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Measuring Formation Pressures and the Degree of Gas Drainage in a Large Coalbed Gas Drainage Field

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

atm	atmosphere	lb	pound (mass)
cm^3	cubic centimeter	lb/ft	pound per foot
cm^3/g	cubic centimeter per gram	lb/ft^3	pound per cubic foot
°F	degree Fahrenheit	lbf/in^2 (ga)	pound (force) per square inch, gauge
ft	foot	lbf/in^2 per month	pound (force) per square inch per month
ft^3	cubic foot	$MMstdft^3$	million standard cubic feet
ft^3/st	cubic foot per short ton	$MMstdft^3$ per month	million standard cubic feet per month
g	gram	pct	percent
g/cm^3	gram per cubic centimeter	V ac	volt, alternating current
gal	gallon		
h	hour		
in	inch		

MEASURING FORMATION PRESSURES AND THE DEGREE OF GAS DRAINAGE IN A LARGE COALBED GAS DRAINAGE FIELD

By David C. Oyler[1] and Paul B. Stubbs[2]

ABSTRACT

The Bureau of Mines and United States Steel Corp. are conducting a joint project to monitor formation pressures at a large (23-well) coalbed gas drainage field near Oak Grove, AL. Three monitor holes were drilled in late 1981, and pressure monitoring began in December 1981. The Bureau of Mines direct method was used to obtain gas content data from cores taken in the monitor holes. Comparison of the 1981 gas content data from the monitor holes with initial gas content values obtained from the production wells in 1977 indicates a 50-pct reduction in adsorbed gas content inside the pattern and a 29-pct reduction at one point 500 ft outside the pattern. The combination of pressure and gas content data has also allowed an in situ isotherm curve, relating the formation pressure to adsorbed gas content, to be developed for the area of the production wells. From the current rate of pressure decline (1 lbf/in^2 per month), the observed changes in gas content, and the isotherm curve, it appears that most of the early gas production came from within the pattern, but since 1981 (and possibly earlier) most of the gas produced has been migrating to the wells from outside the pattern area.

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INTRODUCTION

In the late 1970's the use of hydraulically stimulated vertical wells to drain methane gas from coalbeds developed from an experimental technique to a technology which is now beginning to be used by both the coal mining and the natural gas industries. Work at the United States Steel (USS) Oak Grove Mine in Jefferson County, AL (1-2),[3] Emerald Mine (3) in Greene County, PA, and at other locations, especially in the Western States (4), has shown that vertical boreholes can be drilled to remove methane from coalbeds, both to decrease methane emissions in mines and to produce methane as a marketable natural gas. Several projects have recently been initiated to drill vertical hole patterns with both purposes in mind.

Both reservoir and ventilation engineers need to determine the conditions existing in the coalbed reservoir, so that the progress of depletion of the reservoir can be monitored, and so that intelligent decisions concerning continuing gas production and mining can be made. Unfortunately, geophysical logging techniques and many of the physical sampling methods developed in the oilfield to determine gas reserves are generally not applicable to coal. However, a technique has been developed that is applicable to coal and replaces techniques used in the oilfield. This method uses a measurement of the original in-place gas content obtained from the Bureau of Mines direct method test (5, 7) together with coal adsorption isotherm (8-10) data, either laboratory or field, to relate pressures in the coalbed fracture system to gas content. The method assumes that the pressure and gas content are at equilibrium; this is not completely true in a producing reservoir, but the error from this assumption is relatively small. Several methods are available to determine the fracture system pressure, which can then be related to the adsorption isotherms to give estimates of the absolute in-place gas content of the coalbed.

In the late 1970's, the Bureau of Mines and USS entered into a cost-sharing agreement to test the technique of coalbed degasification from vertical boreholes using a large pattern of wells. In late 1977, 17 wells of a planned 25-well pattern at the Oak Grove Mine in Jefferson County, AL, were completed. By early 1979 the average daily gas production for the pattern had exceeded 1 MMstdft^3, demonstrating the effectiveness of the improved techniques developed during the project. Six more wells were drilled in the summer of 1980, bringing the total to 23 wells. Wells 10 and 20 were never drilled.

In late 1981, the Bureau and USS began a project to drill three holes in the vicinity of the Oak Grove pattern to monitor pressure changes in the coalbed caused by gas production, and to obtain cores for desorption, so that the cumulative effects of gas production could be determined. The holes were completed in the fall of 1981, and pressure monitoring began in December 1981.

MONITOR HOLE DRILLING AND COMPLETION

Figure 1 shows the location of the pressure monitor holes with respect to the production wells. Holes, M1 and M2 are within the area of the degasification well pattern, and M3 is 500 ft due west of the northwesternmost well in the pattern.

DRILLING

The holes were first drilled at a 10-in diameter to depths between 50 and 60 ft, where 7-in-OD surface casing was set and cemented in place. The holes were then rotary-air-drilled at a 6-1/4-in

