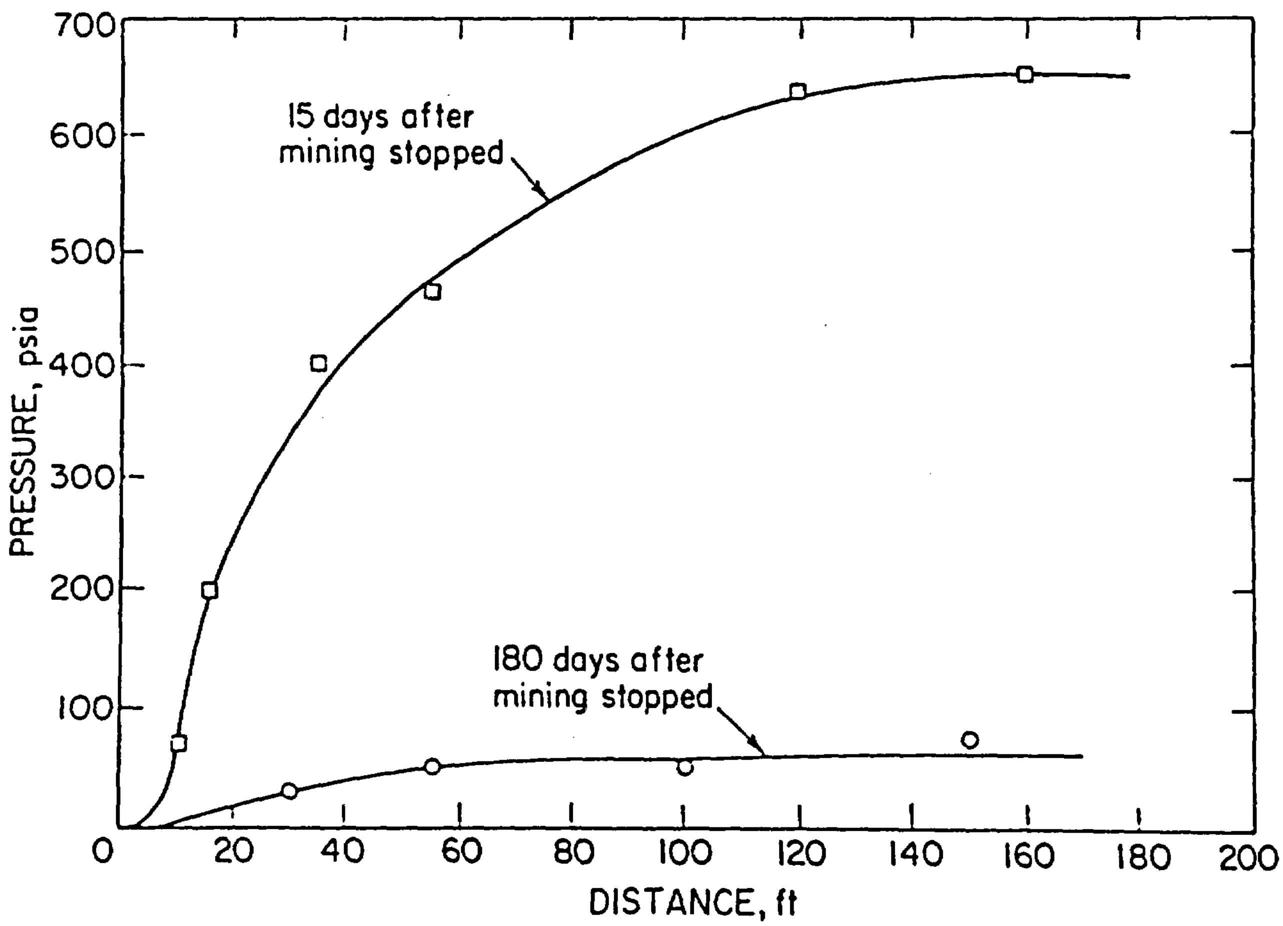

FIGURE 1. - Gas pressure curves from two regions in a deep mine in the Pocahontas No. 3 coalbed (5).

In the same mine, a drainage hole drilled into the working face emitted 7,260 ft^3/day of methane and 72 gal/day of water for several days after drilling. However, on the sixth day, the gas flow rose to 7,960 ft^3/day and the water flow fell to 48 gal/day. This suggested that the permeability increase was a relative-permeability effect.

Subsequently, Zabetakis (15) made a survey of rib emissions in a gassy mine in the Pittsburgh coalbed. For this purpose, a standard ventilation survey was made at a working face in a development section. The return airway was then followed for several thousand feet, and the methane concentration was measured at 100-foot intervals. The rib survey was adjacent to solid coal. The coalbed also contained several gas and oil wells (fig. 2). Zabetakis found that although the wells were contributing more than half of the methane, after the data on the effects of the wells were corrected out, the rib emission was surprisingly constant. This meant that 100 feet of rib

