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ANALYSIS OF THE COALBED DEGASIFICATION PROCESS AT A SEVENTEEN WELL PATTERN IN THE WARRIOR BASIN OF ALABAMA

By K.L. Ancell, INTERCOMP; S. Lambert,
U.S. Dept. of Energy; F.S. Johnson,
INTERCOMP

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ABSTRACT

This paper presents an analysis of the coalbed degasification process. The theoretical and experimental basis of the degasification process are discussed and a simulation model which incorporates all aspects of this process is described. The simulator is demonstrated using actual field data developed by a joint industry/government demonstration project funded by the DOE and U. S. Steel. The basic reservoir description is discussed in detail, including variations of important description parameters with location.

Initial and boundary conditions are demonstrated and analyzed. Initially, the coalbed was saturated with water. With water production, reservoir pressure is lowered, causing gas to desorb from the coal creating a mobile gas saturation. Subsequently, interwell interference effects are demonstrated and the need for such effects explained.

Finally, the long term gas deliverability of the pattern is forecast. This forecast shows that about 45% of the gas within the pattern can be removed if the pattern is in operation six years ahead of mining.

INTRODUCTION

During the process of coalification, considerable quantities of gases are evolved from the indigenous carbonaceous material. These gases include methane and heavier hydrocarbons, carbon dioxide, nitrogen, oxygen, hydrogen, and helium.^{1,2} The primary constituents are methane and carbon dioxide, and these gases have been observed in coal mines since the inception of the industry.

Quantities of methane and air in proper proportions (5 to 15 percent methane) result in explosive mixtures.³ It is these mixtures that when ignited cause the disastrous explosions in coal mines. For many years, the only method of controlling the accumulations of explosive mixtures was a combination of

increasing the ventilation and decreasing the extraction rate. These activities are costly and reduce productivity. With the advent of the energy shortage, the waste of the valuable gas resource makes the practice even more undesirable.

GAS CONTENT OF COALBEDS

Gas can be contained in coal either as free gas in the joints and fractures or as an adsorbed layer on the internal surfaces of the coal.⁴ It is important to understand that the free gas contained in the fracture system will behave according to Boyles and Charles Laws just as gas accumulations in any reservoir rock. On the other hand, the gas which is adsorbed onto the internal surfaces does not behave according to Boyles and Charles Law, but in a very distinctive manner.

It is common knowledge that carbonaceous substances such as charcoal, coke, and coal can adsorb gases preferentially, and this is what gives these substances their filtration properties. It is this same mechanism that stores methane and other gases in coal. In the adsorbed state, the gas molecules are "tightly packed and closely held" to the walls of the minute sized pores in the structure of the coal.⁴

The packing is thought to be only one molecule thick and its density increases with pressure. The large surface area available because of the very fine pore structure of the coal makes it possible to hold large quantities of gas. Fig. 1 is a plot that shows the relationship of the volume of gas that can be retained as a function of pressure for several U. S. coals. This plot is shown as volume in cm³/g of coal as a function of pressure shown in atmospheres and is known as the equilibrium sorption isotherm. At low pressures, the volume adsorbed increases rapidly and almost linearly. At higher pressure when the adsorbed

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SORPTION KINETICS OF COAL

While the measurement and prediction of the gas that can be stored in coal is very important, it does not tell the complete story of production of methane from coal. If the coalification process makes gas available to the coal surfaces, then the coal-methane system will exist in equilibrium at that temperature, pressure and very probably above the critical moisture value because free water exists as a water saturation in the coal fractures.

If the pressure is lowered by the removal of some of its fluids, the coal will desorb some of its adsorbed gases. The amount that would ultimately be desorbed is calculated by the difference between equilibrium volume at initial conditions and that at the reduced pressure. However, the rate at which this happens is a function of another set of parameters which describe the kinetics of the system.

The emission of gas from coal requires the movement of fluids from their storage place, i.e. the micropores of the coal to a surface, i.e. a well, mine face, outcrop, etc. Patching⁴ and others^{5,6,7} postulate that flow in coal can occur in two ways. In solid unfractured coal, the flow is thought to be the very slow diffusion of gas molecules through the pores in response to differences in concentration. In fractured coal, the flow is through fractures in response to pressure gradients. The flow through fractures is much more rapid than the diffusion through solid coal. In large size samples of coal, both types of flow occur simultaneously.

Thimons and Kissell⁸ demonstrated this postulation by flowing methane through very small discs of coal. Their results showed that where fractures existed the flow was laminar flow and could be described by Darcy's Law, and when fractures did not exist the flow was by diffusion.

A system of fractures commonly referred to as "cleat" exists in all coal beds.⁹ This has meaning in the sense that all coal particles are surrounded by fracture planes at some distance. Conclusions from the above references lead to the development of equations which describe the diffusion flow from the solid coal or matrix into the fracture system. Crank and others^{10,11} have shown that utilizing Fick's Laws the differential equation for diffusion into or out of a sphere is

$$\frac{D}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial C}{\partial r} \right) = \frac{\partial C}{\partial t} \dots\dots\dots (1)$$

where C = concentration, cm³/g
r = distance from the center of sphere, cm
D = diffusion coefficients, cm²/sec
t = time, sec

An analytic solution of Equation (1) for the amount of gas entering or leaving the sphere is given by

$$\frac{M_t}{M_\infty} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(-Dn^2\pi^2 t/a^2) \dots\dots\dots (2)$$

where M_t = amount sorbed at time, t
M_∞ = amount sorbed at equilibrium
a = radius of the sphere, cm

Further, it is shown by Crank that the shape of the particle is relatively unimportant and the above equation for a sphere adequately describes the flow for many other shapes as well.

Laboratory investigations of these parameters have been performed by several authors.^{12,13,14} Some of the more important results were presented by Hofer et al.¹³ They showed data that led to the following conclusions:

- (1) The adsorption/desorption process appears to be diffusion controlled.
- (2) The rate curves for adsorption and desorption are the same. The process is reversible.
- (3) The rate of adsorption/desorption is dependent on partial size of the sample.

It is important to note that the solution of the differential equation (1) required the data of diffusion coefficient, D, and the effective fracture spacing, a. However, the system is adequately described by the ratio, D/a² is referred to as the diffusion parameter and is a function of the coal type and the fracture spacing.

RESERVOIR CHARACTERISTICS OF COALBEDS

Although coal beds have several unusual characteristics, the only unique feature about the coal reservoir is the manner in which the gas is stored in the adsorbed state. The mechanisms for the release of the adsorbed gas were discussed in the previous section. Once the gas exists as free gas, the equation applicable to conventional petroleum reservoirs apply. These equations are based on Darcy's Law of fluid flow in porous media and the continuity equation. These are discussed in detail later. A discussion of the more important properties of coal beds follows.

1. Cleat in Coal

Coalbeds universally exhibit a natural system of fractures. Except in areas of high tectonic activity the fracture system is generally perpendicular to the bedding planes of the coal. This system of joints and fractures is commonly referred to as cleat. The origin of cleat in coal is the subject of much discussion; however, it has been observed for many years. Coal mines are traditionally planned to take advantage of the cleat by mining in the direction in which coal breaks most easily.¹²

Frequently there exists a direction in which the cleat system is much better developed than the other. This direction of more frequent fracture spacing and longer, more continuous fractures is called the face cleat. The less developed, shorter fractures are called the butt cleats. The face and butt cleat directions are frequently separated by about 90°.

The variable frequency of fracture spacing with direction yields measurable differences in permeability. Holes or other conduits parallel to the butt cleat direction yield fluid productions up to 10 times greater than those parallel to the face cleat.⁸

2. Porosity of Coal

When determining the porosity of coal, it must be specified that we are looking for the fractional volume of the coal that is capable of being occupied by free gas and not adsorbed gas. This presents somewhat of a problem when measuring porosities of core samples. Taber et al in nearly the only laboratory investigation of coal reservoir properties^{18,19,20,21} reported large differences in porosities between those measured with helium and those measured with water as saturating fluids. Helium porosities on five samples varied from 2.5 to 8.6 percent while water porosities varied from 0.4 to 1.1 percent.

It is thought that this is a function of pore size that the respective molecules could penetrate. The water porosities probably are a better representation of the porosity of the fracture of cleat system. This is consistent with work done by the Bureau of Mines personnel in water infusion experiments. Porosities of fracture systems of about 1 to 4 percent are the best estimates that have been found to date. Kneuper² predicts an effective porosity of 1.3 to 3.9 percent for European coals.