[3] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

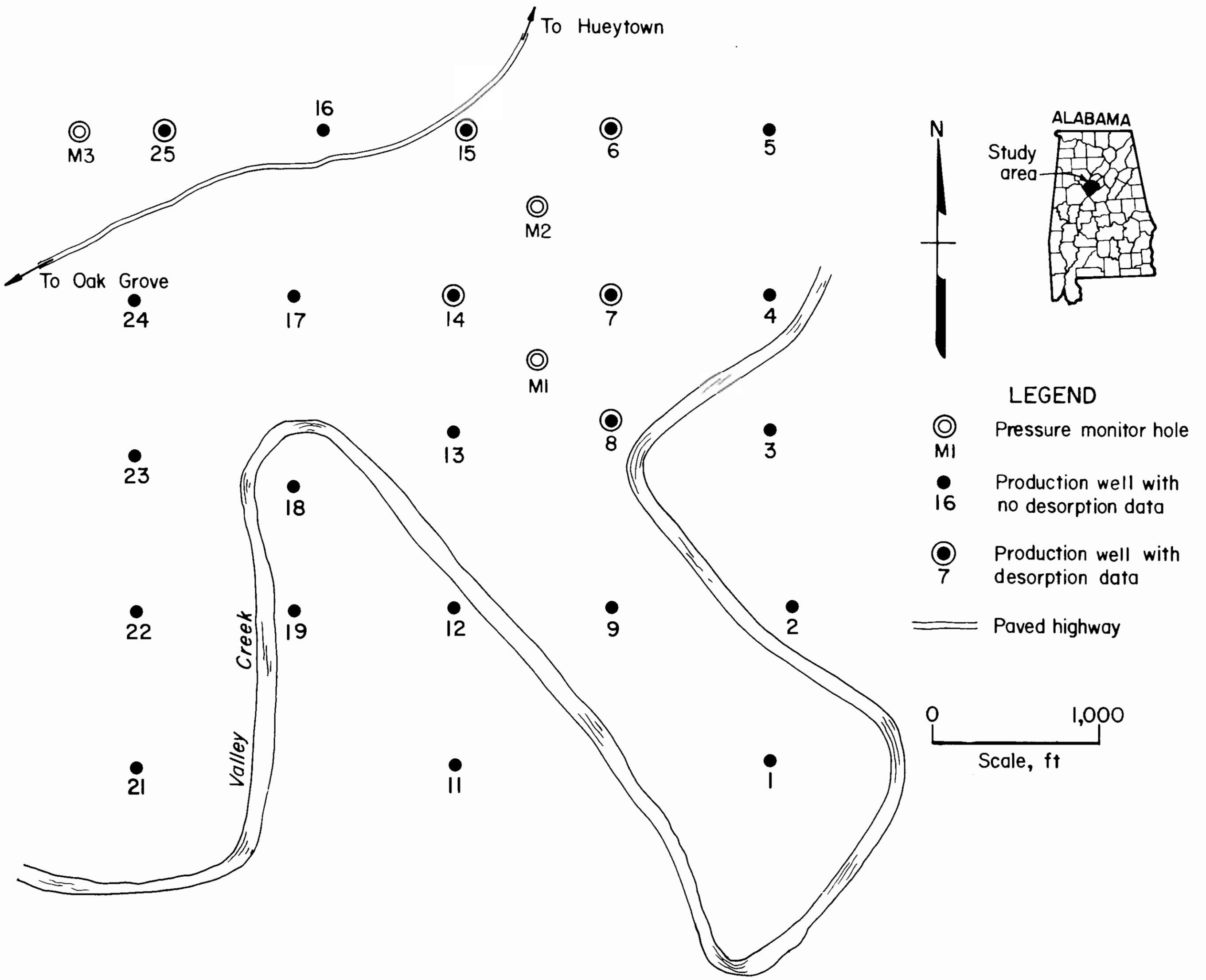

FIGURE 1. - Map of monitor hole and production well locations.

diameter to a point just below the upper bench of the Mary Lee coalbed (figs. 2-3) at about 1,060 to 1,080 ft, where 4-1/2-in-OD, 10.5-lb/ft casing was placed in each hole. The casing was then cemented in place using class A cement with 18 pct salt.

After the holes were cemented, a coring rig was used to core out the float shoe and bottomhole cement plug and to core to approximately 30 ft below the coal seam. The coal core was logged, photographed, and placed in air-tight canisters, so that the Bureau of Mines direct method test could be performed on all of the coal recovered from each hole.

COMPLETION

A geophysical log suite consisting of a gamma-ray, density, and caliper log was run in each hole after coring. The logs were run from total depth to surface, although only the gamma-ray log is useful in the cased portion of the hole. Gyroscopic directional surveys were then run on each hole to determine the exact bottomhole locations in the coalbed.

To ensure that the pressure instruments would see the true formation pressure and all changes in it, a notch was cut in the coalbed in each hole. The notch was designed to remove any coal that might have

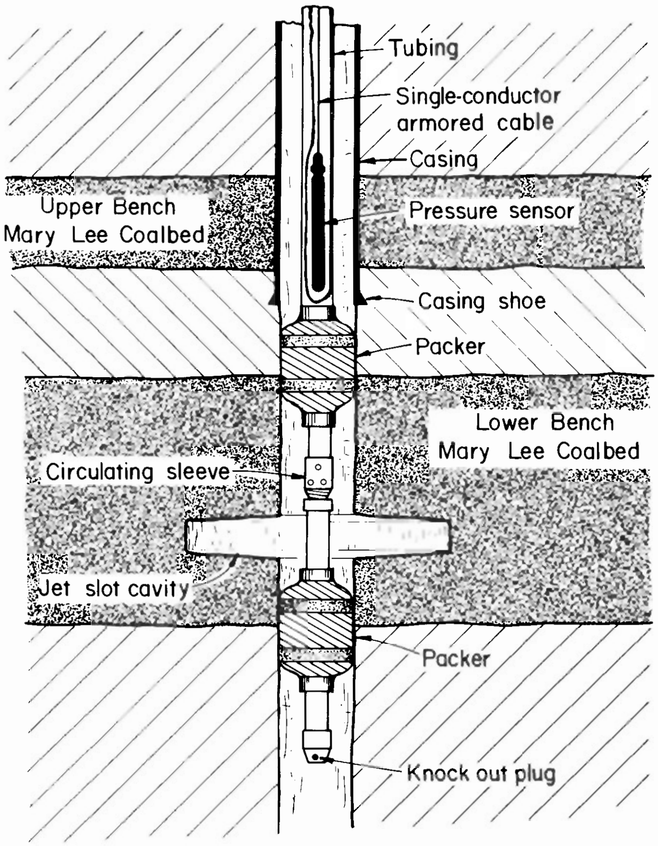

FIGURE 2. - Typical bottom hole assembly of monitor holes.