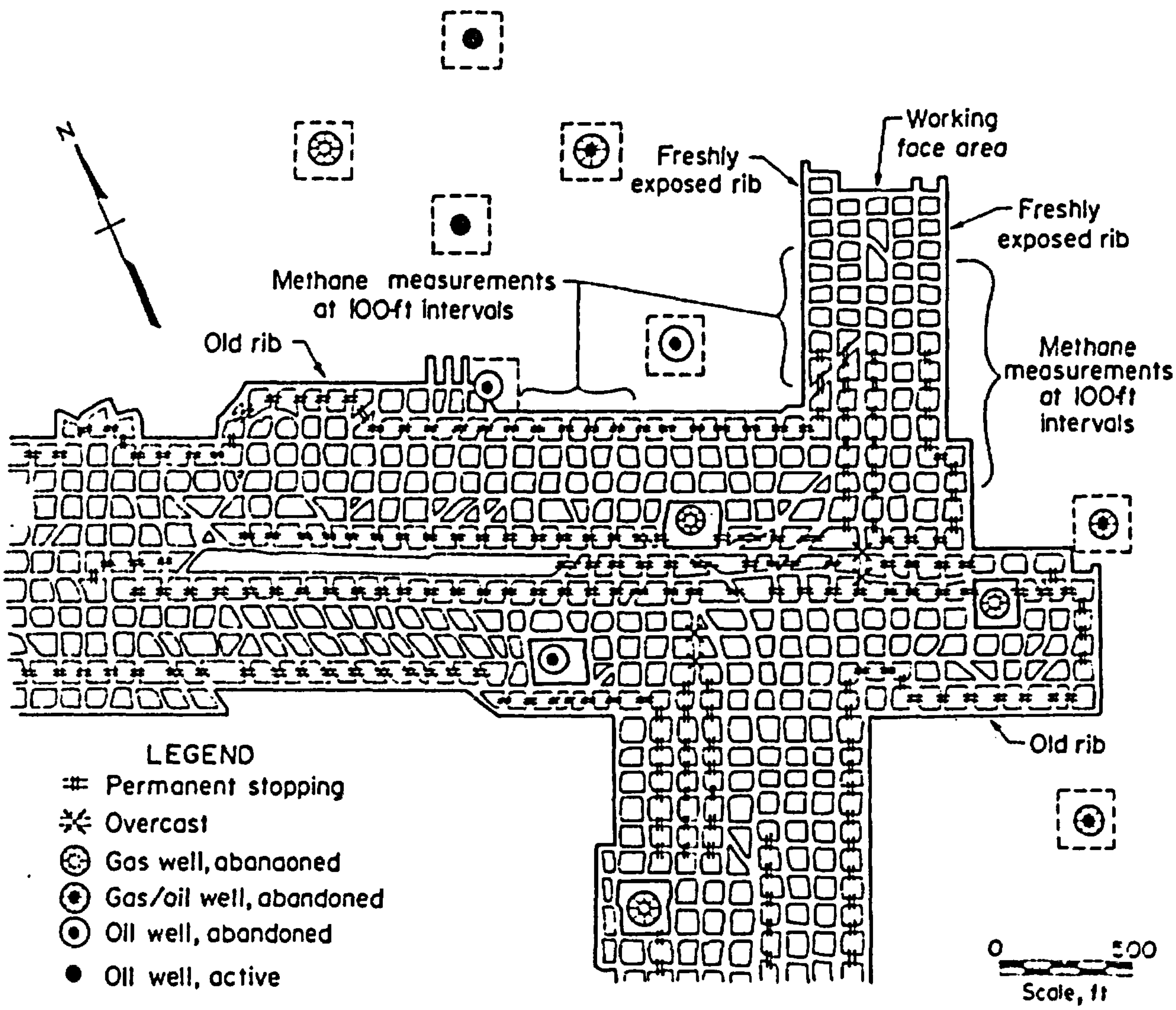

FIGURE 2. - Area of investigation in Zabetakis study (15).

close to the working face and freshly exposed by mining was emitting methane at the same rate as a comparable 100-foot length several thousand feet from the face and exposed for many months. If the rib permeability to methane were constant, this could not have occurred since older ribs would yield considerably less methane than freshly exposed ribs. Zabetakis concluded that the methane permeability of the older rib was higher because of a decrease in the water content of the coal.

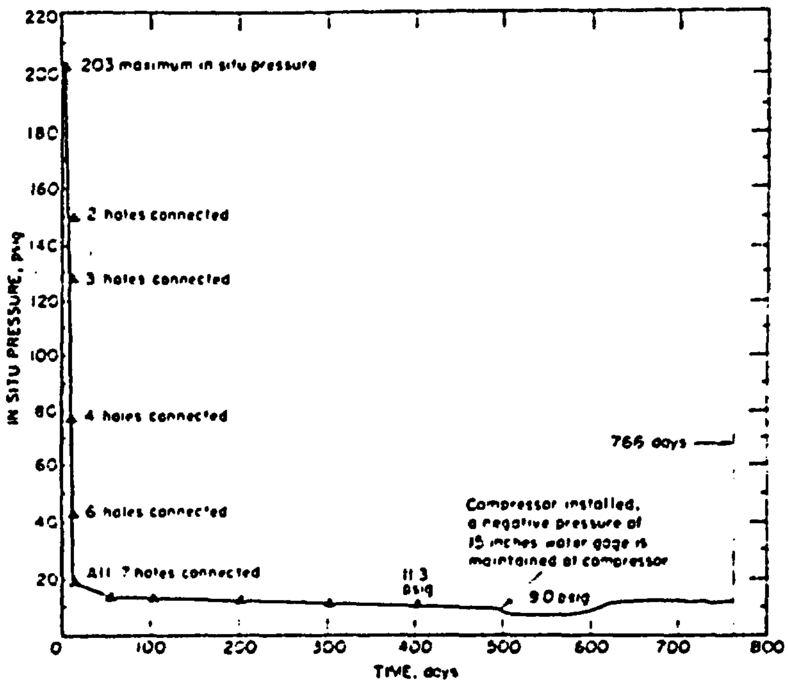

FIGURE 3. - In situ pressure versus time for the large-diameter borehole (4).

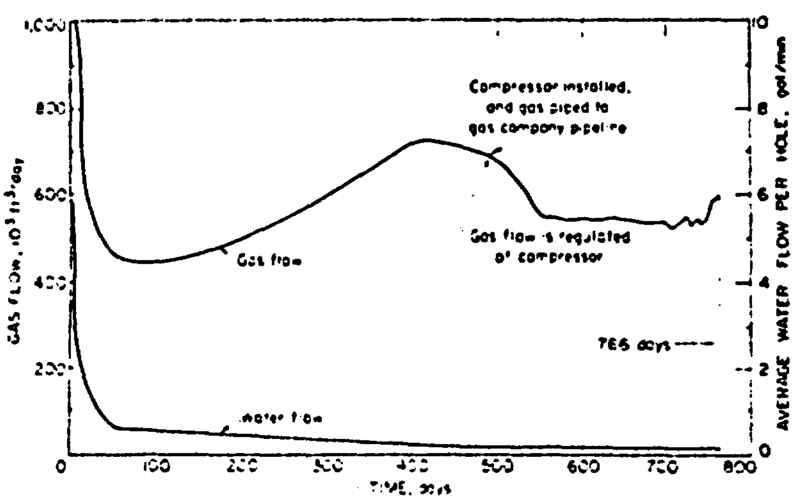

FIGURE 4. - Gas and water flow rates for the large-diameter borehole (4).

In still another project, Fields (3-4) described a virgin area of the Pittsburgh coalbed degasified through a large-diameter borehole drilled into the coal from the surface. At coalbed level, the borehole was enlarged to a small room. From this room, eight 3-inch-diameter holes were drilled out horizontally about 600 feet into the coalbed in a radial fashion similar to spokes on a wheel. One of the eight holes was packed so that the pressure deep in the coal could be measured; the other seven were open to drain gas. Pressure and methane- and water-flow curves are shown in figures 3-4.

In the first 40 days, the pressure at the end of the packed hole fell from 203 psig to 11 psig, a factor of 18. However, the methane flow from the other seven holes fell from 1,121,000 ft^3/day to 444,000 ft^3/day, a factor of only 2.5. After 40 days, the pressure stabilized in the range of 10 to 13 psig, but the flow began to rise. At 400 days, it was slightly in excess of 700,000 ft^3/day. After this, it declined until at 500 days an exhausting compressor was connected by the gas company, which regulated the gas flow.