3. Permeability of Coal

Again, the best work on permeability of laboratory samples is by Taber et al.¹⁸ However, it is simply not possible to accurately measure permeabilities of fracture systems in laboratory samples. Cores taken in a virgin coal bed have been broken by the drilling process, and confining stresses have been relieved.

To date, the best estimates of permeability have been made by "history matching" observed production data. This is discussed in a later section. Absolute permeabilities of from 1/10th to 250 millidarcies have been postulated for various coal beds in the U. S.

4. Saturation Distributions in Coal

There are several keys available that lead to the conclusion that initially the cleat system is saturated with water in virgin coal beds. Drill stem test data (unpublished) show recoveries of water with little or no gas. Nearly all data available on vertical wells show that water rates initially start at high levels and decline while gas rates starts at near zero and increase.^{19,20,21,22,23}

Further, field studies have shown that permeabilities to gas must increase with time.²⁴ This has been consistently demonstrated in several mines in different coalbeds. This is readily explained by the concept of relative permeability. As water is produced and gas is desorbed, the water saturation in the fracture system decreases and gas saturation increases. Increased gas saturation with time results in higher permeability to gas.

5. Relative Permeability and Capillary Pressure of Coal

Again, the only recent work has been done by Taber et al.¹⁸ This work is limited to Pittsburgh and Pocahontas coal, but fortunately these coals cover the range of friable and blocky type coals. Gas relative permeability curves are shown on Fig. 2. Their resulting capillary pressure curve is shown as Fig. 3.

6. Pressure-Depth Relationships in Coal

Reservoir pressures increase with depth in coal beds just as in any other geologic formation. What data is available^{19,20,5} indicates that the pressure gradient is generally somewhat less than a hydrostatic gradient. Several examples tend to indicate a gradient of 0.2-0.4 psi/ft based on some drill stem test data (unpublished) and horizontal holes with packers.^{5,24,6}

Caution should be used when using the hydrostatic gradient because most of the data available is from the eastern United States, and other geological basins are likely to show different pressure depth-relationships.

7. Gas Quality of Coal Beds

The gas produced from coal beds is of high quality. In the most comprehensive study on the composition of coal bed gas, Kim¹ reports that all samples contain large amounts of methane. Quantities do vary from 84 to 99 percent methane. Heating value varied from 840 Btu/cuft to 990 Btu/cuft when calculated at 30 inches of mercury, saturated with water vapor.

Quantities of carbon dioxide do exist in nearly all samples, and in some cases there are measurable quantities of heavier hydrocarbons, oxygen, nitrogen, helium, and hydrogen. It is interesting to note that no sulfur dioxide or hydrogen sulfide has been found in any of the coal bed gas samples, even in high sulfur coal beds.

DEVELOPMENT OF SIMULATION MODEL

The previous sections contained a discussion of individual parameters that determine the flow of gas in coal beds. This section relates the parameters to one another in a mathematical manner that allows quantitative evaluation and validates the calculations with field data.

Mathematical Description of the Coal Gas Process

The production of methane from coalbeds is believed to be dependent upon two distinctly different physical processes (1) diffusion from the interior of a solid coal particle to a crack or macropore in the coal, and (2) two-phase (gas-water) Darcy flow through the fracture or macropore structure to a shaft or production well.^{3,6} The two-phase aspect of the fracture flow in coalbeds is evidenced by the increase in permeability with time that has been consistently observed.²⁴ This phenomenon is readily explained by the relative permeability concept used to describe flow in oil and natural gas reservoirs.

1. Methane Diffusion

Diffusion of methane through solid particles of coal is a much slower process than the fracture flow. Depending on particle size, it may or may not be the controlling factor in production.²⁸ Diffusivities have typically been measured by grinding coal particles to a uniformly small size and comparing rates of desorption to analytical solutions for diffusion in a sphere of comparable diameter.

The differential mass balance describing diffusional transport in a sphere is as follows:¹⁰

$$\frac{D}{r^2} \frac{\partial}{\partial r} (r^2 \frac{\partial C}{\partial r}) = \frac{\partial C}{\partial t} \dots\dots\dots(3)$$

(The nomenclature defining each of the symbols used is found later in this paper.)

The concentration of methane, C, is expressed as moles/unit volume of coal. The boundary conditions for this equation are as follows:

$$\frac{dC}{dr} = 0 \quad \text{at } r = 0 \dots\dots\dots(4)$$

$$C = f(p_g) \quad \text{at } r = a \dots\dots\dots(5)$$

The rate of methane desorption at the surface of the sphere is given by

$$N = (M.W.)4\pi r^2 D \left. \frac{\partial C}{\partial r} \right|_a \dots\dots\dots(6)$$

or expressed on a unit volume basis:

$$N_v = \frac{3(M.W.)D}{r} \left. \frac{\partial C}{\partial r} \right|_a \dots\dots\dots(7)$$

2. Two Phase Fracture Flow

The differential equations describing the flow of gas and water in a coal bed's fracture system result from combining continuity equations with the Darcy expression for flow in a porous medium:

Continuity Equations

$$-\nabla \cdot (\rho_w v_w) - q_{wv} = \frac{\partial}{\partial t} (\phi \rho_w s_w) \dots\dots\dots(8)$$

$$-\nabla \cdot (\rho_g v_g) + N_v - q_{gv} = \frac{\partial}{\partial t} (\phi \rho_g s_g) \dots\dots\dots(9)$$

Darcy Equations

$$v_w = - \frac{kk_r}{\mu_w} (\nabla p_w - \rho_w g \nabla h) \dots\dots\dots(10)$$

$$v_g = - \frac{kk_r}{\mu_g} (\nabla p_g - \rho_g g \nabla h) \dots\dots\dots(11)$$

Substitution of Equations (10) and (11) into (8) and (9) yields

$$\nabla \cdot \left\{ \frac{\rho_w k k_r}{\mu_w} (\nabla p_w - \rho_w g \nabla h) \right\} - q_{wv} = \frac{\partial}{\partial t} (\phi \rho_w s_w) \dots\dots\dots(12)$$

$$\nabla \cdot \left\{ \frac{\rho_g k k_r}{\mu_g} (\nabla p_g - \rho_g g \nabla h) \right\} + N_v - q_{gv} = \frac{\partial}{\partial t} (\phi \rho_g s_g) \dots\dots\dots(13)$$

These two equations contain five dependent variables -- p_w , p_g , s_w , s_g , and N_v . Two additional equations are required to complete the coal gas model.

$$p_g = p_w + p_c \dots\dots\dots(14)$$

$$s_g = 1 - s_w \dots\dots\dots(15)$$

Equations (14) relates the gas phase pressure to the water phase pressure through a capillary pressure p_c , which is a measured function of water saturation s_w (see Fig. 6). Equations (15) just states that the pore space is filled with water and gas.

In order to calculate the gas desorption term, that appears in Equations (13), it is necessary to solve Equation (3) for concentration. The desorption rate is then calculated from the concentration gradient in accordance with Equations (7). The finite difference approximations to the equations and the solution of these equations is shown in the Appendix.

APPLICATION OF SIMULATION MODEL

Validation of the simulation model was achieved by the analysis of laboratory and field studies. The desorption calculations were identical with the results obtained by Bielicki²⁵ and Hofer¹³. Further, the coupling of the desorption calculation with the reservoir was tested against the analytic solution to the diffusion equation. The results were that the laboratory experiments, as well as the analytic solution, could be described by the model.

The field example shown here reflects the data from a seventeen well pattern in Jefferson County, Alabama. The project is a joint effort between U. S. Steel Corporation and the Department of Energy.

Example Simulation

Stubbs, et al²⁶ give a description of the pattern and operation. A more complete description of the depletion and stimulation methods used in the pattern given by Lambert, et al.²⁷ The pattern, drilled in the same coalbed being mined is far enough away from the mine to be at least five years in advance of min-

Fig. 4 shows the surface well pattern with valley creek running through the pattern. Subsurface depths are also indicated with suspected structural faults. The faults indicated to the east and southeast of the pattern were shown on a core hole map used in deciding prospective mine locations. Both surface and subsurface features indicated possible faulting around well 22. The 1100 ft. deep wells penetrate a 5.2 ft. coal seam. Most of the wells were completed open hole

began from well 22 on August 5, 1977, but the last well was not put on production until March 1, 1979. Production data was available through October 31, 1979.