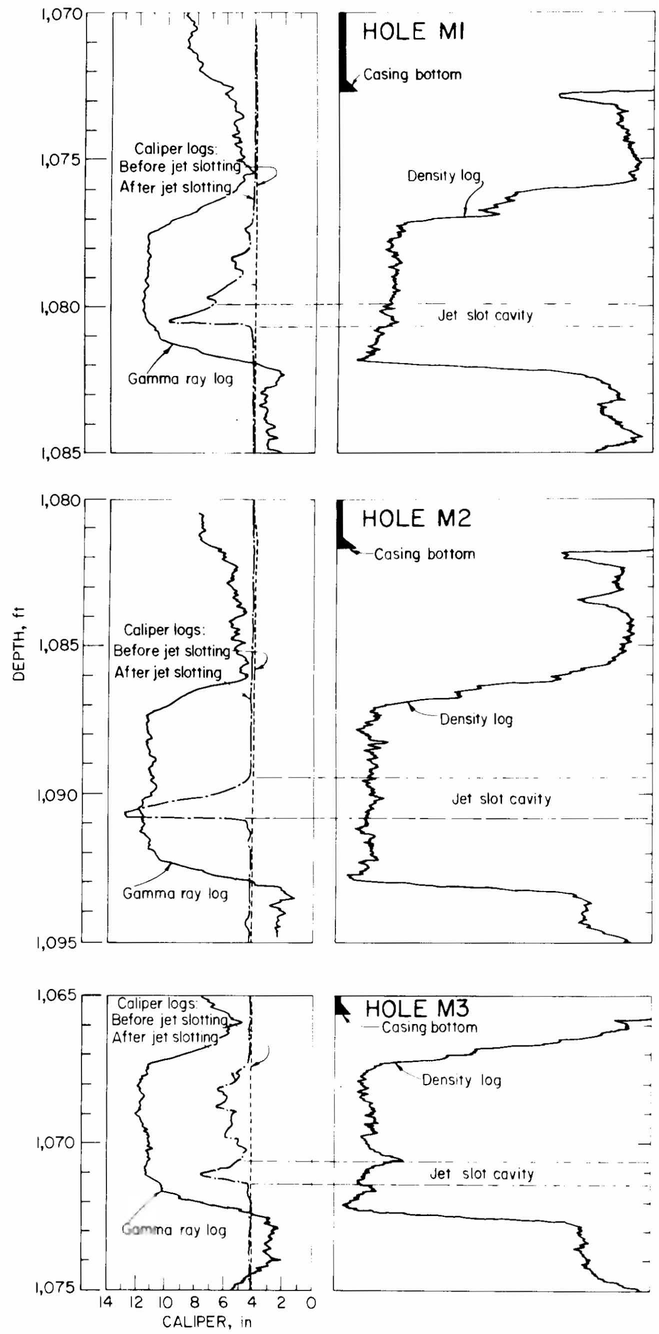

FIGURE 3. - Geophysical logs of monitor holes showing jet slotting cavities.

had its permeability reduced by cement or drilling fluids. The notch was cut by running a tool containing three small (about 3/16-in-diam) ports on the bottom of the tubing to the depth of the coalbed. A slurry of sand and water was then pumped down the tubing and through the ports, at pressures of 2,500 to 3,000 lbf/in^2(ga), to create a high-velocity jet which abraded away the first 6 to 12 in of the coal from the wall of the hole. Since some sand had been used in the notching process, it was also necessary to flush out the holes with water after notching to remove the sand. After the notching had been completed, an additional gamma-ray caliper log was run in holes M1 and M3 to determine the size and location of the notches, and to ensure that the packers used later were not set in the notches. This log was not run in hole M2 until after the packer had been set in the notch. A reproduction of the geophysical logs (including the density log run earlier) is shown in figure 3.

After notching, the tubing was removed from the holes and rerun with two Lynes production-injection packers[4] on bottom to straddle and isolate the coalbed. The use of the packers was primarily a

[4]Reference to specific products does not imply endorsement by the Bureau of Mines.

precaution, since the formations exposed in the borehole above and below the coalbed were impermeable shales and fire clays. The packers were set simultaneously by inflating them with water injected through the tubing. A hand pump was used to establish a pressure of between 1,100 and 1,500 lbf/in^2(ga) within the tubing and the packers, and a check valve in each packer prevented them from deflating when the tubing pressure was bled down. (The packers are deflated by rotating and pulling on the tubing.) After the tubing pressure had been relieved, a 1-in steel bar was run into the hole on wire rope (the workover rig sandline) to shear a pin in a Lynes model B circulating sleeve (fig. 2) between the packers. Shearing this pin opened ports in the sleeve and allowed communication between the coalbed and the tubing.

The first packers installed (in M2) were inflated to 1,400 lbf/in^2(ga), at which time the lower packer ruptured. A caliper, gamma-ray log, run subsequently, indicated that the lower packer had been set in the notched cavity. The packers were removed from the hole, a replacement was obtained for the one that had ruptured, and they were then run back in the hole and successfully set. Had the lower packer been set in a portion of hole that was in-gauge or to a pressure below 1,400 lbf/in^2(ga), no failure would have taken place. The incident did indicate the toughness of the packers. When packers were to be set in holes M1 and M3, caliper gamma-ray logs were run to check the exact location of the notched cavity.

As soon as the sleeve was opened, the water in the tubing began to enter the coalbed, and within 48 h the hydrostatic pressure in the tubing was within 5 lbf/in^2(ga) of the formation pressure.

PRESSURE SENSOR SYSTEM

SENSOR UNIT

Pressure measurements were made using a Lynes Sentry pressure sensor installed in each hole. This tool uses a helical-shaped bourdon tube, connected by a shaft to a sapphire disc covered with a pattern of small transparent and opaque areas. On one side of the disk is a row of light-emitting diodes, and on the other is a row of photosensitive diodes. Rotation of the disk caused by a change in pressure produces a change in the pattern of signals seen in the photosensitive diodes. Each pattern represents a different position of the bourdon tube and a different pressure. Because the disk is divided into 500 individual patterns, the sensitivity of the tool is limited to 1/500, or 0.2 pct of the full-scale reading. For the 0-500 lbf/in^2(ga) sensors used in holes M1-M3, this means that pressures can only be discriminated to within ±1 lbf/in^2. The pressure signal and a temperature reading are sent uphole through a 7/32-in-diameter armored single-conductor cable, and a computer at the surface converts the signal to a pressure reading. Power for the tool is supplied by the surface unit through the signal cable. The Sentry tool is 1.5 in in OD by 37.75 in long (fig. 4) and weighs about 15 lb.

SURFACE UNIT

The surface unit is a Lynes model DSR-2 P/T digital surface recorder (DSR). The unit can handle signals from up to 15 holes. At Oak Grove, a single centrally located DSR is being used, with signals transmitted from each hole by coaxial cable. The pressure data are recorded every 8 h and printed on a paper tape. Each reading includes the well number, a pressure reading, a temperature reading (the last two printed twice), and a time interval. The time interval is printed in place of a time and date, and to convert it to an exact time and date both the time of the initial reading and the interval length must be known. The unit does not contain batteries and can only operate on 120-V-ac power. This lack of a battery backup can be a handicap in the event of a power failure.

FIGURE 4. - Sentry unit being installed in monitor hole M3.

FIGURE 5. - Wellhead assembly.

