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Site-Specific and Regional Geologic Considerations for Coalbed Gas Drainage

By W. P. Diamond

UNITED STATES DEPARTMENT OF THE INTERIOR

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SITE-SPECIFIC AND REGIONAL GEOLOGIC CONSIDERATIONS FOR COALBED GAS DRAINAGE

By W. P. Diamond[1]

ABSTRACT

The Bureau of Mines has been involved in the drilling of vertical, horizontal, and directional coalbed gas drainage boreholes for mine safety since 1964. In that time, boreholes have been drilled in most of the major coal regions of the United States under a wide variety of geologic conditions. Many of the geologic conditions that occur in the coal measures are detrimental to gas drainage; others may be beneficial. Analytical techniques to determine the gas content of coal samples and evaluate regional trends of gas distribution have been developed. Drilling techniques that maximize the acquisition of coalbed gas data and geologic information have been determined.

Although some of the geologic factors influencing the placement and potential success of coalbed gas drainage boreholes have been reported in papers on individual projects, a complete, systematic compilation has not previously been available. The objective of this paper is to provide information on specific geologic factors that should be considered prior to, during, and after the drilling of coalbed gas drainage boreholes. Many of the commonsense considerations that have been learned through many years of Bureau of Mines experience, but have generally not been reported formally, are included for those who may be considering coalbed gas drainage drilling for the first time, or who have not had the opportunity to encounter a substantial number of geologic situations.

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INTRODUCTION

The Bureau of Mines has been investigating the occurrence of gas in coal and techniques to remove the gas in advance of mining since 1964 (28).[2] The goal of the Bureau's research program has primarily been to increase mine safety by reducing the explosion hazard of methane-air mixtures. Many of the coalbed gas observations and techniques developed have applications both for mine safety and for energy resource delineation and utilization. The evaluation procedures and geologic considerations for drilling sites discussed in this paper are relevant to both mine safety and gas utilization programs.

It is estimated that coalbeds in the United States contain as much as 21.7 trillion m^3 (766 trillion ft^3) of in-place gas (table 1). The gas is distributed in varying unit volumes throughout the extensive coal reserves of the United States (fig. 1). Gas contents ranging from essentially 0.0 cm^3/g (0.0 ft^3/ton) to 21.6 cm^3/g (691 ft^3/ton) have been measured. Table 2 is a list of the highest measured gas contents of U.S. coalbeds. A list of 583 gas content tests on 125 coalbeds in 15 States can be found in Bureau of Mines RI 8515 (8).

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

TABLE 1. - Estimates of total in-place methane volumes for U.S. coalbeds

Source	Trillion m^3	Trillion ft^3
Bureau of Mines (6)..	21.7	766
National Energy Plan II (33)........	1.4-19.8	50-700
National Petroleum Council (24)........	11.2	398

TABLE 2. - Highest measured gas contents of U.S. coalbeds

Coalbed or formation	County and State	Depth		Gas content		Coal rank
		m	ft	cm^3/g	ft^3/ton	
Peach Mountain......	Schuylkill, PA..	209	685	21.6	691	Anthracite.
Pocahontas No. 3....	Buchanan, VA....	568	1,864	21.5	688	Low-volatile bituminous.
Tunnel..............	Schuylkill, PA..	185	608	18.3	586	Anthracite.
New Castle..........	Tuscaloosa, AL..	650	2,132	17.5	560	
Mary Lee............	.....do.........	666	2,185	17.4	557	Low-volatile. bituminous.
Hartshorne..........	Le Flore, OK....	439	1,439	17.1	547	Medium-volatile bituminous.
Mesaverde Fm........	Sublette, WY....	1,065	3,495	17.0	544	High-volatile A bituminous.
Beckley.............	Raleigh, WV.....	253	830	15.3	490	Medium-volatile bituminous.
Vermejo Fm..........	Las Animas, CO..	547	1,793	15.3	490	Do.
Pratt...............	Tuscaloosa, AL..	416	1,365	15.1	483	

An indirect measure of the possible safety hazard of methane in coal mines, as well as the resource potential of coalbed methane, is the volume of methane vented from U.S. coal mines. As of the last survey by the Bureau of Mines in 1975 (15), over 5.7 million m^3 (200 million ft^3) of methane per day was being vented. The seven States with the highest methane emissions are listed in table 3. Sixty individual mines vented 0.03 million m^3 (1 million ft^3) or more per day.

TABLE 3. - States with highest measured gas emissions from coal mines (1975)

State	Gas Emissions	
	Million m^3/d	Million ft^3/d
West Virginia..........	2.7	96.4
Pennsylvania	1.2	43.1
Virginia...............	.6	22.1
Alabama................	.5	16.6
Illinois...............	.4	14.7
Colorado...............	.3	9.1
Ohio...................	.2	6.1

ACKNOWLEDGMENTS

Appreciation is extended to Arie M. Verrips, Executive Director, American Public Gas Association (APGA), for providing data from the Unconventional Gas Recovery and Utilization drilling program. Carol Tremain and Donna Boreck, geologists, Colorado Geological Survey, are acknowledged for providing geologic correlations for the APGA wells at Trinidad, CO.