Fig. 5 shows the production data for the first 700 days of operation. The first 300 days reflect production from only three wells 7, 9, and 22. As shown on Fig. 4, these wells are widely spaced within the pattern and did not interfere with one another. The result is that 150 - 200 bpd of water was produced with little gas production. As soon as more wells were placed on production, the gas volumes started to increase. This is caused by interference between wells which creates large areas of pressure drawdown.

The purpose of the simulation was the extension of a matched production history to predict future gas production. To simulate the reservoir, a two-dimensional grid was constructed such that two grid blocks would separate each block that contained a well. Since the wells were 1000 feet apart, grid blocks in the pattern area were 333.3 feet square. The grid blocks become larger away from the well area as shown in Fig. 6. Several longer grid blocks were eliminated to the east and southeast simulating the suspected barrier faults in these directions. The gradual increase in depth of the coalbed to the southeast was simulated by tilting the grid in both the x and y directions.

Other data used in the simulation model came from several different sources. The equilibrium sorption isotherm data used are shown in Table 1. The original data, taken on a sample of the Mary Lee coal was adjusted slightly to give an average gas content of 482 SCF/ton at the reservoir pressure of 421 psia. The gas properties were calculated assuming methane as the major constituent of the gas. Data obtained by matching early time desorption rates from the core samples with a simple desorption model showed that the D/a^2 , diffusion parameter, varied over several orders of magnitude. The limited values we had showed D/a^2 increased to the east. Using the same trend, values used in this simulation ranged from 1×10^{-10} to 1×10^{-11} sec^{-1} . A relative permeability curve was developed during the matching process which has a critical gas saturation of 20 percent as shown in Fig. 7. This curve is not dissimilar from the laboratory curve for friable coal shown on Fig. 2.

The primary unknown variables in making the history match were the porosity and the permeability. During the early matching process porosities as high as 5 percent was used for the whole pattern. However, to enable gas saturations to build up high enough to flow gas in most wells, the porosity was eventually lowered to 1.2 percent. Early matching attempts used permeabilities as low as 3 md. Low permeabilities did not allow enough interference between wells and caused the well blocks to decline in pressure too rapidly. A permeability of 75 md. over most of the area corrected this problem although this had to be increased in some areas. Fig. 6 shows areas in which the permeability and porosity were adjusted above these normal values.

The model was initialized with the fracture system saturated with water. The gas content of the coal was at equilibrium with the initial pressure of 421 psia. The individual wells were simulated by a point source

located. The wells were subsequently produced by specifying a water production rate consistent with the wells demonstrated pump capacity. Limiting bottomhole pressures were calculated from liquid level determinations and surface pressures. The well then produced pump capacity or reservoir deliverability against the calculated limiting pressure. The gas-water ratio was then determined by the relative permeabilities of the two phases in the grid block containing the well. The limiting bottomhole pressures were decreased in a stepwise manner consistent with the measured decline in the wells.

The individual wells were assigned production rates at times corresponding to actual first production. The major shut in periods were simulated by periods of zero flow.

The simulation results for the pattern are shown plotted with the actual production in Fig. 8. There are too many wells to show all of the individual wells however, a few will be shown to illustrate the capabilities of building into the simulation model certain geological and operational features necessary to understand why the wells perform as they do.

For instance, well 22 produced at a fairly constant high water rate and low gas rate. The actual and simulated production rates are shown in Fig. 9. The high water rate compared to other wells in the pattern could indicate a source of water other than that normally in the immediate vicinity of the well. This mode allowed us to simulate an area of increased porosity and permeability in the same general area as the possible faulted zone indicated on Fig. 6.

As a different example, well 4 indicates an immediate gas rate response when the well is turned on with the water rate falling off rapidly. See Fig. 10. This indicates the possibility of a barrier near the well which causes rapid pressure draw down along with increased gas saturation. The two faults shown to the east and southeast of the well pattern on Fig. 6 could cause this phenomena. In the model, the symmetrical grid was ended at grid block 21 and the other blocks eliminated on the southeast to simulate these barrier faults.

Well 7, shown in Fig. 11, is located inside the pattern. Its high gas rate beginning after 582 days is indicative of the effect of surrounding wells being placed on production creating interwell interference. Pressure interference between wells results in a rapid lowering of the pressure between wells. Thus, the gas was released at the maximum rate at which the diffusivity function will allow in this interwell area. This well was probably effected by the previously discussed well 4, among others. The high permeability in the area of wells 3, 4, 7, and 8 was necessary to obtain this type of interference. Actually, during fracture communications were demonstrated between wells 4 and 7.

Not all the individual wells were good matches. For instance, well 25, shown in Fig. 12 shows that the computed water rate was low. However, looking at the well data, it produced at a very low rate even though the water rate remained high. One reason for this is the well is an outside well in the pattern; thus, it was not subjected to as much interference as internal wells. Limited echometer data indicated that this well was not being pumped off and thus retained a high fluid

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field was increased to provide more water to be produced before the critical gas saturation was reached. The well finally started producing gas after 735 days when the well began to be pumped off as indicated by the fall off in water rate starting at this time. Although we increased the porosity in the vicinity of this well, the high bottomhole pressure lowered the water rate until the high pressure was removed.

The relatively good match of individual well production rates and the excellent match of the total pattern production rates give credence to predicting what the pattern will produce in the future. Fig. 13 shows the result of continuing to produce the model for 20 years into the future. It can be seen that after only a few months of continued increase in gas production, the rate begins to decline. However, a stable rate of about 400 MCFD is predicted after nine years of production. This rate continues through the remainder of the 20 year period and the recovery at that time is calculated to be 3.8 BCF of gas. At the end of 20 years, about 77percent of the producible gas was removed from the area covered by the 17 well pattern. This means that approximately 2.6 BCF of the gas was produced from the area outside the limits of the pattern.

At the end of six years, which corresponds to the projected time of mining, approximately 45% of the producible gas will be removed from the area covered by the 17 wells. This amount of removal will materially reduce the methane emissions anticipated during mining. Further, the gas recovered is at a rate that is significant from a gas supply standpoint and should be sold or utilized.

This example demonstrates that gas can be recovered from coalbeds at rates that can materially affect the gas content of coal ahead of mining. Further, this rate is significant for a gas supply.

NOMENCLATURE

a	=	radius of coal particle, cm
C	=	Concentration, g.mole/cm ³
D	=	diffusivity, cm ² /sec
g	=	acceleration of gravity, cm/sec ²
G	=	gas gravity, air-1.0
h	=	subsea depth, m
k	=	permeability, md
k _r	=	relative permeability
M	=	volume sorbed, cm ³
M.W.	=	molecular weight, g/g.mole
N	=	rate of methane desorption, g/sec
N _v	=	rate of methane desorption per unit coal volume, g/cm ³ -sec
P	=	hydraulic pressure in the fracture system, g/cm-sec ²
P _c	=	capillary pressure, g/cm-sec ²
q	=	production rate, g/sec
Q	=	flow rate, Mcf/d
q _v	=	rate of production per unit volume, g/cm ³ -sec
r	=	radial distance from the center of a sphere or circle, cm
t	=	time, sec
T	=	transmissibility, Darcy-cm
v	=	velocity, cm/sec
V	=	volume adsorbed, cm ³
V _c	=	grid block volume, cm ³
-	=	compressibility factor

φ	=	volume of the fracture system relative to total coal volume (effective porosity)
μ	=	viscosity, cp
θ	=	angular displacement, degrees

Subscripts

g	=	gas
i	=	grid block index (x or r direction)
j	=	grid block index (y direction)
k	=	grid block index (z direction)
NR	=	number of grid blocks in radial direction
t	=	time
T	=	total
v	=	volume
w	=	water
x	=	x coordinate values
y	=	y coordinate values
z	=	z coordinate values

Superscripts

n	=	present time level
n+1	=	next time level

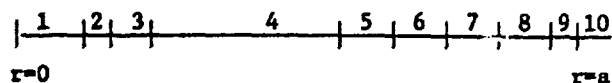
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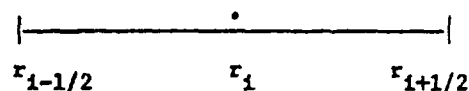
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APPENDIX1. Finite Difference Approximation of the Gas Diffusion Equations

The model sphere on which concentration solutions are to be obtained is subdivided into a series of spherical shells. This subdivision can be illustrated on a line segment, since the solution is one-dimensional and dependent only on the distance from the center of the sphere:



Each of the intervals into which the radius of the sphere is divided is called a grid block. In the coal gas program, the boundaries of the grid blocks are located at $a/8$, $a/6$, $a/4$, $0.5a$, $0.6a$, $0.8a$, $0.9a$, $0.95a$, and a . To avoid complications that occur at $r=0$, the problem is solved for a half sphere with the $a/8$ boundary treated as a no flux boundary as indicated by Equation (4). (Ignoring the particle volume for $r < 0.125a$ is of little consequence since this represents only 0.2 percent of the total volume.) The center of each grid block is taken to be the harmonic average of the block boundaries.



$$\frac{1}{r_i} = 0.5 \left(\frac{1}{r_{i-1/2}} + \frac{1}{r_{i+1/2}} \right) \dots\dots\dots$$

A finite difference approximation to Equation (1) can be written for each grid block:

$$A_{i-1/2} (C_{i-1}^{n+1} - C_i^{n+1}) - A_{i+1/2} (C_i^{n+1} - C_{i+1}^{n+1}) = B_i (C_i^{n+1} - C_i^n) \dots\dots\dots$$

or rearranged,

$$A_{i-1/2} C_{i-1}^{n+1} - A_{i-1/2} C_i^{n+1} + A_{i+1/2} C_i^{n+1} + B_i C_i^{n+1} + A_{i+1/2} C_{i+1}^{n+1} = -B_i C_i^n \dots\dots\dots$$

where the following definitions apply:

$$A_{i-1/2} = \frac{4\pi D}{\frac{1}{r_{i-1}} - \frac{1}{r_i}} \dots\dots\dots$$

$$A_{i+1/2} = \frac{4\pi D}{\frac{1}{r_i} - \frac{1}{r_{i+1}}} \dots\dots\dots$$

$$B_i = \frac{4\pi}{3\Delta t} (r_{i+1/2}^3 - r_{i-1/2}^3) \dots\dots\dots$$

Equation (A-3) is a backward difference approximation of Equation (1). It is second

**ANALYSIS OF THE COALBED DEGASIFICATION PROCESS
AT A SEVENTEEN WELL PATTERN IN THE WARRIOR BASIN OF ALABAMA**

time step size.

This equation can be written for every grid block, except for the first and last, where boundary conditions must be considered. At $i+1$ the first term in Equation (A-2) is dropped because of the no flux boundary, leaving

$$-(A_{i+1/2} + B_1)C_1^{n+1} - A_{i+1/2}C_{i+1}^{n+1} = -R_1C_1^n \dots\dots\dots (A-7)$$

At $i=NR(r=a)$, we have the following equation:

$$A_{NR-1/2}C_{NR-1}^{n+1} - (A_{NR-1/2} + B_{NR})C_{NR}^{n+1} = -B_{NR}C_{NR}^n + N \dots\dots\dots (A-8)$$

where N is the rate of methane desorption. Furthermore, we know that $C_{NR}^{n+1} = f(p_g^{n+1})$.

2. Finite Difference Approximation of the Fracture Flow Equations

Equations (12) and (13) are written in terms of Cartesian coordinates; however, the coal gas simulator can solve them either in Cartesian or cylindrical coordinates. After substitution of Equations (14) and (15), Equations (12) and (13) may be approximated as follows:

$$\Delta \cdot \left\{ T \frac{\rho_w^{n+1} k_{rw}}{\mu_w^n} (\Delta p_w^{n+1} - \rho_w^n g \Delta h) \right\} - q_w^{n+1} = \frac{V}{\Delta t} \{ (\phi \rho_w S_w)^{n+1} - (\phi \rho_w S_w)^n \} \dots\dots\dots (A-9)$$

$$\Delta \cdot \left\{ T \frac{\rho_g^{n+1} k_{rg}}{\mu_g^n} (\Delta p_w^{n+1} + \Delta p_c^{n+1} - \rho_g^n g \Delta h) \right\} + N_T^{n+1} - q_g^{n+1} = \frac{V}{\Delta t} \{ (\phi \rho_g)^{n+1} (1 - S_w)^{n+1} - (\phi \rho_g)^n (1 - S_w)^n \} \dots\dots\dots (A-10)$$

where the following definitions apply:

$$T_x = \frac{k_x \Delta y \Delta z}{\Delta x}; T_y = \frac{k_y \Delta x \Delta z}{\Delta y}; T_z = \frac{k_z \Delta x \Delta y}{\Delta z} \dots\dots\dots (A-13)$$

$$V = x y z \dots\dots\dots (A-14)$$

$$N_T = V c N_v \dots\dots\dots (A-15)$$

$$\Delta \cdot (E \Delta F) = \{ E_{i-1/2} (F_{i-1} - F_i) - E_{i+1/2} (F_i - F_{i+1}) \}_{j,k} + \{ E_{j-1/2} (F_{j-1} - F_j) - E_{j+1/2} (F_j - F_{j+1}) \}_{i,k} + E_{k-1/2} (F_{k-1} - F_k) - E_{k+1/2} (F_k - F_{k+1}) \}_{1,j} \dots\dots\dots (A-16)$$

All relative permeabilities required at grid block boundaries are based on the saturation of the upstream grid block, i.e. the block from which that

is flowing. These finite difference equations are first order correct in both space and time and no significant stability limitation.

3. Solution of the System of Finite Difference Equations

It is assumed that all of the coal particles be represented as spheres and furthermore that these spheres are identical in size. Thus, the rate of methane entering the fracture system in given fracture grid block is the rate of desorption for a typical sphere contained in that block multiplied by the number of such spheres required to up the total mass of coal in the block.

Thus, to solve the fracture flow equations (Equations (A-9) and (A-10)) we must simultaneously solve the set of equations describing diffusion in a typical sphere of coal (Equation (A-3)), one such sphere for each fracture grid block. The total of equations consists then of $2 \cdot NX \cdot NY \cdot NZ$ fracture flow equations ($NX \cdot NY \cdot NZ$ equations for both water and gas) plus $(NX \cdot NY \cdot NZ) \cdot NR$ diffusion equations (NR equations for each model sphere).

All of these equations could be collected together in a large matrix equation and solved either directly or iteratively. It is possible, however, to greatly reduce the dimensionality of the problem. The key to this is the fact that none of the equations describing diffusion in a coal particle couple equations for other particles, and only the grid at the exterior boundary of a sphere couples to the fracture system. As a consequence, the following procedure, called static condensation, can be implemented.

- (1) Collect the equations for a given sphere into a tridiagonal matrix equation.
- (2) Factor this matrix into upper and lower halves. (The factors will be identical for every sphere for any given time since the same grid is used for all diffusivities is treated as a constant)
- (3) Perform the forward elimination for the set of diffusion equations.
- (4) As explained below, the last equation of each set can now be put in the form $N = b_1 + b_2 p_{ijk}^{n+1} \dots\dots\dots$
- (5) Substitute Equation (A-17) into Equation (A-10) and solve the resulting set of equations for p_w and S_w . (This is either direct elimination or iteration)
- (6) Use the new pressure solution to get the boundary concentration on the diffusion equations for each typical sphere and perform the back substitutions to generate new concentration distributions.

Steps 4 and 5 of the above procedure require further explanation.

When the diffusion equations for a given sphere are collected together, the resulting set of equations is tridiagonal. The last two equations may be represented as follows:

$$E_{NR-1} C_{NR-2}^{n+1} + F_{NR-1} C_{NR-1}^{n+1} + G_{NR-1} C_{NR}^{n+1} = R_{NR-1} \quad \text{.....(A-18)}$$

$$E_{NR} C_{NR-1}^{n+1} + F_{NR} C_{NR}^{n+1} = R_{NR} + N \quad \text{.....(A-19)}$$

where

$$E_1 = A_{1-1/2} \quad \text{.....(A-20)}$$

$$F_1 = -(A_{1-1/2} + A_{1+1/2} + B_1) \quad \text{.....(A-21)}$$

$$G_1 = A_{1+1/2} \quad \text{.....(A-22)}$$

$$R_1 = -B_1 C_1^n \quad \text{.....(A-23)}$$

After the forward elimination has proceeded through equation NR-1, the last two equations are

$$C_{NR-1}^{n+1} + H_{NR-1} C_{NR}^{n+1} = U_{NR-1} \quad \text{.....(A-24)}$$

$$E_{NR} C_{NR-1}^{n+1} + F_{NR} C_{NR}^{n+1} = R_{NR} + N \quad \text{.....(A-25)}$$

If we algebraically eliminate C_{NR-1}^{n+1} between these two equations, the result is:

$$N = (-R_{NR} + U_{NR-1} E_{NR}) + (F_{NR} - E_{NR} H_{NR-1}) C_{NR}^{n+1} \quad \text{.....(A-26)}$$

We now write C_{NR} as a locally linear function of fracture pressure, p_g :

$$C_{NR}^{n+1} = f(p_g^n) + \frac{df}{dp_g} (p_g^{n+1} - p_g^n) \quad \text{.....(A-27)}$$

When this is substituted into Equation (A-26), we have an equation of the form

$$N = b_1 + b_2 p_g^{n+1} \quad \text{.....(A-28)}$$

After solving for p_g^{n+1} , we calculate C_{NR}^{n+1} , find its equilibrium pressure functionality, insert it into Equation (A-24), and solve for C_{NR-1}^{n+1} . The back substitution for the remaining C_i^{n+1} , then proceeds in the normal fashion.