To obtain true pressure values, a correction must be applied to the DSR readings, since the sensors are actually located several feet above the coalbed (fig. 2). The vertical distance from the sensor to the center of the coalbed (used as the reference depth for all pressure calculations) ranges from 10.2 to 12.4 ft. The additional pressure added to the DSR readings is 5 lbf/in^2 in holes M1 and M3 and 6 lbf/in^2 in hole M2.

PRESSURE SENSOR INSTALLATION AND WELLHEAD EQUIPMENT

The sensors in the monitor holes were run through the tubing and suspended in the hole (fig. 2) from a small steel clamp (fig. 5) tightened around the cable. The cable was run in the holes by gravity.

The remainder of the wellhead assembly (fig. 5) consists of a 4-1/2-in tubing head with slips to hold 2-in tubing, a tee above the tubing bushed down for installation of a 3/8-in valve and a pressure gauge, a packing gland to clamp around the cable and seal off the tubing, and a clamp to hold the weight of the cable and sensor. The clamp rests upon the top of the packing gland, which carries the weight of the cable and the tool (about 120 lb).

RESULTS

GAS CONTENT

Table 1 shows the gas content data for the cores obtained in monitor holes M1, M2, and M3. The core from each hole was divided into four samples, each of which was placed in a separate desorption canister. A gas content measurement was made on each sample using the standard Bureau of Mines direct method. Because the samples were split, with portions being sent for petrographic analysis, only about one-third to one-fourth of each sample was available for use in determining the residual gas content. The residual gas content is that portion of the gas which (at 1 atm pressure) is not given off until the coal is crushed to a fine powder. In this case, the residual gas content was determined for the smaller portion, and it was assumed that the value thus obtained was representative of the entire sample. To better ensure that this was the case, the original cores had been crushed to 1/8-in diameter after the desorption process was completed, and the

TABLE 1. - Gas content determination for monitor holes

Monitor hole and sample	Sample interval, ft	Laboratory gas content determination							Estimated in situ gas content, ft^3/st
		Coal sample dry weight, g		Gas volume, cm^3		Gas content, cm^3/g			
		Entire sample	Residual gas portion[1]	Lost and desorbed	Residual[2]	Lost and desorbed	Residual	Total[3]	
M1:									
D......	1,077.00-1,078.47	1,204	382	9,237	185	7.7	0.5	8.2	263
C......	1,078.47-1,079.94	1,197	462	9,137	190	7.6	.4	8.0	256
A......	1,079.94-1,081.67	1,309	446	8,790	360	6.7	.8	7.5	240
B......	1,081.67-1,082.60	839	378	4,934	280	5.9	.7	6.6	211
Total or av	NAp..............	4,549	1,668	32,098	1,015	[4]7.0	[4].6	[4]7.6	[4]244
M2:									
B......	1,086.20-1,087.86	1,564	561	10,167	200	6.5	.4	6.9	221
C......	1,087.86-1,089.74	1,753	857	10,736	350	6.1	.4	6.5	208
A......	1,089.74-1,091.50	1,575	395	9,530	340	6.0	.9	6.9	221
D......	1,091.50-1,093.20	1,493	564	8,618	350	5.8	.6	6.4	205
Total or av	NAp..............	6,385	2,377	39,051	1,240	[4]6.1	[4].5	[4]6.6	[4]211
M3:									
A......	1,066.60-1,069.20	1,312	449	13,136	105	10.0	.2	10.2	327
B......	1,069.20-1,070.11	696	312	7,215	230	10.4	.7	11.1	356
C......	1,070.11-1,071.61	1,038	321	10,796	220	10.4	.7	11.1	356
D......	1,071.61-1,071.50	674	292	7,473	200	11.1	.7	11.8	378
Total or av	NAp..............	3,720	1,374	38,620	755	[4]10.4	[4].5	[4]10.9	[4]350

NAp Not applicable.

[1]The residual gas was measured for only this portion of the entire sample.

[2]This gas came from crushing the part of the entire sample indicated in the column labeled "Residual gas portion."

[3]The sum of the lost and desorbed gas content and the residual gas content.

[4]Computed from totals.

samples riffle-split to obtain the portion used for the residual gas determination. The residual gas content for each sample was computed on a cm^3/g basis by dividing the residual gas volume (cm^3) by the weight of each residual gas sample (g). The lost-and-desorbed gas content was similarly determined for each sample by dividing the lost-and-desorbed gas volume (cm^3) for each sample by the entire sample weight. The sum of the residual and lost-and-desorbed gas contents for a single sample (both in cm^3/g) gave the total gas content of that sample.

To obtain the gas content of the entire coalbed in each hole, all four sample weights and gas volumes (both lost-and-desorbed and residual) for each hole were summed to give the total weight of the entire sample in that hole, the total weight of the residual gas sample for the hole, the total lost-and-desorbed gas volume for the hole, and the total residual gas volume for the hole. The same methods used earlier in determining the gas contents of individual samples were then used to determine the lost-and-desorbed and residual gas contents for the entire coalbed at each hole (in cm^3/g). These two values were then added to give the total gas content of the coalbed at each hole (table 2). The total gas contents of holes M1, M2, and M3 were, respectively, 7.6, 6.6, and 10.9 cm^3/g (244, 211, and 350 ft^3/st).

To determine the reduction in gas content caused by degasification, initial gas content values for the Oak Grove pattern were required. The original drilling program in 1977 included coring and direct method gas content determinations for six of the wells. Table 2 shows the resulting gas content values and the initial formation pressures determined for those wells. The pressures were obtained from stabilized water levels measured in the wells in 1977 prior to the start of gas production.

The arithmetic mean of the gas content values in the wells adjacent to each pressure monitor hole have been used to give estimates of 14.5, 14.9, and 15.3 cm^3/g (465, 477, and 490 ft^3/st) for the original gas contents at each of the monitor hole locations. The gas content values obtained from the monitor holes were 7.6, 6.6, and 10.9 cm^3/g (244, 211, and 349 ft^3/st) from holes M1, M2, and M3, respectively. The data indicate that over a 4-year period of degasification the reductions in adsorbed gas content at the monitor hole sites were 48, 56, and 29 pct (table 3), or roughly a 50-pct decrease in gas content within the pattern area and a 25- to 30-pct decrease as far as 500 ft away from the outside boundary of the pattern.