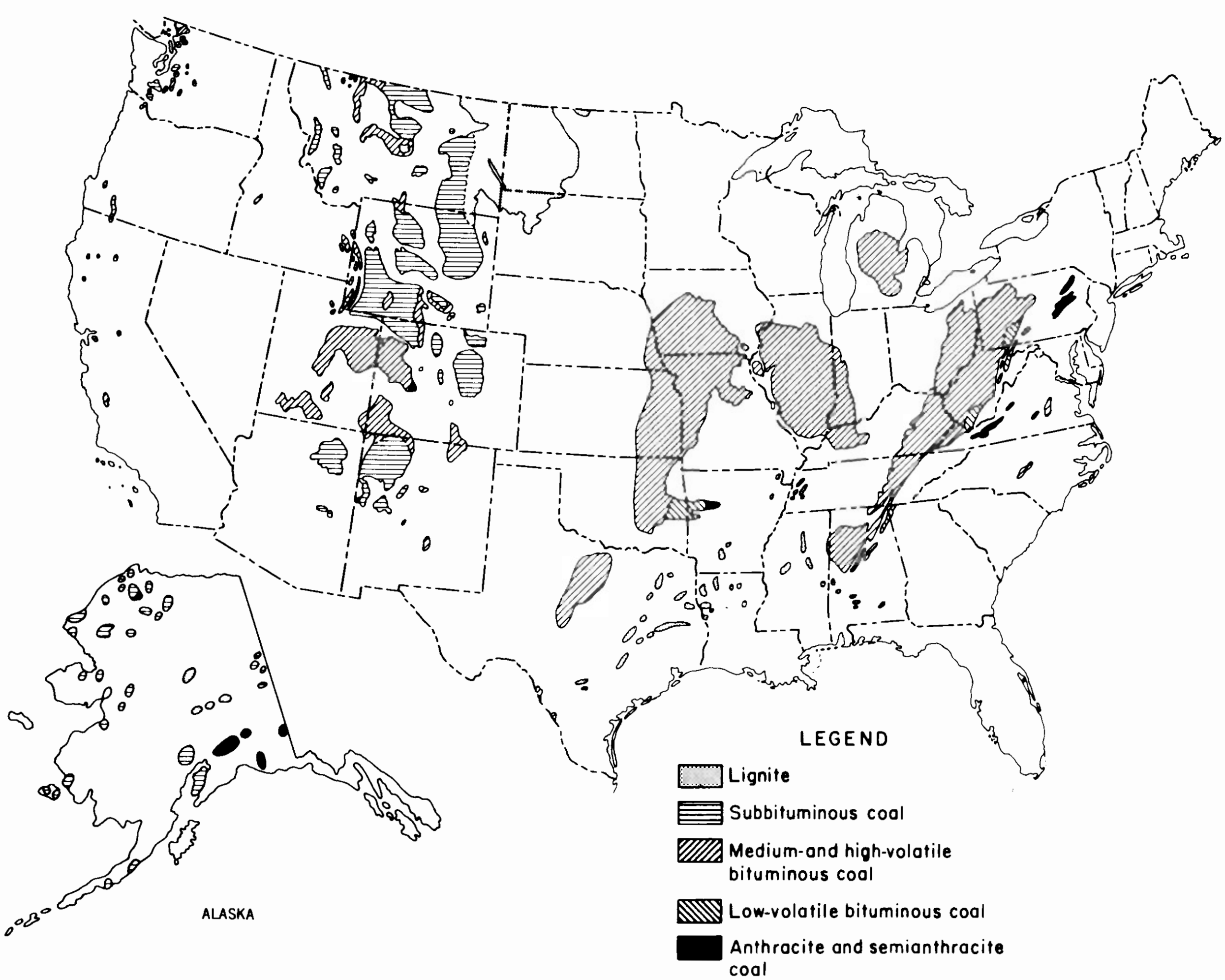

FIGURE 1. - Coalfields of the United States.

THE COALBED AS A GAS RESERVOIR

The fundamental principle to accept when considering coalbeds as gas reservoirs is that they are not the same as as "traditional" gas reservoirs (such as sandstones) and do not behave in accordance with the same reservoir mechanics. In a traditional sandstone reservoir, the gas exists as free gas in the void spaces between sand grains, and transport of that gas through the reservoir is governed by pressure gradients as described by Darcy's law.

In a virgin coalbed reservoir, only a small portion of the methane is found as "free" gas in the fractures (cleat). Most of the methane is adsorbed on the coal surface in the extensive micropore structure of the coal (5). The transport of the methane from the micropores through the "solid" coal is governed by concentration gradients as described by Fick's law of diffusion. Once the methane has reached the coalbed fracture system, the transport of the gas through the cleat to a well bore or mine opening is governed by Darcy's law.

In a virgin coalbed reservoir, the pressure in the fracture system and the concentration of methane in the micropore structure are in equilibrium (5). To induce a flow of methane from the solid coal, the equilibrium must be disrupted by lowering the pressure in the fracture system. Coalbeds are generally saturated with water, which when removed, either by pumping from a vertical borehole or by "natural" drainage into a mine opening or horizontal borehole, disrupts the equilibrium. Methane can then desorb from the coal micropores and is made available for flow through the fracture system. Gas flows will normally continue as long as equilibrium conditions are disrupted but can quickly decline if equilibrium is reestablished. The continued lowering of the coalbed reservoir pressure to ensure gas flow is completely opposite to the situation with a traditional reservoir, where maintaining a high reservoir pressure is required to provide the energy to flow large volumes of gas.