TABLE 1 - EQUILIBRIUM ADSORPTION ISOTHERM DATA USED IN SIMULATION

Pressure (Atm)	Gas Adsorb Std. cc/
0.0	0.0
5.0	4.21
10.0	7.61
15.0	10.43
20.0	12.79
25.0	14.80
30.0	16.54

FIGURE 1
EQUILIBRIUM ADSORPTION ISOTHERMS, U.S. COALS

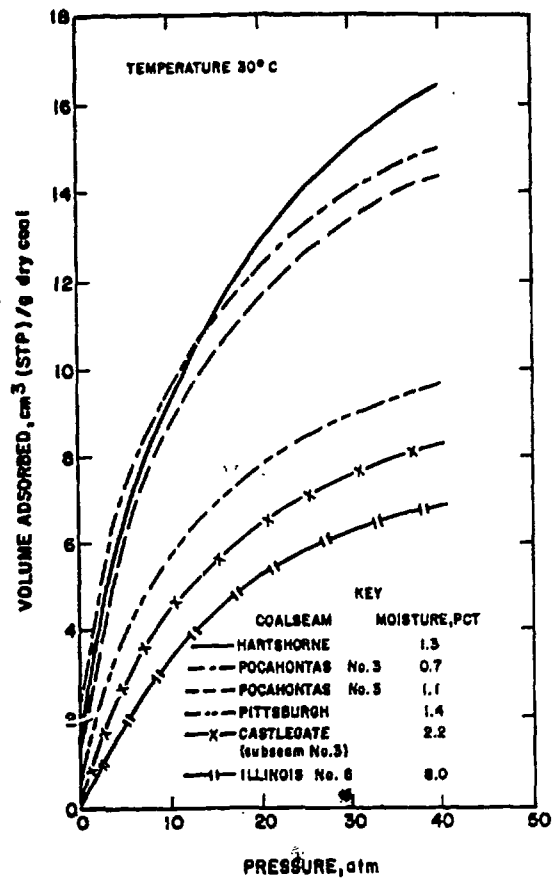


FIGURE 2
GAS RELATIVE PERMEABILITY CURVES

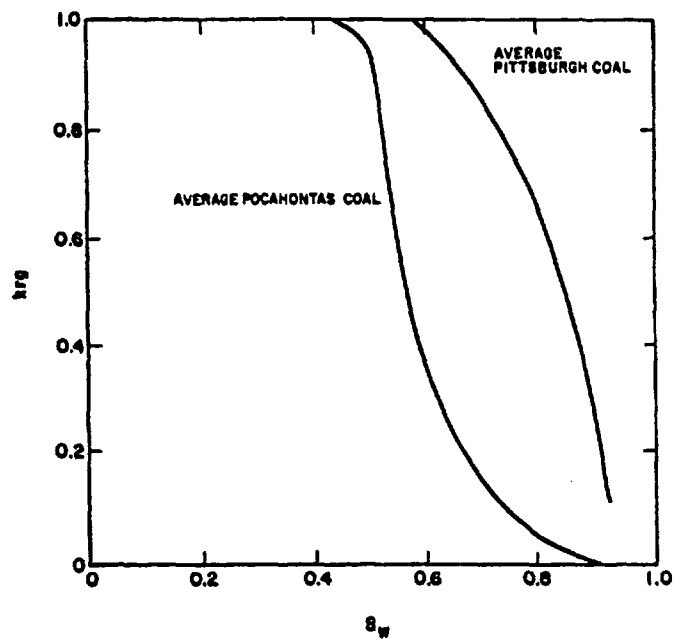


FIGURE 4
OAK GROVE DEGASIFICATION PATTERN
MARY LEE COALBED, JEFFERSON CO., ALABAMA

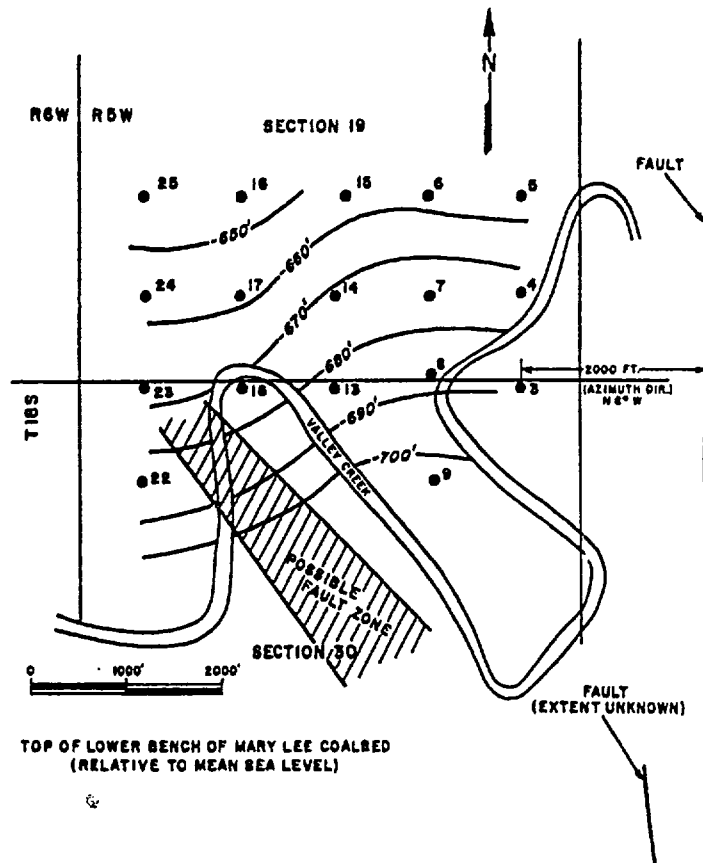
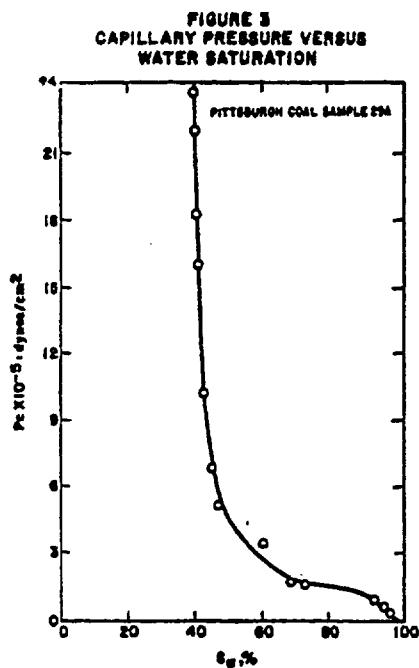