TABLE 2. - Gas content values and formation pressures measured at time of gas content determination

Sample location	Gas content values		Formation pressure, lbf/in^2(ga)
	Laboratory measured, cm^3/g	Estimated in situ, ft^3/st	
Completely desorbed core[1].....	0.0	0	0
M1.........	7.6	244	122
M2.........	6.6	211	112
M3.........	10.9	350	247
Well 6.....	15.3	490	417
Well 7.....	13.7	439	423
Well 8.....	15.3	490	429
Well 14....	14.5	465	422
Well 15....	15.9	509	414
Well 25....	15.3	490	410

[1]At 1 atm absolute pressure.

TABLE 3. - Estimated coalbed gas content reduction at monitor holes[1]

	M1	M2	M3
Gas content, cm^3/g:			
Initial 1977 estimate..	14.5	14.9	15.3
Measured in 1981.......	7.6	6.6	10.9
Reduction (10/77-10/81)	6.9	8.3	4.4
Gas content reduction pct..	48	56	29

[1]Gas production from 10/77 through 10/81.

The gas content reductions observed could be caused by uncertainty in the gas content measurements. There are two potential sources of uncertainty. The first is in the direct method itself, and the second is possible variation in the actual gas content of the coalbed from point to point. To date no estimates have been published of the degree of error to be expected in a direct method measurement, so an estimate of the direct method uncertainty has not been attempted here. However, the 1977 and 1981 direct method measurements were made in the same manner and should have the same degree of uncertainty. Also, since the two sets of samples were taken from the same area of the same coalbed, the variations to be expected in gas content measurements due to actual variations in gas content should be similar. It is then anticipated that if a measure of the uncertainty of the direct method measurements could be found for either set of samples, it could be applied to both the 1981 and the 1977 gas contents. Fortunately, the 1977 gas content values represent the coalbed at one condition, that is, before any degasification had taken place. This sample of six gas content values may then be used to obtain a statistical estimate of the variation of the Oak Grove gas content measurements. The mean gas content in the six holes is 15.0 cm^3/g with a standard deviation of 0.777 cm^3/g, indicating that the true original gas content of the coalbed at Oak Grove has a 95-pct probability of being between 16.6 and 13.4 cm^3/g (within two standard deviations of 15.0 cm^3/g). If the same standard deviation is applied to hole M3, then the gas content at that location in 1981 has a 95-pct probability of being between 12.5 and 9.3 cm^3/g. This analysis shows that there is a 95-pct probability that the gas content recorded in hole M3 represents a reduction in the gas content of the coalbed at that location of between 7 and 44 pct. Similar analyses can be made for holes M1 and M2.

It has been assumed here that the adsorbed gas content values above represent the total gas content of the coalbed. However, this need not be the case. It is possible for gas to exist as free gas in the fracture system of the coalbed. Most of this gas would be lost during any coring operation and would not be measured, giving an erroneously low coalbed gas content figure. This problem exists both for the initial measurements and for those made in the monitor holes. However, it is potentially more serious in the case of the monitor holes, since it is possible that a larger fraction of the desorbed gas could be held in the fracture system, replacing the water originally present in the formation.

To obtain an estimate of the error in the gas content measurement that could be caused by replacement of formation water by gas, assume that all of the water in the fracture porosity of a particular volume of coal is displaced by gas in the course of water and gas production. Also assume a fracture porosity of 5 pct (a value chosen to be as high as or higher than common estimates of coal fracture porosities) and a coalbed bulk density of 1.32 g/cm^3, a figure obtained from density logs run in the monitor holes. In table 4, the maximum fracture system gas storage has been calculated for the vicinities of holes M1, M2, and M3. The calculations indicate that the total error from this cause would be no higher than 8 to 11 pct. The error is sensitive to changes in the formation pressure and total current gas content, since the higher the pressure or the lower the gas content, the larger the proportion of the total gas content that could potentially be held in the fracture system. The calculations in table 4 assume a reasonable, but fairly high, porosity and probably an unreasonably high change in water saturation (from 100 to 0 pct). Taking these factors into account, it is reasonable to state that fracture system gas storage will not cause serious errors in gas content estimates.

The gas content information from the pattern wells and the monitor holes was used to calculate the quantity of gas removed from the pattern through November 1981. This calculated value was then compared to the actual gas production figures. Because the available data are so limited, a set of rather rough assumptions have been made:

1. The original in-place gas content was 15 cm^3/g (480 ft^3/st).

2. The average gas content within the area of the pattern (fig. 6) in November 1981 was 7.1 cm^3/g (227 ft^3/ton), based

TABLE 4. - Error in direct method gas content measurement caused by change in fracture system gas saturation[1]

	M1	M2	M3
Adsorbed gas content:			
Mass basis....................cm^3/g..	7.6	6.6	10.9
Volume basis[2,3].....................	5.8	5.0	8.3
Formation pressure.......lbf/in^2(ga)..	122	112	247
Gas volume in fractures[2,4].............	0.46	0.43	0.88
Gas in fractures:			
As pct of original in-place gas[5].....	4	4	8
As pct of current in-place gas.......	8	9	11

[1]Based upon a change in system gas saturation from 0 to 100 pct.
[2]Volume of gas (STP) per volume of coal.
[3]Based upon a coal density of 1.32 g/cm^3.
[4]Assuming a 5-pct coal fracture system porosity.
[5]Based upon an original adsorbed gas content of 15 cm^3/g, or 11.36 volumes of gas (STP) per volume of coal.