The attractiveness of coalbeds for commercial gas production is illustrated in figure 2, which compares the theoretical gas volumes that can be stored at various pressures in equal rock volumes of both traditional reservoirs of 10-pct porosity and representative coalbeds. Even at the relatively low reservoir pressures commonly found in coalbeds, the unit volume of coal can store several times the gas volume of the 10-pct porosity nonreactive traditional reservoir rock.

An additional factor to be considered for coalbed reservoirs is the influence of "boundaries" on the reservoir and gas flow rates. A boundary, either natural (such as a fault) or created (interference from other boreholes or mine openings), can reduce the time needed to lower the coalbed pressure and induce gas flows (3, 21). The boundaries effectively limit the size of the reservoir, and the pressure is more efficiently reduced in the resulting area, with an accompanying decrease in the time needed

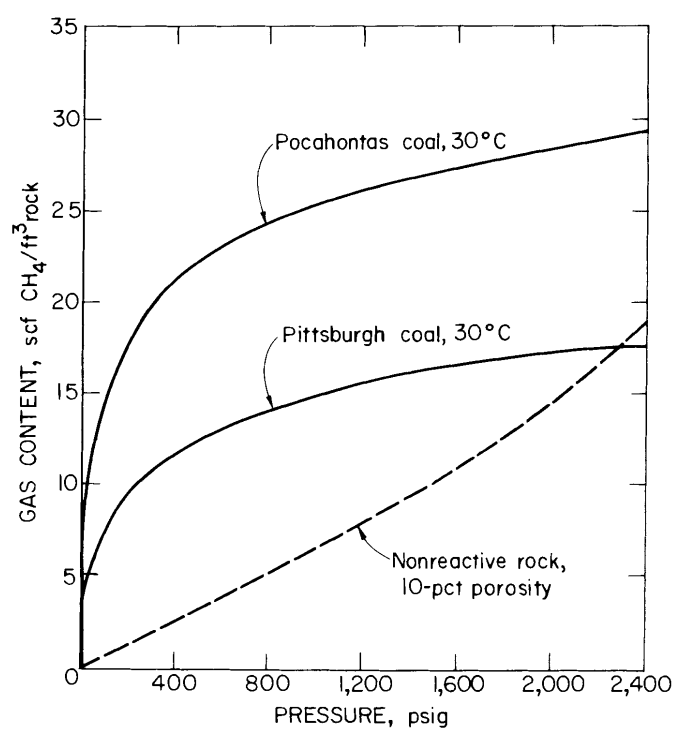

FIGURE 2. - Comparison of the gas storage potential of coal and 10-pct-porosity nonreactive reservoir rock versus reservoir pressure (26).

to achieve gas production. Several publications (3, 5, 20-21) detail the reservoir characteristics of coalbeds and provide mathematical descriptions of the reservoir mechanics.

SITE-SPECIFIC CONSIDERATIONS

Site-specific considerations of the methane potential of coalbeds include both determining the in-place gas content and identifying geologic factors that may affect the flow of gas from the coalbed reservoir to methane drainage systems or underground mines.

Direct Method Determination of the Gas Content of Coal

The Bureau of Mines originally became interested in determining the gas content of virgin coal as an aid in estimating the amount of gas that would be released in active underground mines. The initial research results were used to construct a graph (fig. 3) that related direct method test values to the actual measured methane emissions of nearby mines.

Sampling

Coal samples for determination of gas content are obtained either from continuous wire line core holes or from rotary-drilled boreholes by means of conventional coring of selected zones. Schematic diagrams of wire line and conventional types of coring equipment are shown in figure 4. In general, the continuous wire line technique is preferred for obtaining coal samples for gas content determination. The time required to remove the coal sample from the hole and seal it into a desorption container is important for good test results. (See "Calculation of Gas Content" section.) The retrieval of samples by the wire line coring technique is very fast since the inner barrel containing the coal is brought through the drill pipe to the surface by the wire line without having to pull the entire string of drill pipe from the hole, as with conventional coring equipment. The difference in retrieval time can be several hours at depths greater than 305 m (1,000 ft).

An additional problem that is frequently encountered with the conventional coring of selected zones is missing the coalbed that is to be cored, or coring excessive lengths of section while searching for the coal. In the conventional coring technique, the hole is rotary-drilled (no core taken) to a point (depth) estimated to be near the top of the coalbed; then the drill pipe is pulled from the hole, the rotary drill bit is taken off, and the core barrel is installed. The core barrel is then run into the hole on the end of the drill