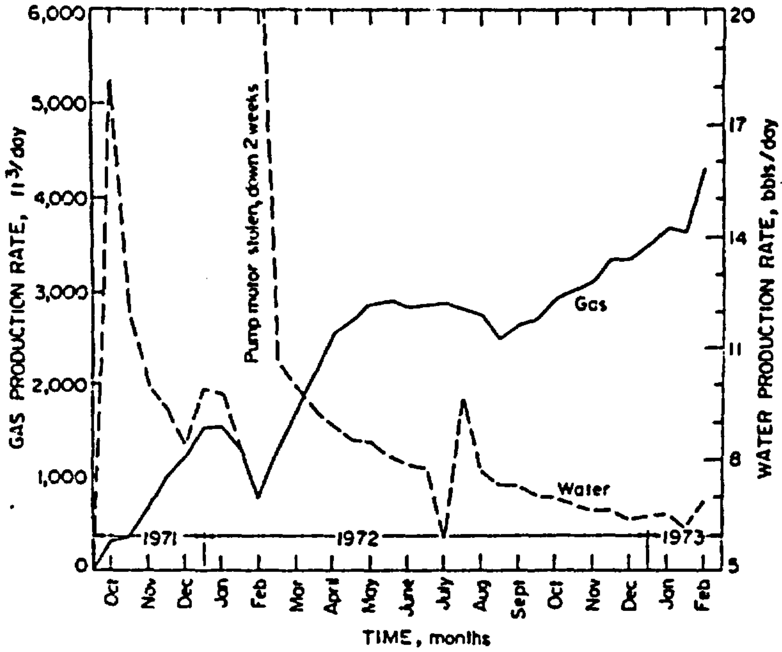

FIGURE 5. - Gas and water emission curves for a vertical borehole drilled into a coalbed (2).

In addition to the gas, water flowed from the holes at a rate that varied in a manner similar to that of the pressure. Initially it was 43 gal/min for all seven holes; after 40 days it was less than 7 gal/min, and subsequently it stabilized at about 3.5 gal/min.

Another experimental method for degasifying a coalbed in advance of mining is to drill a number of small-diameter vertical boreholes into the coalbed. Duel (2) reported results obtained with 53 such holes, most of them drilled into Appalachian coals. Since the holes were cased and cemented above the coal, all gas and water produced by the holes came from the coalbed. A typical flow curve for one of these holes (fig. 5) shows that the gas flow rises only as the coal is dewatered; over a period of about 1-1/2 years, a very substantial amount of water is removed from the coal. Thus a relative-permeability effect is again indicated.

The rising methane flow rates reported by Fields and Deul seem to rule out any effects due to strata movements and subsequent destressing. No mine was nearby. Only small-diameter holes were drilled into the coalbed and, although there was some destressing near each hole, it is unlikely this dould produce the long-term changes in figures 3-5. The rising methane-emission rate common during the mining of coal (5, 7) occurs because the mining machine exposes fresh coal as it digs forward; this is an entirely different phenomenon than that involved with rising flows from boreholes.

COMPUTER SIMULATION OF TWO-PHASE FLOW

Under a Bureau of Mines contract, Intercomp Resource Development and Engineering developed a theoretical computer model for methane flow in coalbeds (10). Its capabilities include the following:

1. Two-dimensional, low-Reynolds-number, laminar (Darcy) flow;

2. PVT properties as functions of pressure-viscosity, density, and compressibility factors;

3. Single-phase gas flow and two-phase flow of methane and water;

4. Variable reservoir properties such as porosity, permeability, thickness, and elevations; and

5. A moving boundary to simulate the advancing working face of the mine.

In previous applications of the model (11), only the single-phase part of the program was used to any degree. The two-phase part of the computer code required a larger amount of input data, including the relative permeabilities of water and gas, capillary pressures, and initial water saturation. Because none of these data were available, and because the single-phase part of the computer code already had many variables, it was felt that pursuing the two-phase work would not be meaningful.

More recently, however, data on relative permeability and capillary pressure have been obtained for coal (1, 12, 14), and the unique rise in gas flow has been noted by Fields and by Deul. This suggested the the effort spent in simulating two-phase flow would be worthwhile.

Three major characteristics were noted in the experimental field studies:

1. Gas coalbed pressures in the vicinity of the mine fall more quickly than those expected for constant gas permeability (6),

2. Rib gas emissions remain higher than those expected for constant gas permeability (15), and

3. Borehole gas flow rates increase and then pass through a maximum, sometimes after an initial decrease (2-3).

The first and second characteristics require some estimate of what was expected, which is often difficult. Because the last characteristic represents an unequivocal test of a two-phase effect, an attempt was made to simulate increasing gas flow, which then passes through a maximum.

The flow is initiated and maintained by the pressure difference between the gas in the entry (atmospheric) and the gas in the coal seam. The gas (water) flow rate is proportional to the product of gas (water) relative permeability and the pressure gradient. This is formally expressed by Darcy's law:

$$V_w = -k \frac{K_{rw}}{\mu_w} \rho_w \nabla \Phi_w \qquad (1)$$

$$V_g = -k \frac{K_{rg}}{\mu_g} \rho_g \nabla \Phi_g \qquad (2)$$

where K = absolute permeability,

K_{rw} = water relative permeability,

K_{rg} = gas relative permeability,

$\mu_{g(w)}$ = gas (water) viscosity,

$\rho_{g(w)}$ = gas (water) density,

$V_{g(w)}$ = gas (water) velocity at average flowing pressure, and the flow potentials are defined by

$$\Phi_g = \int_{P_0}^{P_g} \frac{dp}{\rho_g} - Gz \quad (3)$$

$$\Phi_w = \int_{P_0}^{P_w} \frac{dp}{\rho_w} - Gz \quad (4)$$

where $P_{g(w)}$ = gas (water) pressure,

G = acceleration due to gravity,

and z = height of gas-water contact.

It is seen from equations 1 and 2 that the relative permeabilities K_{rg} and K_{rw} will influence the flow rates. They are functions of the water saturation, which changes with time. This makes them likely causes of a nonmonotonic decrease in flow rates. Because only relative-permeability effects on the gas flow rate were to be investigated, the model was restricted to a homogeneous coalbed with flow in one dimension. Otherwise, the same procedures used by Price (11) were used.