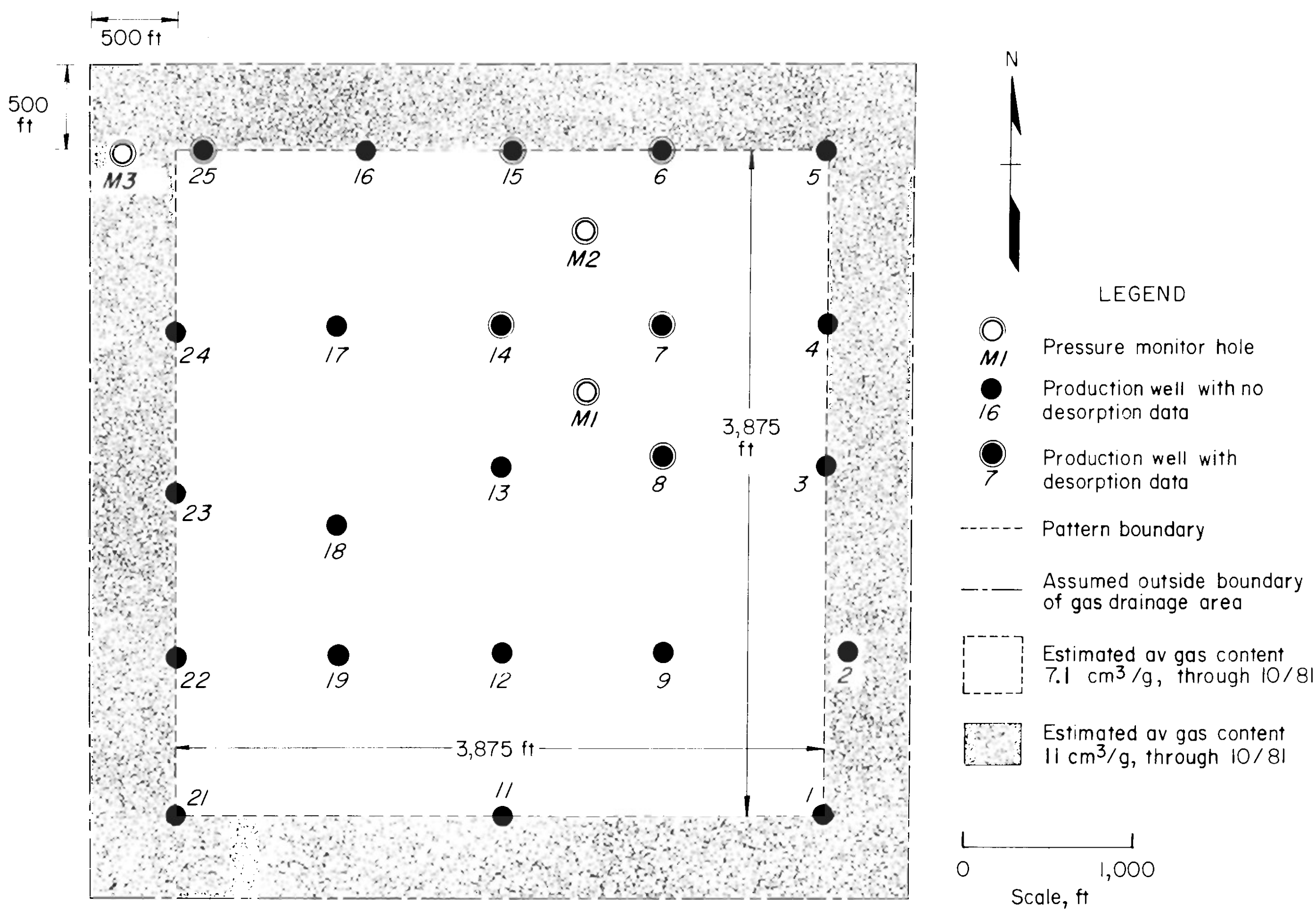

FIGURE 6. - Pattern area and estimated area of gas drainage.

upon the average of the gas content values at holes M1 and M2.

3. The average gas content in a block of coal from the outside edge of the pattern to 500 ft away from the pattern was 11 cm^3/g (352 ft^3/st), based upon the gas content at hole M3.

4. No desorption of gas took place outside the two previously mentioned blocks of coal (fig. 6).

5. The coal density is 1.32 g/cm^3.

6. The average coal thickness is 66 in.

Based upon these assumptions, the calculated reduction in gas content was 980 $MMstdft^3$, of which 860 $MMstdft^3$ came from within the pattern and 120 $MMstdft^3$ came from the area outside of the pattern. The actual gas production through October 1981 was 1,110 $MMstdft^3$. The calculated gas production is about 12 pct lower than the actual gas production.

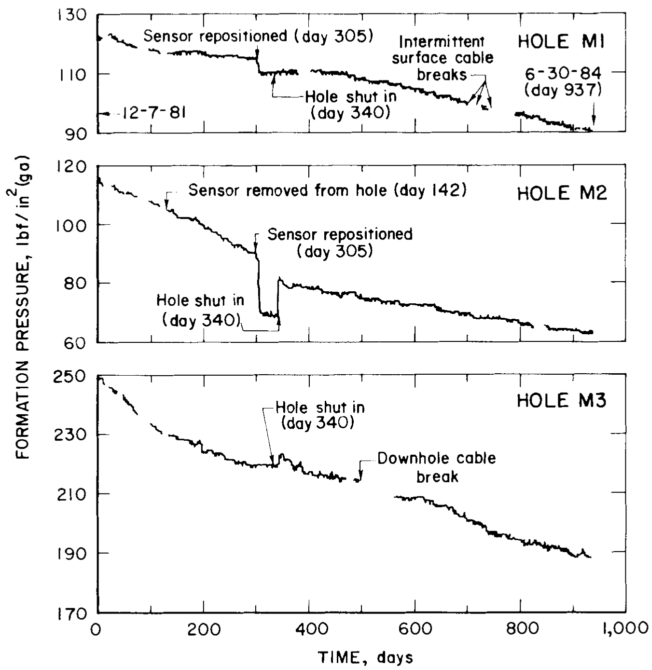

FIGURE 7. - Pressure decline curves for monitor holes M1, M2, and M3.

PRESSURE DATA

The pressure decline curves for holes M1-M3 have been plotted in figure 7 for the period December 7, 1981, through June 30, 1984 (a total of 937 days). These pressures have been corrected for the distance from the center of the coalbed to the pressure sensors. This portion of the hole is water filled, so the correction is just the pressure of the water column. The initial stabilized pressures recorded in holes M1, M2, and M3 were 122, 112, and 247 lbf/in^2(ga) respectively. The initial pressure declines were about 4.5 to 7.5 lbf/in^2 per month in hole M3 and 2.1 to 2.9 lbf/in^2 per month in holes M1 and M2. By late 1982, the rates had been reduced to about 1 lbf/in^2 per month in holes M1 and M2, and to 2 lbf/in^2 per month in hole M3. The probable reason for this is that gas and water production from the pattern, which had been deliberately curtailed in mid-1981, were abruptly increased in late 1981 to begin gas sales. Gas production sharply increased in November 1981 and peaked in May 1982. Monthly water production, which hit a 3-year low of 119,000 gal in October 1981, increased to 345,000 gal in November 1981 and peaked at 346,000 gal in December 1981. These large production changes caused a large transient change in formation pressure.