FIGURE 5
TOTAL PATTERN PRODUCTION DATA

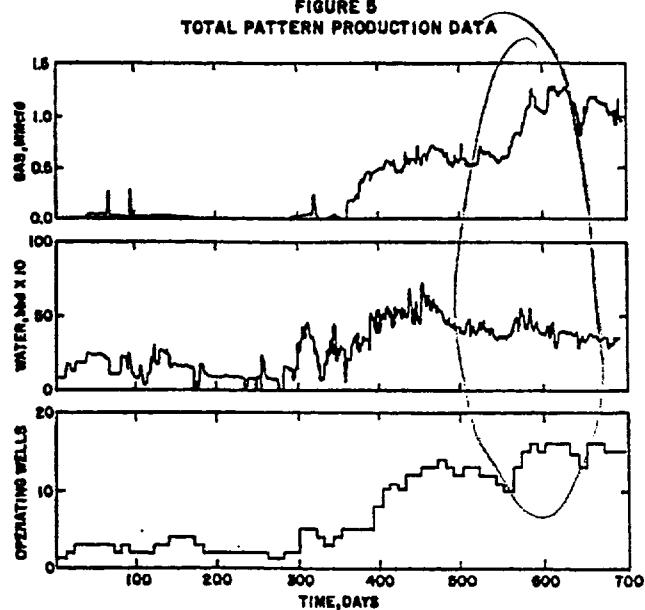


FIGURE 6
GRID USED IN SIMULATION MODEL SHOWING AREAS
OF ADJUSTED PERMEABILITY AND POROSITY

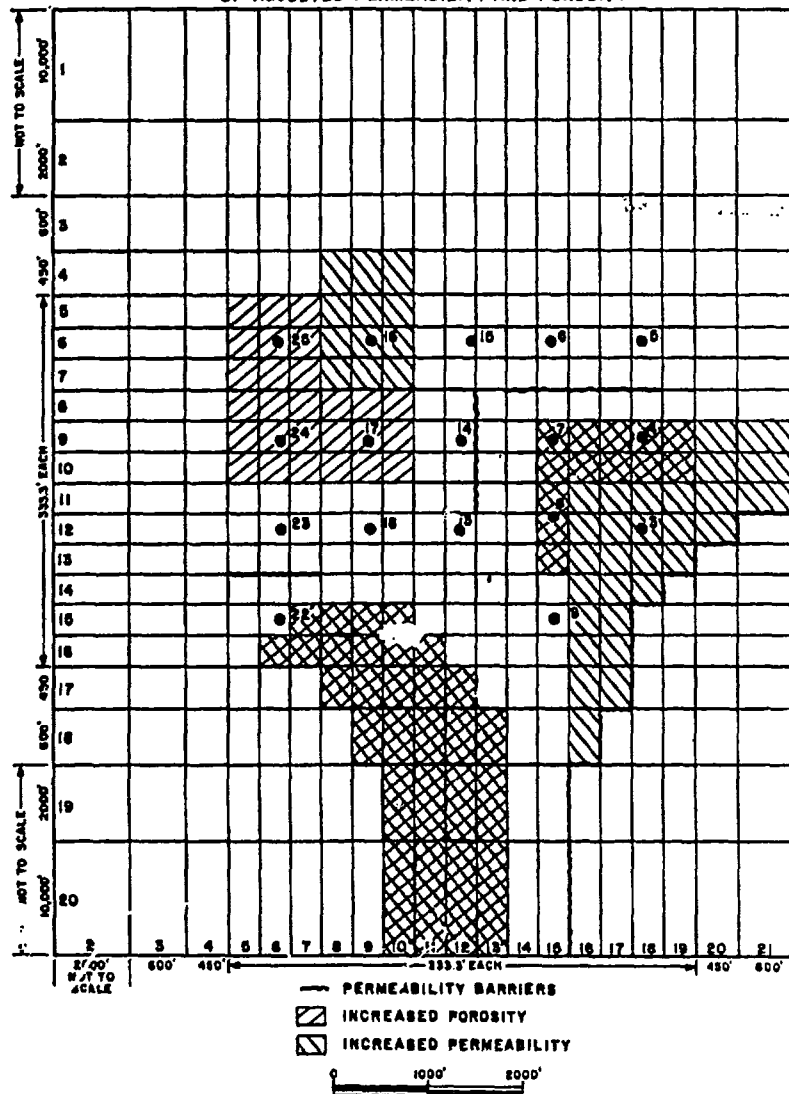


FIGURE 7
RELATIVE PERMEABILITY CURVES USED IN
OAK GROVE PATTERN SIMULATION

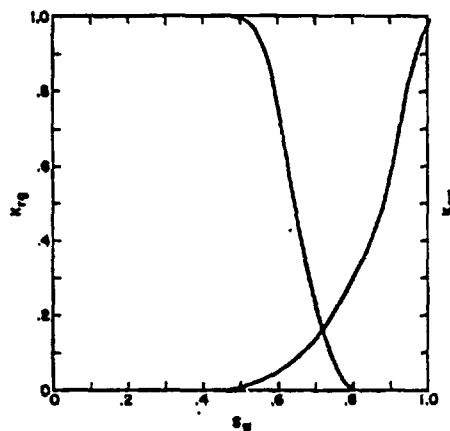