Five cases were studied. The first three were identical in all respects except for the initial water saturation. The relative-permeability and capillary-pressure data used was reported by Taber (14) for Pittsburgh coal at a simulated overburden pressure of 600 psi. Figure 6 gives the drainage curves for the relative permeability of gas and water. The capillary-pressure curve was represented by three linear segments (fig. 7). Other physical properties selected to define the coalbed system were as follows:

Water viscosity	0.8 cp
Gas viscosity	0.0125 cp
Water density	62.4 lb/ft^3
Gas density	50 lb/Mft^3
Water compressibility	3×10^{-6} vol/vol/psia
Rock compressibility	7×10^{-8} vol/vol/psia
Residual gas saturation	0.225
Irreducible water saturation	0.55
Gas relative permeability at connate water saturation	0.68
Water relative permeability at residual gas saturation	0.1
Average temperature in mine entry	540° R
Average pressure in mine entry	14.7 psia
Initial gas pressure	400 psia
Absolute permeability	2.5 md
Porosity	0.25
Width of coal section	400 ft
Height of coal section	8 ft
Depth of coal section	Infinite
Grid spacing	440 ft
Time step for computation	0.025 day for the period 0 to 0.1 day 0.1 day for the period 0.1 to 5 days 0.25 day for the period 5 to 15 days 1.0 day for the period 15 to 30 days 2.0 days for the period 30 to 200 days 4.0 days for the period 200 to 360 days

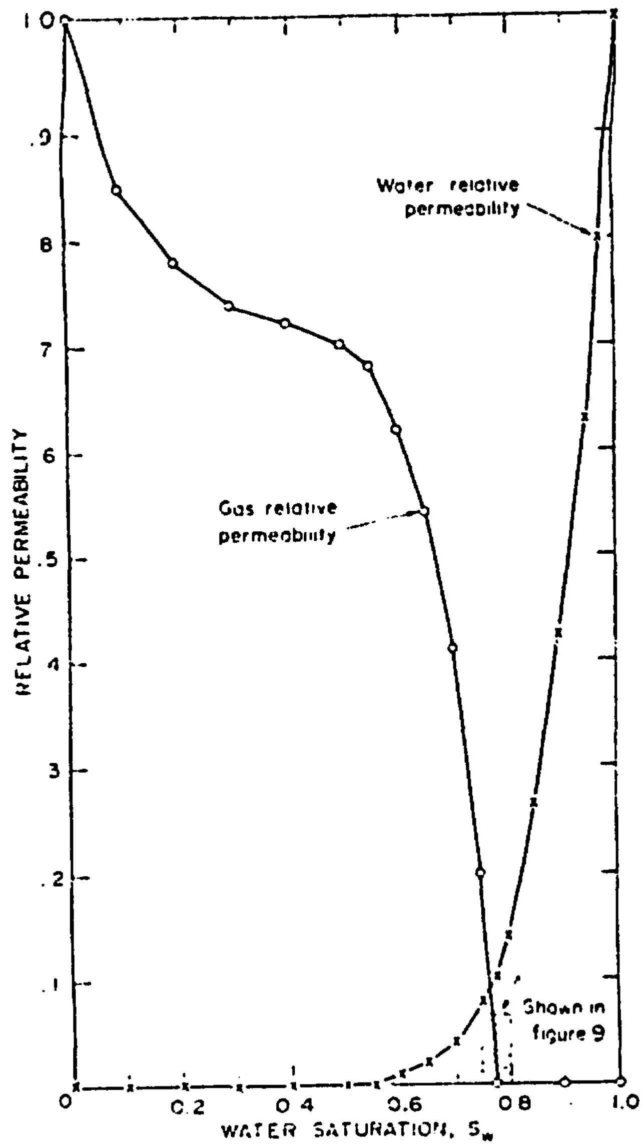

FIGURE 6. - Gas and water relative-permeability curves used in computer model (14).

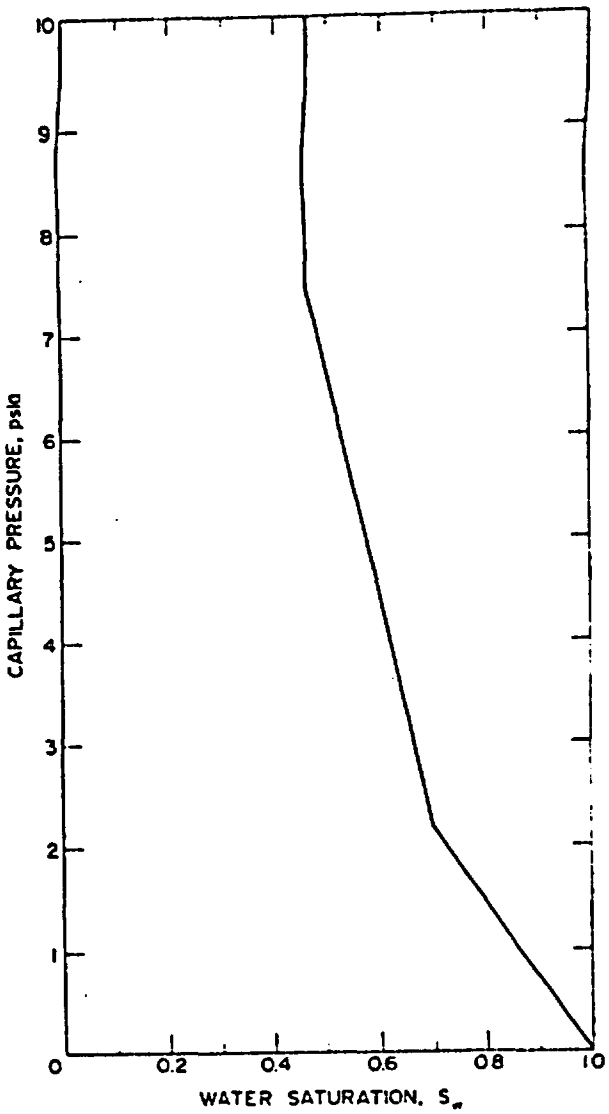

FIGURE 7. - Capillary-pressure curve used in computer model (14).

In the Bureau of Mines computer model, the initial water saturation is determined by specifying the height of the gas-water contact. This, in turn, specifies the initial relative-permeability values in figure 6 and the initial gas and water flow rates.

Figure 8 gives three methane flow curves[4] computed with the Bureau of Mines model for a coal mine face 400 feet wide by 8 feet high in a coalbed initially pressurized to 400 psi. Only the initial water saturation varies (fig. 8). In case 1, the gas flow rate is appreciable at first, then it decreases monotonically with time. The initial water saturation was 0.7660, and the initial relative permeability to methane was about 0.072.