Although it was not possible to install pressure-monitoring equipment soon enough to see the beginning of this transient, it appears that the rate of change in formation pressure was affected well into 1982 by the large production changes. It can be assumed that the rates of pressure decline observed in the monitor holes in 1983 probably more closely represent the normal pressure decline at the Oak Grove site for stable gas and water production rates.

Two problems discovered in late 1982 make use of the pressure data difficult. The first is that the sensors in holes M1 and M2 (but not hole M3) were originally set directly upon the tops of the packers, causing a metal-to-metal contact which may have sealed off the tubing from the coalbed and prevented the transmission of pressure changes to the sensors. These seals were not complete since some pressure changes were observed, but a partial seal may have been sufficient to cause small errors or a lag in the pressure readings. The magnitudes of these errors are not known for certain, and the errors may not have remained constantly at the same magnitude. For example, the sensor in hole M2 was removed on April-27, 1982 (day 142) and reinstalled on May 1 (day 146) with no pressure change, but when the sensor was permanently raised on October 7 (day 305) to ensure that the tubing was not sealed, the pressure dropped by 16 lbf/in^2. The pressure drop in hole M1 on October 7 was only 4 lbf/in^2.

The second problem was a small (essentially unmeasurable) gas flow which caused reductions in the measured formation pressures. This was corrected on November 12, 1982 (day 341) by shutting in and packing off the holes to prevent further gas flow. No pressure change was observed in hole M1, but the pressure in hole M2 increased by 13 lbf/in^2 and a 3 lbf/in^2 increase was seen in hole M3.

Although it is impossible to determine the exact magnitude of these errors in the pressure measurements, it appears that the total error from both causes was small in holes M1 and M3; it was at most less than 5 lbf/in^2 and may have averaged less since the two causes had opposite effects, which to some extent tended to cancel out. Also, because the pressures measured in December 1981 were determined from a water column which was falling rapidly to equalize the wellbore and formation pressures, there was probably no gas flow and no sealing off of the tubing at the time, so the early pressure readings are probably accurate. None of the pressure data since November 1982 have been affected by these problems.

The most difficult data to interpret are those from hole M2 during the period October 7 to November 11, 1982 (days 305 to 340). After the sensor was raised, the pressure dropped drastically (by 16 lbf/in^2). The pressures were maintained in this range until the hole was shut in. When the hole was shut in, the pressure immediately increased, apparently back to its initial range of October. It is tempting to assume that the pressures during that period are anomalous and that both the earlier (before October 7) and later (after November 11) pressures are correct. However, it is more likely that the pressures recorded in holes M1 and M2 from May through October 1982 were in error due to two opposite effects. The raising of the sensors in October eliminated the source of an artifically high pressure reading, and the subsequent shut in of the wells eliminated a source of reduction of the recorded pressures. This means that most of the data from hole M2 from May to November 12, 1982, are in error by some unknown amount, and that similar, but fortunately smaller, errors are present in the data from holes M1 and M3 during the same period. Analysis of trends in the pressure decline before November 1982 is probably risky, although the trend of high initial pressure changes, with a gradual reduction of the rate of change, appears to be real.

ISOTHERM CURVE

An additional use can be made of the gas content and pressure data of table 2. Plotting the pressures versus the gas content values creates a graph which is the equivalent of an isotherm curve. This has been done in figure 8. In this case, the curve is based upon 10 data points: 1 each for the 3 monitor holes; 6 closely spaced points representing initial or virgin coalbed conditions, obtained from production well data; and a 0 gas content point at 1 atm, or 0 gauge pressure. A power curve regression was run to obtain the relationship shown in figure 8 between gas content and pressure. The curve thus obtained averages the properties of a large volume of coal, essentially representing the northern portion of the Oak Grove pattern, and because it is from in situ data, it in effect averages over such factors as coalbed moisture and differences in rank and volatile matter which can affect the ability of the coal to adsorb gas.

The following assumptions have been made in developing this pseudo-isotherm curve. First, it has been assumed that the initial formation pressures and adsorbed gas contents obtained from the