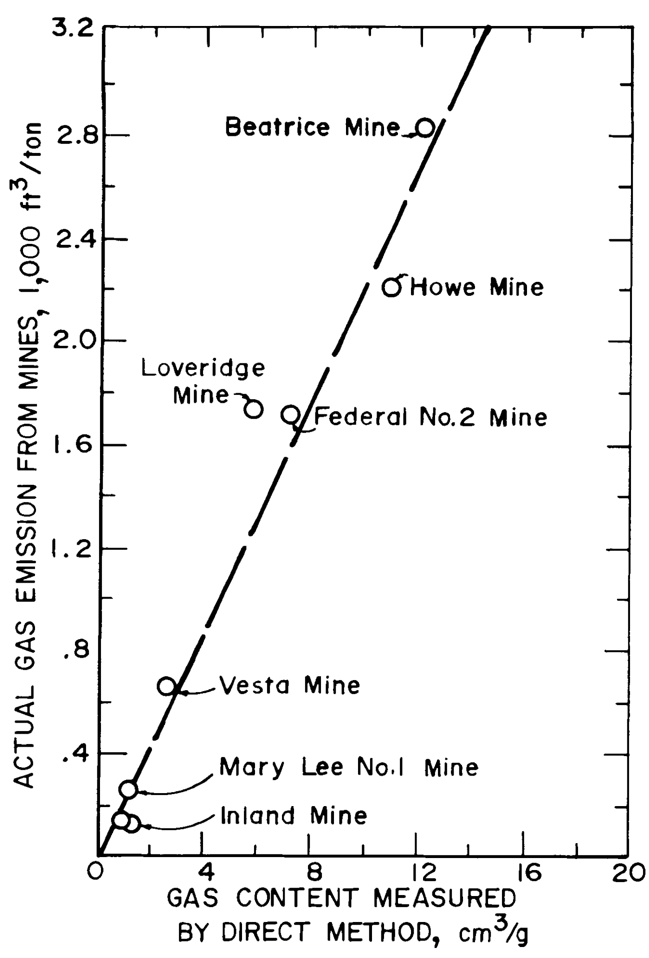

FIGURE 3. - Gas content of coal versus actual mine emissions.

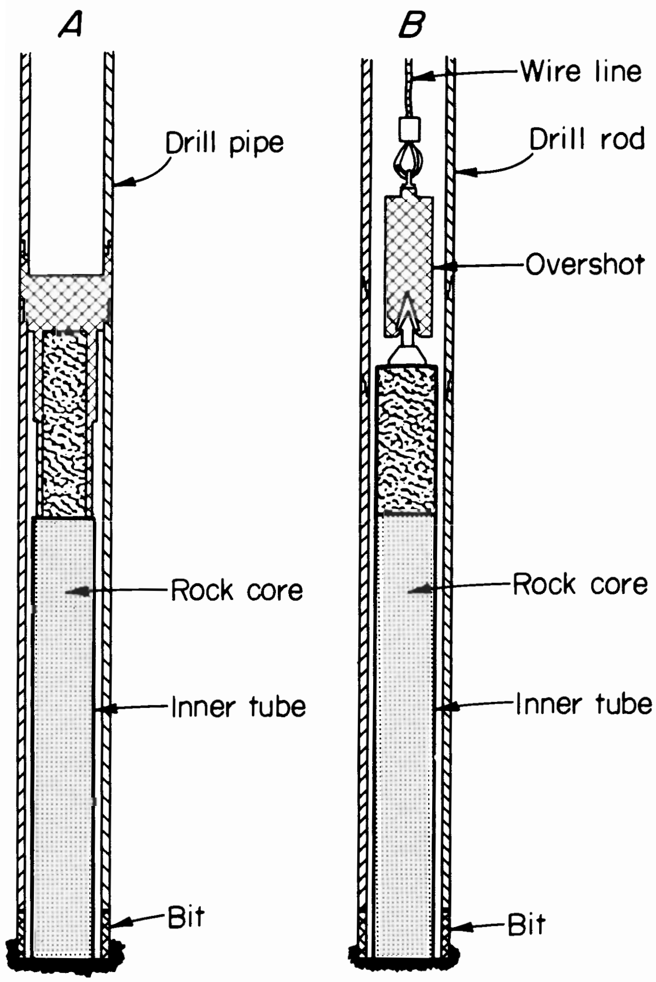

FIGURE 4. - *A*, Conventional, and *B*, wire line coring equipment.

pipe, and hopefully the position of the coalbed has been estimated with sufficient accuracy to have the entire coalbed in a single run of the barrel, which is typically 3.05 to 6.10 m (10 to 20 ft) in length.

Figure 5 illustrates several of the problems that can be encountered in attempting to predict (correlate) where coalbeds should be encountered if sufficient geologic data are not available or if the geologic section is variable. Commonly a nearby data source, such as a previously drilled well or regional geologic trends, is used to determine the core points where the conventional core barrel will be installed to obtain samples. Usually core points are projected using marker beds and interval thicknesses. In the example in figure 5, a marker bed from a nearby, previously drilled hole (well A) has been identified while rotary drilling well B. The interval between the bottom of the marker bed in well A and the top of coalbed A is known and is used to project a core point (I) in the new hole, well B. Unfortunately, the interval has thinned towards well B, putting coalbed A above the projected core point. If the driller were given only the depth below the marker bed as guidance for the core point, it is quite likely that the coalbed would be drilled through and no core obtained.

Once it has been found that the interval between the marker bed and coalbed A has thinned in well B, a decision must be made on the core point to obtain coalbed B. Several options are available:

1. Assume that the position of coalbed B has no relationship to the coalbeds in well A, and conventional-core the entire interval below coalbed A until coalbed B is obtained, which could be very time consuming and expensive.

2. Assume that the intervals between coalbed A and coalbed B are the same in wells A and B, which would put the core point (II) in the correct position to obtain a sample.