In case 2, the initial water saturation is slightly higher at 0.7748; thus, the initial gas relative permeability is reduced from 0.072 to 0.0016. This in turn substantially reduces the initial gas flow rate. However, instead of decreasing, the gas flow rate increases. This happens because the increase in gas relative permeability caused by a loss of water from the coal is more than sufficient to counteract the decrease in flow caused by a pressure loss (equations 1 to 4). The gas flow rate steadily rises to a maximum at 86 days and then falls.

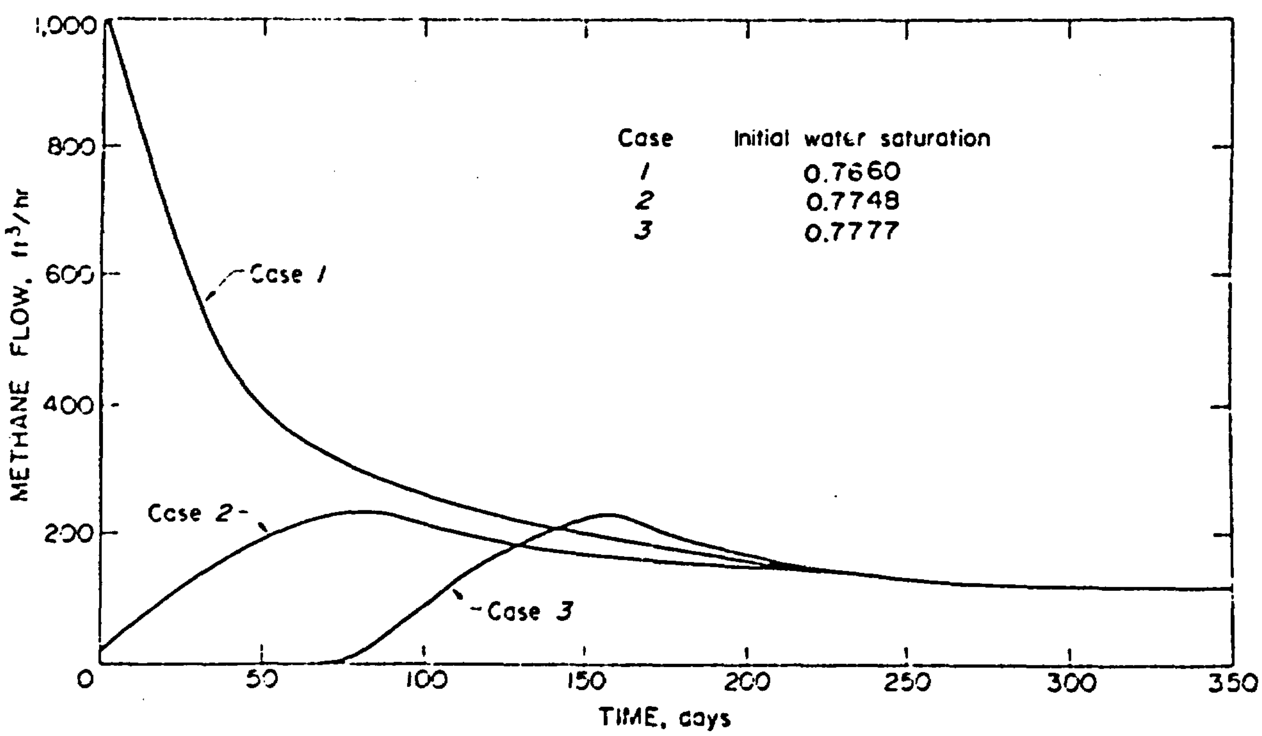

FIGURE 8. - Methane flow curves for three hypothetical cases with different initial water saturations.

---

[4] The curves in figures 8 and 10 have been smoothed. Each curve also had several minor peaks and valleys that deviated about 10 or 15 percent from the smoothed curve shown.

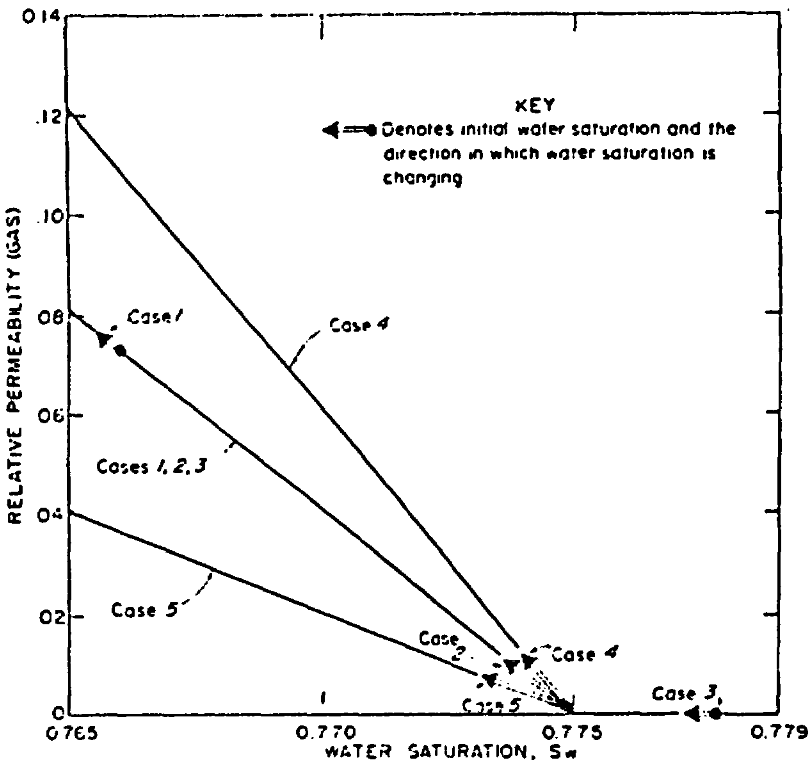

FIGURE 9. - Gas relative-permeability curves and initial water saturation for cases 1-5.