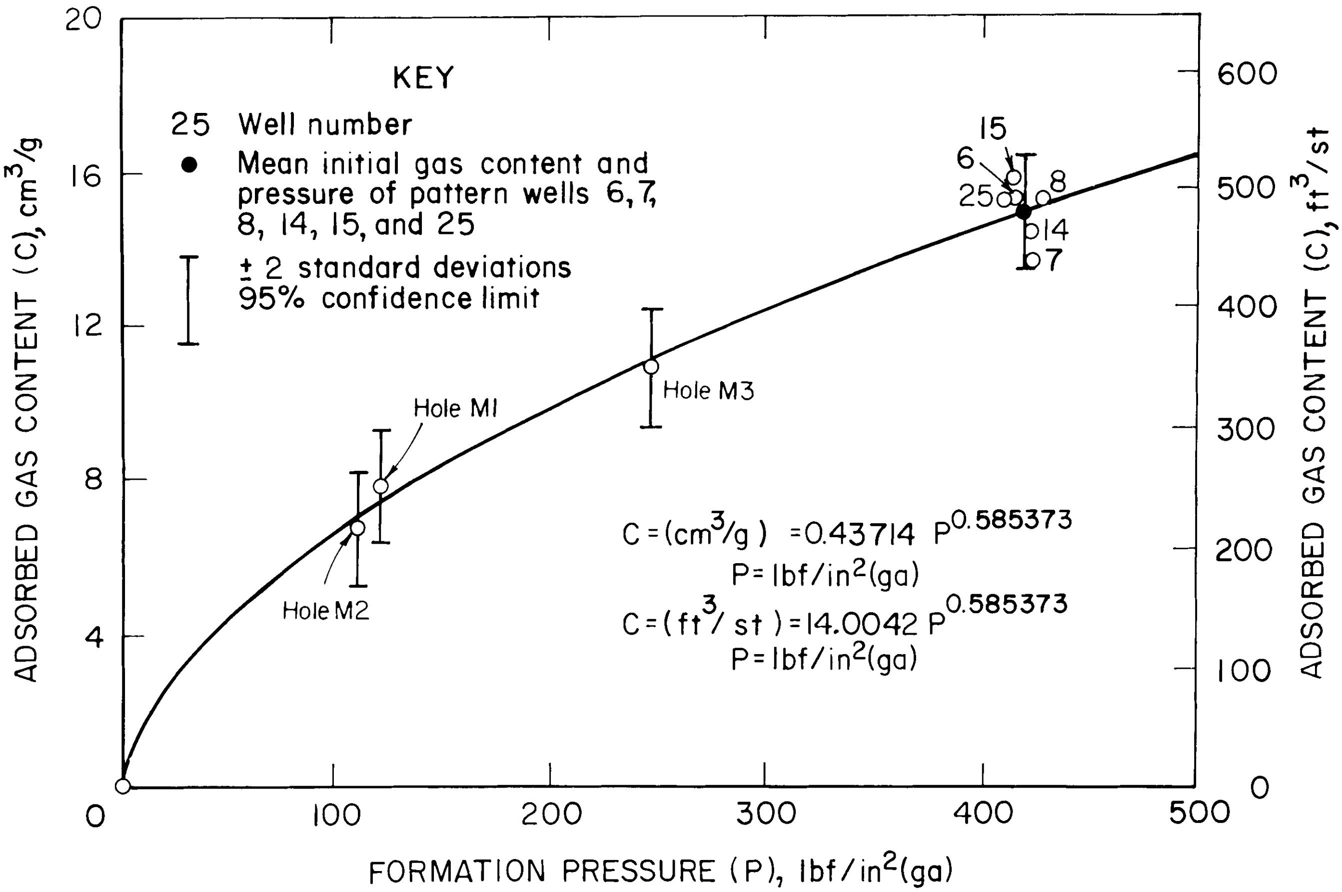

FIGURE 8. - Isotherm curve derived from field gas content and pressure data.

production wells are in equilibrium as specified by the isotherm for the coalbed. It is possible that in the coalbed the initial fluid pressures measured are higher than required to adsorb the gas actually present. If this is the case, then the curve gives a pessimistic estimate of the ability of the coalbed to adsorb gas at high pressure. The curve need not necessarily be inaccurate for the low-pressure range, however. It has also been assumed that the gas content and pressure readings are currently in equilibrium. However, for free gas to be present and for gas to flow, the system must be slightly out of equilibrium. The effect should be small and should not significantly affect gas content measurements made from pressure data (table 4).

Second, it has been assumed that the pressures in the monitor holes in early December 1981 were the same as those present in the holes in mid-November 1981 when the holes were cored. The rates of change of pressures in December were sufficiently low, about 2 to 5 lbf/in^2 per month, that the errors here are small.

Finally, the variability in measurements using the direct method and in the gas content of the coalbed must be considered. The 1977 gas content data from the production wells have been used to give an estimate of the 95-pct (two-standard-deviation) confidence limit of direct method gas content measurements made in the Oak Grove area. This value is the gas content value ± 1.55 cm^3/g. This confidence interval applies only to direct method measurements made from the Lower Bench of the Mary Lee Coalbed in the Oak Grove area, since it includes local variations in the gas content of the coalbed whose magnitudes are unknown and cannot be independently estimated from the available information. Additional data points would help reduce the size of this confidence interval, as would improvements in the accuracy of the direct method. Some methods that have been suggested by other researchers for improving the direct method are described in reference 11. The use of additional data points is, of course, expensive since it is necessary to drill or core a hole and make a formation pressure determination to obtain each point, a process which can cost $30,000 per point.

The material balance computation made earlier in this report in which the total desorbed gas volume through October 1981 was estimated to be 980 MMstdft^3, compared to an actual 1,110 MMstdft^3, indicates that the isotherm curve of figure 8 is reasonably accurate (within 12 pct), despite the limited data from which it is derived.

The pseudo-isotherm curve was used to estimate the rate of gas desorption in April 1983 from within the area of drainage shown in figure 6; this includes the shaded area within 500 ft of the outside of the pattern boundary and the pattern area. At that time the rate of pressure decline was about 1 lbf/in^2 per month within the pattern (1.2 lbf/in^2 per month in hole M1 and 0.9 lbf/in^2 per month in hole M2) and 1.8 lbf/in^2 per month in hole M3. The pressures in holes M1 and M2 were 108 and 76 lbf/in^2(ga), respectively, and the pressure in hole M3 was 214 lbf/in^2(ga). The average pressure inside the pattern was assumed to be 92 lbf/in^2(ga), the mean of the pressures in holes M1 and M2. The average pressure used for the shaded area of figure 6 was the mean of the pressure in hole M3 and the 92 lbf/in^2(ga) value, or 153 lbf/in^2(ga). The calculated changes in gas contents for the two areas per month were 1.3 and 2.0 ft^3/st. The pattern area has been assumed to contain 3.4 × 10^6 st of coal and the shaded area 2.0 × 10^6 st of coal. Using these figures, the 3,875- by 3,875-ft pattern area should have produced 4.4 MMstdft^3 of gas, and the shaded area within 500 ft of the pattern boundary should have produced 4.0 MMstdft^3, or a total of 8.4 MMstdft^3. The actual gas production from the pattern wells in April 1983 was 32.8 MMstdft^3. This large disparity indicates that, at the present time, most of the gas being produced by the Oak Grove pattern is migrating to the wells from far outside the pattern boundaries, although it appears that before 1981 most of the gas produced had come from within the pattern.

CONCLUSIONS

The core data from the Oak Grove pattern show that the initial 4 years of degasification (1978-81) caused a reduction of approximately 50 pct in the adsorbed gas content of the coalbed within the pattern area and a reduction of approximately 25 to 30 pct at a distance of 500 ft from the outside boundary of the pattern.

Simple calculations using core and pressure data indicate that, through 1981, most of the gas produced from the pattern, perhaps 70 to 90 pct, had come from within the area of the pattern itself. However, calculations using a derived isothermlike curve indicate that since 1981 most of the gas produced is migrating from areas outside the pattern.

The project data demonstrate that the adsorbed gas content of the coalbed has decreased as the formation pressure decreased. An isothermlike curve was developed from desorption data to allow computation of the adsorbed gas content given the formation pressure. This curve, although developed from limited data, appears to agree with the observed gas production data.

Difficulties experienced in measuring formation pressures in the monitor holes indicate that, once desorption has begun to take place and free gas becomes present in the coalbed, water level measurements alone cannot be relied upon to give accurate formation pressure readings in coalbeds. It is necessary to shut in monitor holes to prevent the flow of free gas from reducing apparent pressure readings below the true values. The data from Oak Grove suggest that, as one might expect, as the absolute pressure in the formation declines and the proportion of free gas in the fracture system increases, the effect becomes more significant.

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