3. Assume that the intervals between the marker bed and coalbed B are the same in wells A and B, which would put the core point (III) below the actual position of coalbed B, and the coalbed would probably be missed for coring.

4. Assume that the interval between coalbeds A and B in well B thins by the same amount as the interval between the marker bed and coalbed A in the same well, which would put the core point at a depth slightly below the protected core point (I), requiring unnecessary and expensive coring before encountering coalbed B.

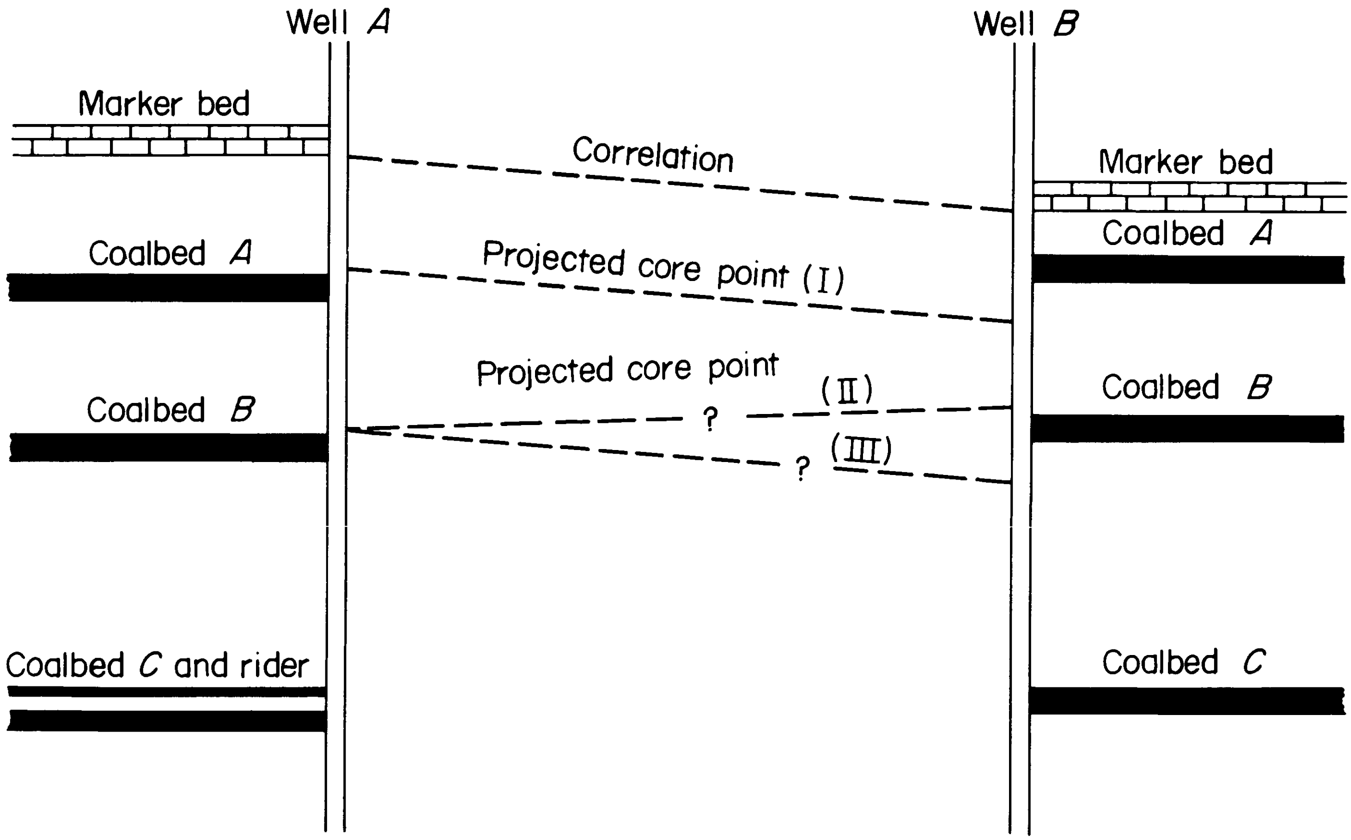

FIGURE 5. - Coalbed correlation problems.

Coalbeds are frequently overlain by thin rider coals which can be used as marker beds for conventional core points. Coalbed C in well A has a rider coal above it; however, the rider is not present in well B. If the driller on well B had been told to stop when the rotary drilled into the first coalbed below coalbed B (supposedly coalbed C rider) and switch to the core barrel to core the main coalbed, part of coalbed C would have been penetrated and the coal lost. Many of the situations described above for picking core points for conventional coring would result in a loss of coal for gas content determinations and/or additional unprogrammed expense for excessive core drilling. The use of continuous wire line coring would eliminate or minimize the described problems.

In unknown geologic areas where wire line coring cannot be used for reasons such as cost or lack of suitable drilling rigs, recovery of all coalbeds using conventional coring can be enhanced by "twinning." A rotary hole is first drilled through the entire section of interest, without taking any cores. The hole is then logged with geophysical equipment to precisely define the depth and thickness of the coalbeds. The drilling rig is then moved over a few meters (feet), and a second ("twin") hole is rotary-drilled. Since the exact location of each coalbed is known from the first hole, the conventional core barrel can be used at core points precisely located above each coal. The variability in distribution of coalbeds over a small geographic area is illustrated with an example from a drilling project near Trinidad, CO (fig. 6), where the wells are approximately 150 m (500 ft) apart.