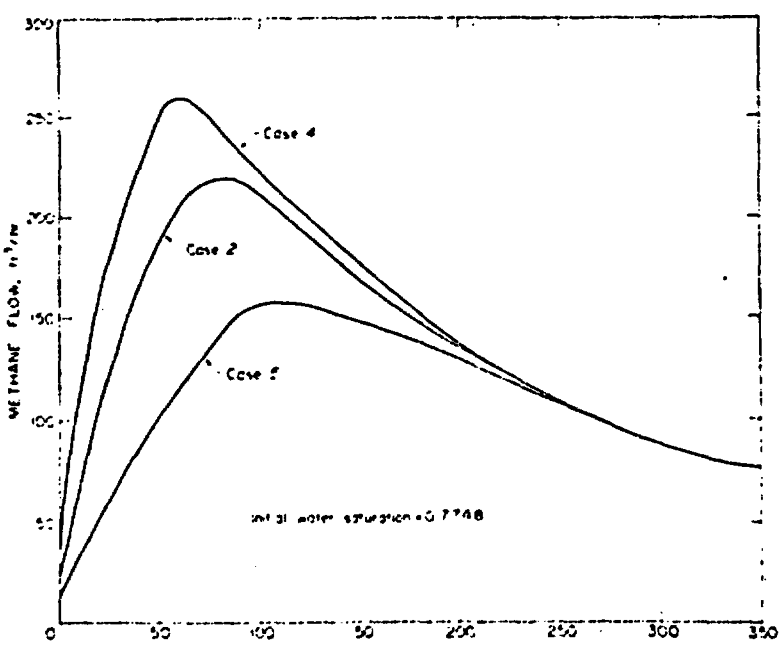

FIGURE 10. - Methane flow curves for three hypothetical cases with gas relative-permeability curves of different slope.

In case 3, the water saturation is even higher at 0.7777, and gas relative permeability is zero. As a result, no gas flow occurs until 74 days, whereupon enough water has drained out that the gas relative permeability can begin to rise. In case 3, a distinct maximum is obtained at 160 days.

Since minor changes in initial water saturation apparently have such large effects on the methane flow curves, other parameters were varied to assess their effect. Moderate shifts in the capillary-pressure and water relative-permeability curves caused little change in the methane flow rate; however, the slope of the lower end of the gas relative-permeability curve was critical.

Figure 9 gives the gas relative-permeability curve used in all five cases. In case 4, the slope of the gas relative-permeability curve is increased; in case 5, it is decreased. In both instances, the initial water saturation is 0.7748, similar to case 2. For comparison, the initial water saturations for cases 1-3 are also shown.

Figure 10 gives the methane flow curves computed from the Bureau of Mines model. Cases 2, 4, and 5 are shown, since they all have the same initial water saturation. When the slope of the relative-permeability curve is increased, the methane flow maximum is higher and occurs earlier.

It is clear that changes in relative permeability and initial water saturation can explain the increase in the methane flow rate. The relative-permeability effect takes place over an extremely small range of water saturations, at least for the homogeneous system postulated for the computer model. Systems that have initial water saturations in this critical range or higher will exhibit a maximum in the methane flow rate.

ANALYSIS OF PRODUCTION HISTORY

Wells drilled into gas sands for natural gas have emission rates that decline with time, and peaks are not observed. However, where the natural gas is produced from a "gas drive" oil reservoir by the method of pressure

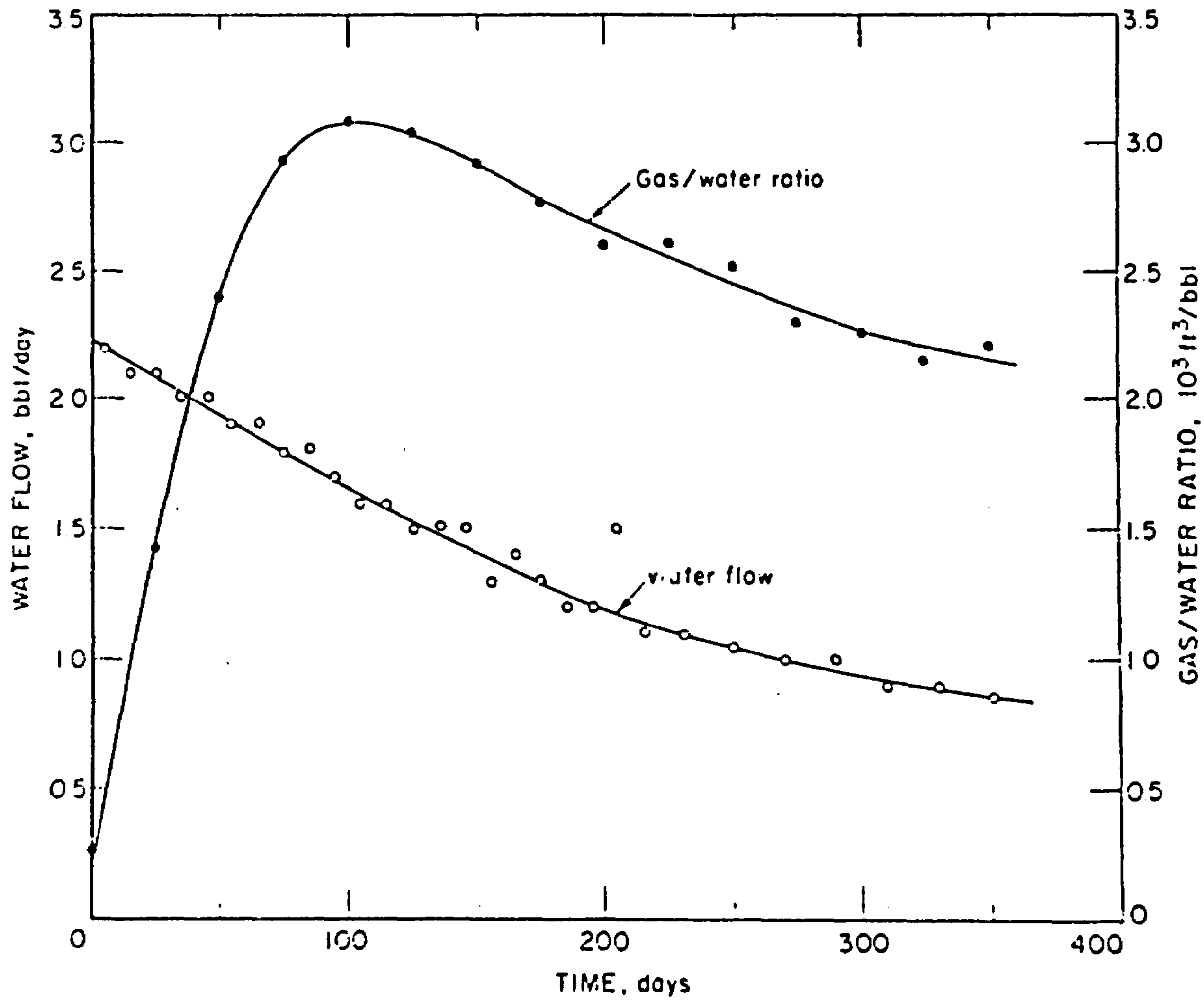

FIGURE 11. - Water flow and gas-water ratio calculated by the Bureau of Mines model for case 2.

depletion, a rising methane emission due to two-phase effects may be observed. Muskat (9, p. 462) gives some production histories of early gas-drive oil reservoirs that were produced "wide open," and were unaffected by withdrawal restrictions, a free-gas cap, gas injection, or water-drive action. These show a rise in the gas-oil ratio as the pressure in the reservoir depletes. Since the oil production from a single well falls monotonically in such a case, a peak in the gas-oil ratio may correspond to a peak in the gas flow.