FIGURE 8
TOTAL PRODUCTION RATE FROM PATTERN -
COMPAIED TO SIMULATION RESULTS

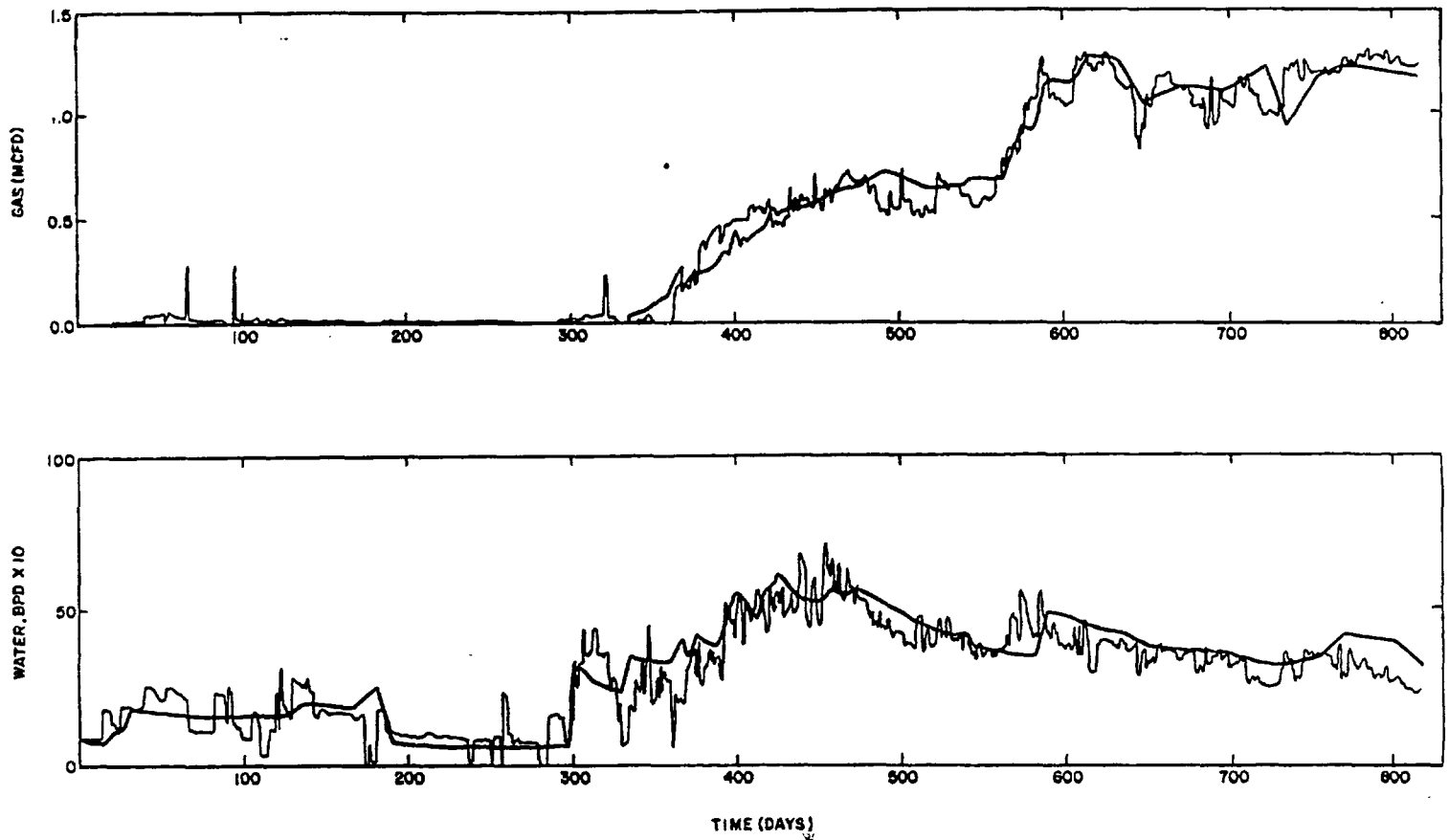


FIGURE 9
WELL 22 PRODUCTION RATES COMPAIED TO SIMULATION

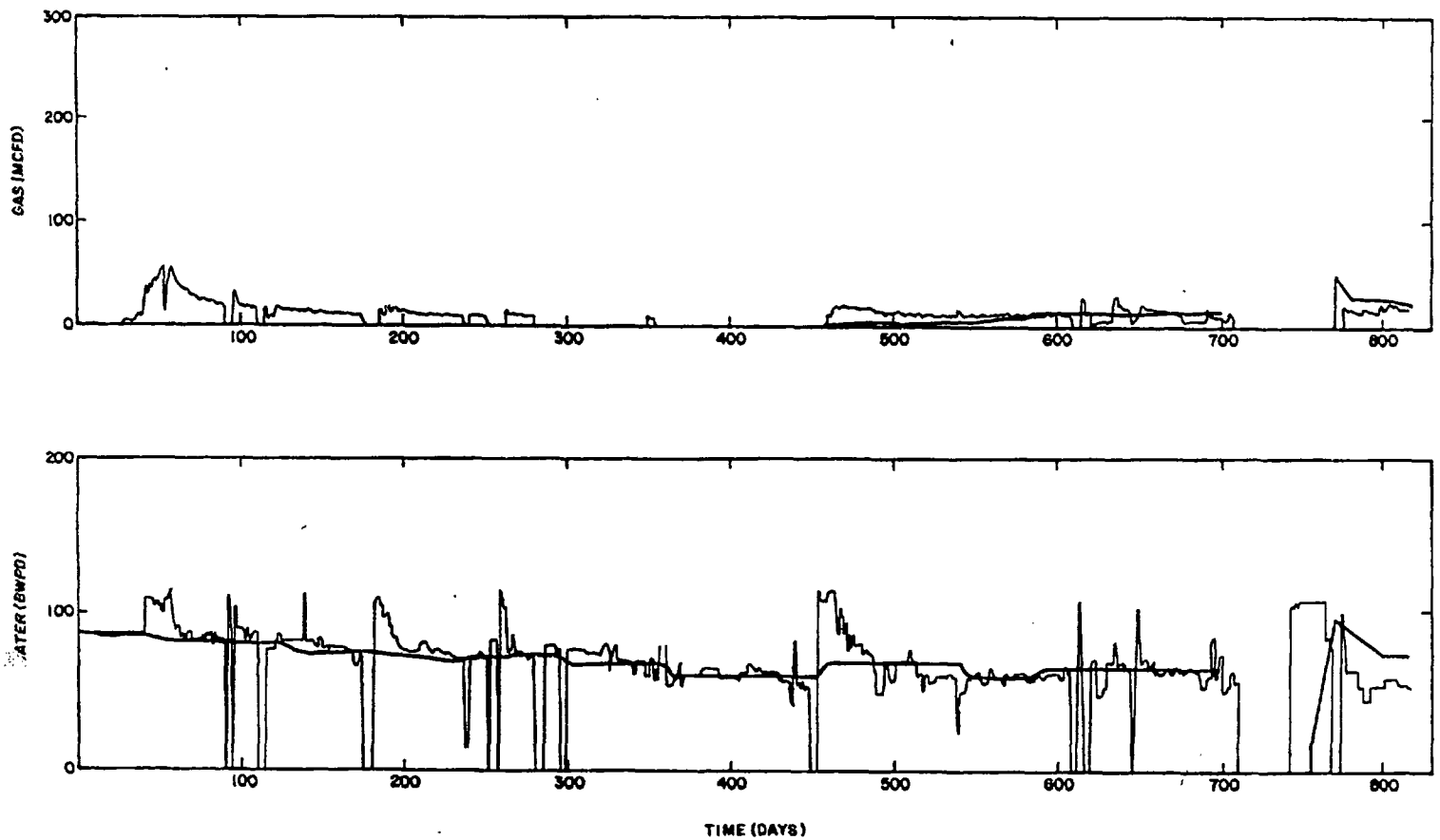


FIGURE 10
WELL 4 PRODUCTION RATES COMPARED TO SIMULATION

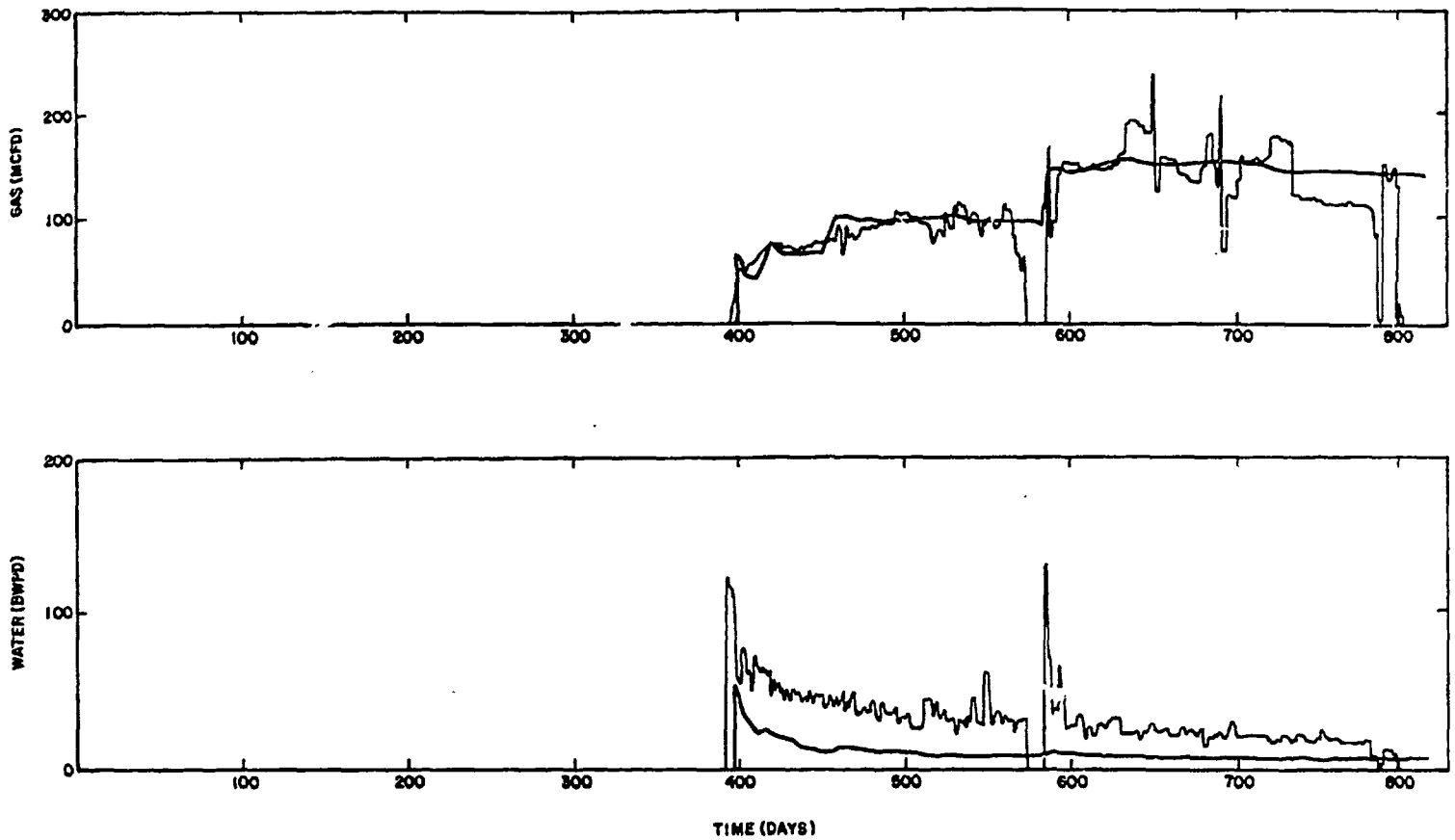