Multiple testing, or preferably testing of the entire coalbed, is the preferred sampling strategy. Variations in gas content are commonly observed on multiple samples from the same coalbed in a core hole. A single test on a small portion of a coalbed may yield a falsely low or high value for the entire coalbed.

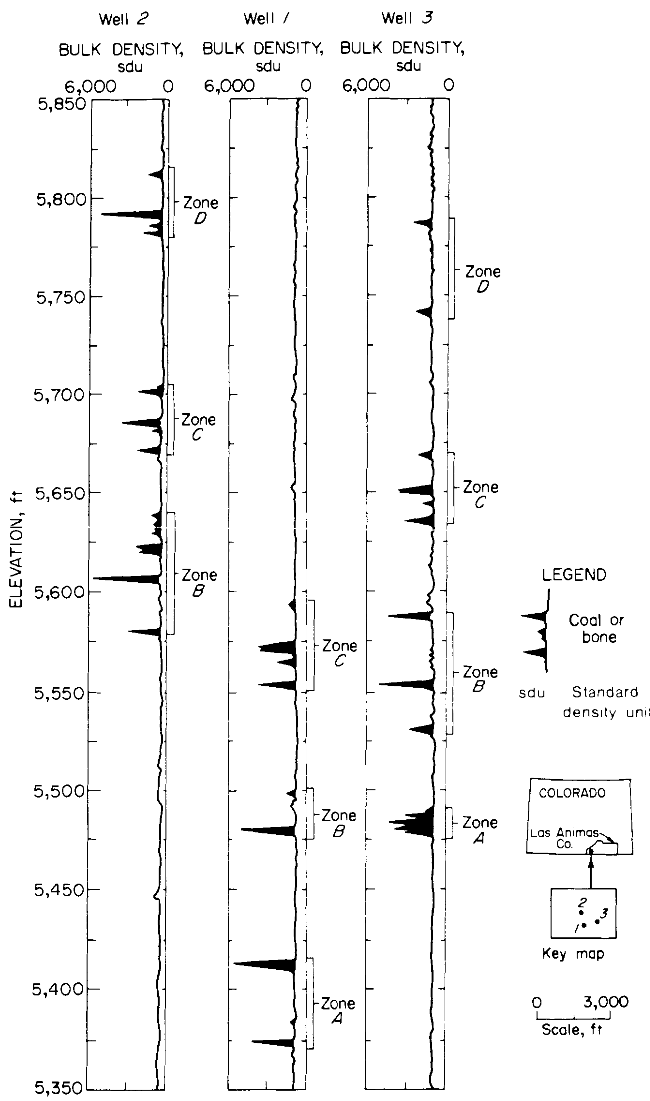

FIGURE 6. - Variable distribution of coalbeds in three wells, Trinidad, CO. *(Correlations courtesy of Colorado Geological Survey.)*

Test Equipment

Sample containers of several shapes and sizes that have been constructed for various testing purposes are shown in figure 7. The standard container (can A) used by the Bureau is made from a 0.3-m (1-ft) piece of aluminum pipe, having an inside diameter of 10 cm (4 in). A top flange and bottom plate have been welded to the pipe section, and a removable lid that attaches to the top flange can be fitted with a gage and various types of valve assemblies. Valves with a quick-connect capability are preferred for convenience and time savings if a large number of samples are tested at the same time.

Less expensive alternatives to the metal canisters are the various plastic water filter housings (cans B, C, and D) available from many plumbing supply outlets. These containers are sometimes awkward to use because of their rounded bottoms (cans C and D), or because of the difficulty of opening and/or sealing the large screw-type caps. Thus, standard metal containers are preferred because of their flat bottoms and durability, especially in long-term collection programs. In general, any container that can be easily sealed airtight, can contain about 2 kg (4.4 lb) of sample, and can hold approximately 414 kPa (50 lb/in^2 g) of internal pressure would be adequate for the test.

It has been suggested that containers of greater length, perhaps even long enough to hold an entire core of an coalbed, should be used for testing. Although it would be preferable to test the entire core, several complications may arise in using large containers. Occasionally, a sample container will leak, invalidating the test. If six individual 0.3-m (1-ft) sections of a 1.8-m (6-ft) coalbed are tested separately, a leak in one can is of little consequence. But if the entire 1.8 m (6 ft) is placed in one can and it leaks, little usable data may be obtained. Furthermore, coal samples that are friable and very gassy will usually give off large volumes of gas early in the desorption procedure. If very large amounts of coal of this type are sealed into a large canister, then bleeding the large volume of gas into the measuring apparatus, which will be described later, can require an excessive amount of time (several minutes). Long measuring times may invalidate the calculation of the lost gas, which requires graphing of gas volumes at instantaneous points in time.