In coalbeds, the liquid phase being produced is water and not oil. Also, the methane gas is adsorbed in the coal and not dissolved in the liquid phase. However, it may be that these differences are not very critical and that much the same sort of two-phase effects are taking place.

Figure 11 gives the water flow and the gas-water ratio calculated by the Bureau of Mines model for case 2. The gas-water ratio peaks at 100 days.

Figure 12 gives the gas-water ratio taken from Fields' published gas and water flows for the large-diameter borehole (4). No peak similar to that in figure 11 or the gas flow curve in figure 4 was observed; at most there is a flattening of the gas-water ratio curve in the region of 400-500 days. At least for analytical purposes, the exhausting compressor was installed at an unfortunate time.

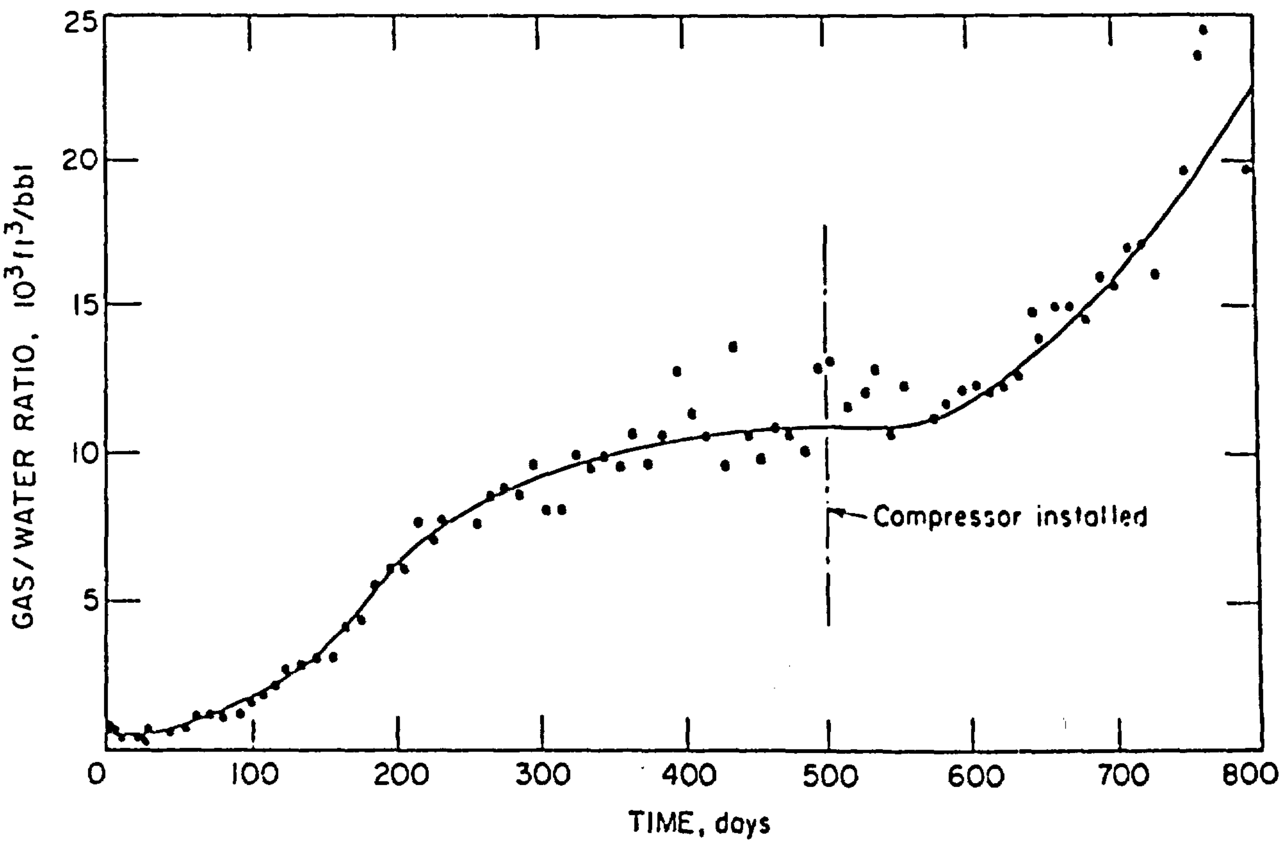

FIGURE 12. - Gas-water ratio from Fields large-diameter multipurpose borehole (4).

depletion, a rising methane emission due to two-phase effects may be observed. Muskat (9, p. 462) gives some production histories of early gas-drive oil reservoirs that were produced "wide open," and were unaffected by withdrawal restrictions, a free-gas cap, gas injection, or water-drive action. These show a rise in the gas-oil ratio as the pressure in the reservoir depletes. Since the oil production from a single well falls monotonically in such a case, a peak in the gas-oil ratio may correspond to a peak in the gas flow.

In coalbeds, the liquid phase being produced is water and not oil. Also, the methane gas is adsorbed in the coal and not dissolved in the liquid phase. However, it may be that these differences are not very critical and that much the same sort of two-phase effects are taking place.

Figure 11 gives the water flow and the gas-water ratio calculated by the Bureau of Mines model for case 2. The gas-water ratio peaks at 100 days.

Figure 12 gives the gas-water ratio taken from Fields' published gas and water flows for the large-diameter borehole (4). No peak similar to that in figure 11 or the gas flow curve in figure 4 was observed; at most there is a flattening of the gas-water ratio curve in the region of 400-500 days. At least for analytical purposes, the exhausting compressor was installed at an unfortunate time.