FIGURE 11
WELL 7 PRODUCTION RATES COMPARED TO SIMULATION

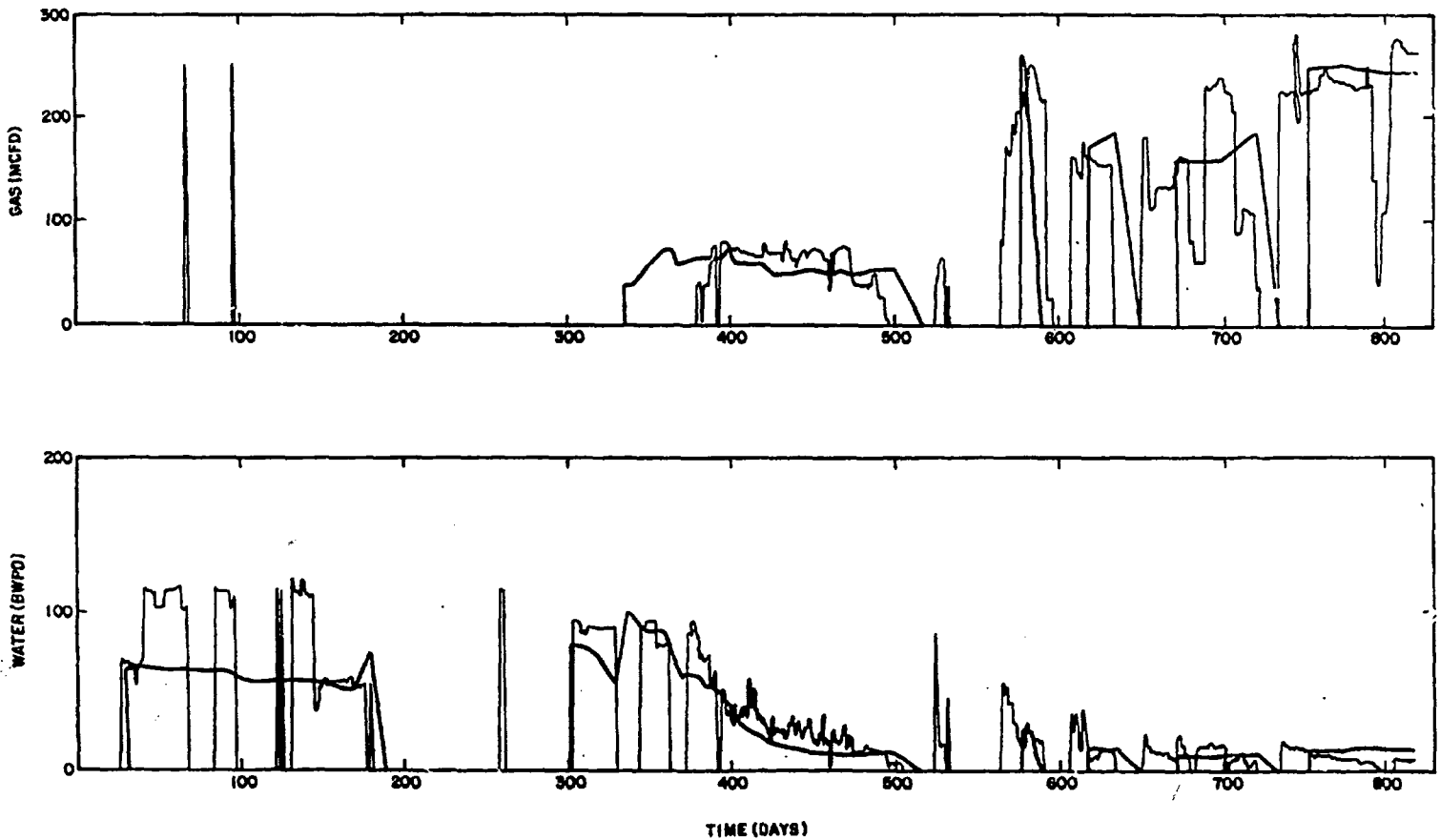


FIGURE 12
WELL 25 PRODUCTION RATES COMPARED TO SIMULATION

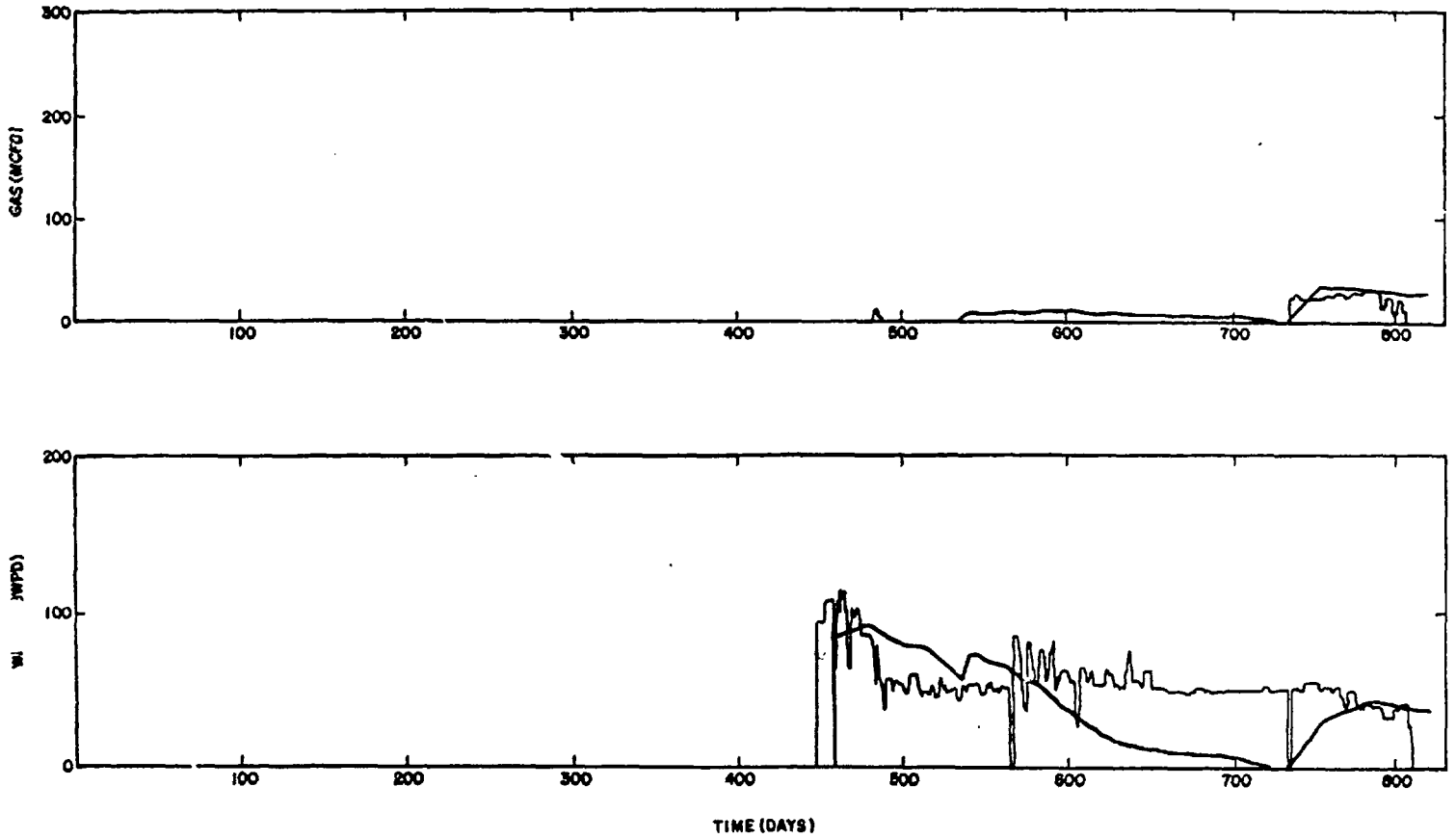


FIGURE 13
20 YEAR PRODUCTION PREDICTION

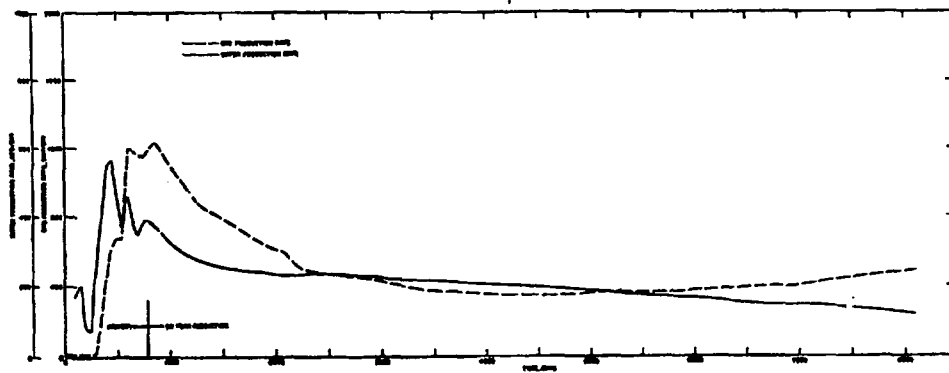


FIGURE 5
TOTAL PATTERN PRODUCTION DATA