The equipment (fig. 8) needed to measure the actual volume of gas desorbing

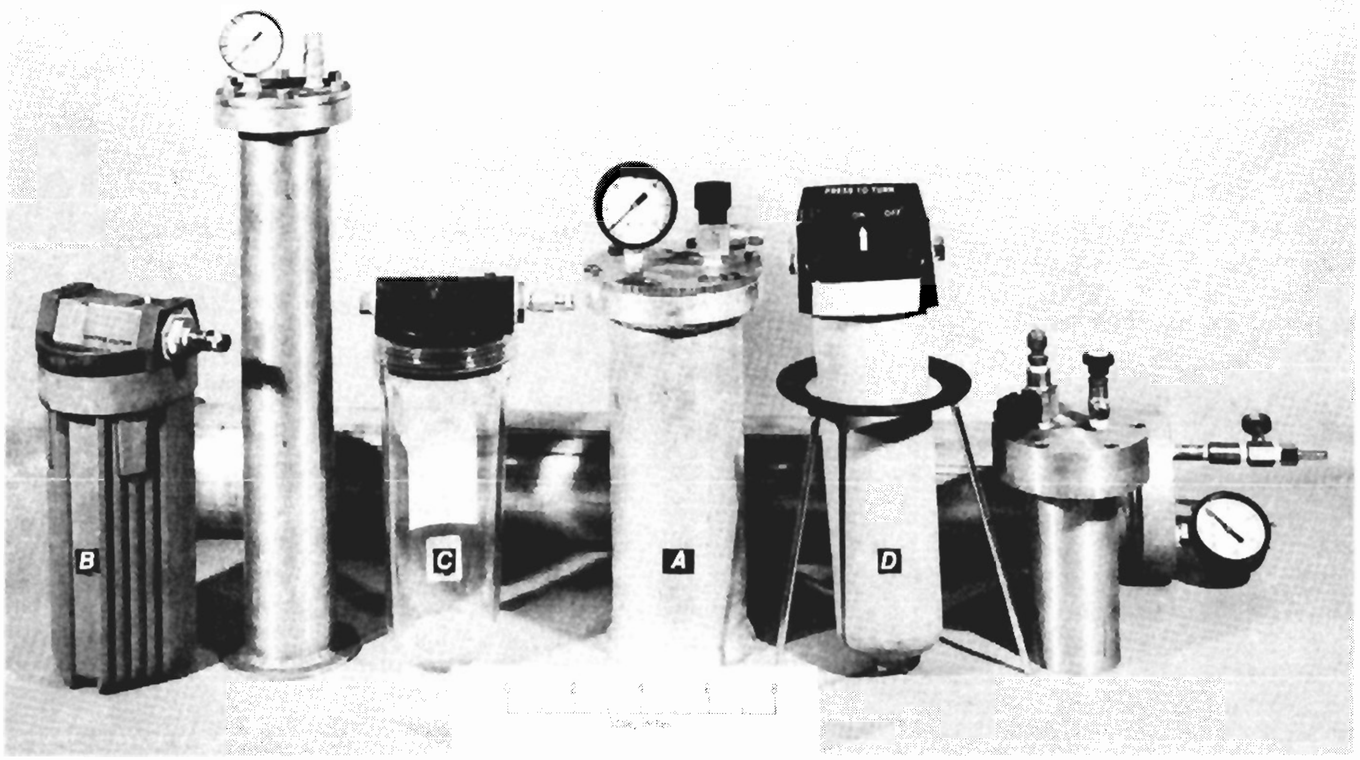

FIGURE 7. - Sample containers used for direct-method testing of coal samples. Can A–standard container; cans B, C, and D–plastic water filter containers.

from the coal sample consists of an inverted graduated cylinder sitting in a pan filled with water and a ring stand

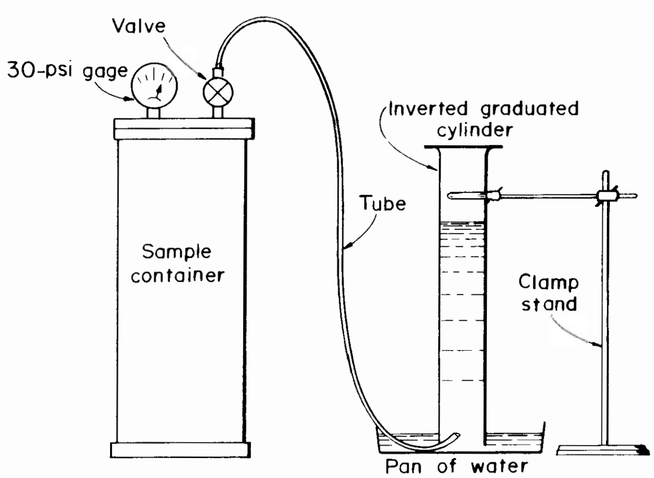

FIGURE 8. - Equipment for direct-method testing of coal sample.

and clamps to hold the graduated cylinder in place. The desorbed gas that collects in the canister is periodically bled into the graduated cylinder and measured as the volume of water displaced. This procedure is performed both at the drill site and subsequently in the laboratory.

Calculation of Gas Content

The gas content of a particular sample is composed of lost, desorbed, and residual gas, each of which is determined by slightly different techniques. A core sample actually begins to desorb gas before it is sealed in the sample container. The amount of this lost gas depends on the drilling medium and the time required to retrieve, measure, and describe the core, and seal the sample in the can. The shorter the time required to collect the sample and seal it into the can, the greater the confidence in the lost-gas calculation. As discussed previously, because of its speed, wire line retrieval of the core is preferable to conventional coring. If air or mist is used in drilling, it is assumed that the coal begins desorbing gas immediately upon penetration by the core barrel. With water, desorption is assumed to begin when the core is halfway out of the hole; that is, when the gas pressure is assumed to exceed that of the hydrostatic head.