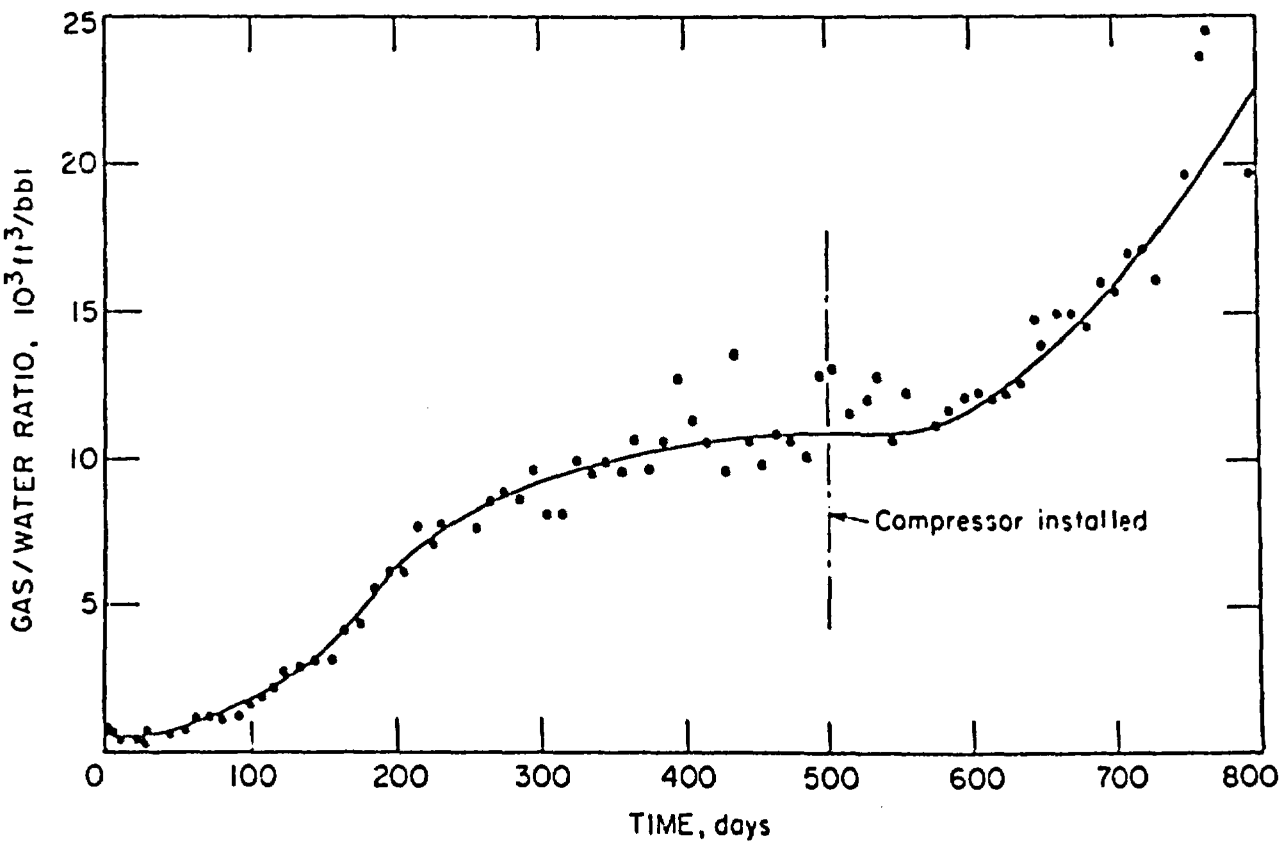

FIGURE 12. - Gas-water ratio from Fields large-diameter multipurpose borehole (4).

CONCLUSIONS

The Bureau of Mines model for two-phase flow of methane and water in coalbeds can be used to simulate a maximum in the methane-emission rate from a face that is not being mined. Experimental data obtained by Fields and by Deul show that such a maximum exists in flow from boreholes. A rough similarity exists between results obtained at the large-diameter borehole and those obtained at early gas-drive oil wells produced wide open.

REFERENCES

1. Dabbous, M. K., A. A. Reznik, J. J. Taber, and P. F. Fulton. The Permeability of Coal to Gas and Water. SPEJ., v. 6, 1974, pp. 563-572.

2. Deul, M., and C. H. Elder. Degasification Through Vertical Boreholes in Methane Control in Eastern U.S. Coal Mines. BuMines IC 8621, 1973, 96 pp.

3. Fields, H. H., S. Krickovic, A. Sainato, and M. G. Zabetakis. Degasification of Virgin Pittsburgh Coalbed Through a Large Borehole. BuMines RI 7800, 1973, 27 pp.

4. Fields, H. H., J. H. Perry, and M. Deul. Commercial-Quality Gas From a Multipurpose Borehole Located in the Pittsburgh Coalbed. BuMines RI 8025, 1975, 14 pp.

5. Kissell, Fred N. Methane Migration Characteristics of the Pocahontas No. 3 Coalbed. BuMines RI 7649, 1972, 13 pp.

6. _____. The Methane Migration and Storage Characteristics of the Pittsburgh, Pocahontas No. 3, and Oklahoma Hartshorne Coalbeds. BuMines RI 7667, 1972, 22 pp.

7. Kissell, Fred N., J. L. Banfield, Jr., R. W. Dalzell, and M. G. Zabetakis. Peak Methane Concentrations During Coal Mining--An Analysis. BuMines RI 7885, 1974, 17 pp.

8. Moffat, D. H., and R. W. Weale. Sorption by Coal of Methane at High Pressure. Fuel, v. 34, 1955, p. 449.

9. Muskat, M. Physical Principles of Oil Production. McGraw-Hill Co., 1949, 922 pp.

10. Price, H. S., and A. A. Abdalla. A Mathematical Model Simulating Flow of Methane and Water in Coal. BuMines OFR 10-72, 1972, 39 pp.; available from National Technical Information Service, Springfield, Va., PB 209 273. Cards are available from F. N. Kissell, Bureau of Mines, 4800 Forbes Ave., Pittsburgh, Pa. 15213.

11. Price, H. S., R. C. McCulloch, J. C. Edwards, and F. N. Kissell. A Computer Model Study of Methane Migration in Coalbeds. Can. Min. and Met. Bull., September 1973, 10 pp.

12. Reznik, A. A., M. K. Dabbous, P. F. Fulton, and J. J. Taber. Air-Water Relative Permeability Studies of Pittsburgh and Pocahontas Coals. SPEJ., v. 6, 1974, pp. 556-562.

13. Stewart, I. McC. Diffusional Analysis of Seam Gas Emission in Coal Mines. Can. Min. and Met. Bull., April 1971, pp. 62-70.

14. Taber, J. J., P. F. Fulton, M. K. Dabbous, and A. A. Reznik. Development of Techniques and the Measurement of Relative Permeability and Capillary Pressure Relationships in Coal. BuMines OFR 22-74, 1974, 80 pp.; available from National Technical Information Service, Springfield, Va., PB 232 244.

15. Zabetakis, M. G., T. D. Moore, Jr., A. E. Nagel, and J. E. Carpetta. Methane Emission in Coal Mines: Effect of Oil and Gas Wells. BuMines RI 7658, 1972, 9 pp.

☆U.S. GOVERNMENT PRINTING OFFICE 1975 603 752 10 INT.-BU.OF MINES,PGH.,PA. 20475