The lost gas can be calculated by a graphical method based on the relationship that for the first few hours of emission, the volume of gas given off is proportional to the square root of the desorption time. A plot of the cumulative emission after each reading against the square root of the time that the sample has been desorbing ideally would produce a straight line.

A sample of experimental data (table 4) and supplementary information used to construct a lost-gas graph follows:

Drilling medium--water.

Time coalbed encountered (A)--
12:01 a.m.

Time core started out of hole (B)--
12:30 a.m.

Time core reached surface (C)--
12:40 a.m.

Time core sealed in canister (D)--
12:50 a.m.

Lost gas time:

(D-A) if air or mist is used

$(D-C) + \frac{C-B}{2}$ if water is used

$$(12{:}50-12{:}40) + \frac{(12{:}40-12{:}30)}{2}$$

$$= 10 + \frac{10}{2}$$

$$= 15 \text{ minutes.}$$

The resulting graph is shown in figure 9. The intercept on the X axis is the square root of the elapsed time (lost-gas time) in minutes from the time gas desorption begins and the sample is sealed in the container. The estimated value of the lost gas is the point at which the constructed line intercepts the the negative Y axis.

The desorbed gas is simply the total volume of gas drained from the sample and measured in the graduated cylinder. The desorbing of a sample is generally

TABLE 4. - Data for lost-gas graph

Reading No.	Time, a.m.	Time since placed in can, min	$\sqrt{\text{Time in can+15}}$, $min^{1/2}$	Gas released		Total gas	
				cm^3	10^{-3} ft^3	cm^3	10^{-3} ft^3
1...........	12:50	0	3.87	0	0	0	0
2...........	1:05	15	5.48	92	3.25	92	3.25
3...........	1:20	30	6.71	84	2.97	176	6.22
4...........	1:35	45	7.75	55	1.94	231	8.16
5...........	1:50	60	8.66	36	1.30	267	9.46
6...........	2:05	75	9.49	40	1.41	307	10.87
7...........	2:20	90	10.25	33	1.17	340	12.04

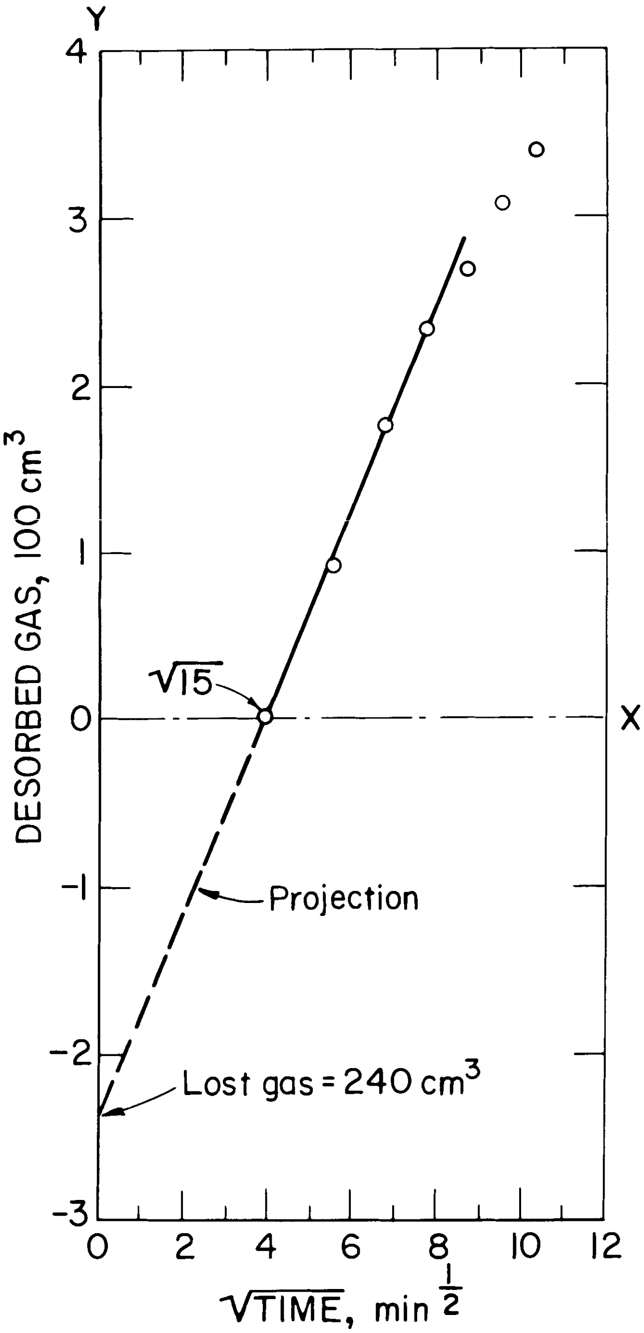

FIGURE 9. - Lost-gas graph.

allowed to continue until a very low emission rate is obtained, generally an average of less than 10 cm^3 (0.35 × 10^{-3} ft^3) of gas per day for 1 week. The time required to reach this low rate of emission will vary considerably and is affected by many things, including the size of the sample, the physical characteristics of the coal, and the amount of gas contained in the sample.

When it is determined to discontinue the measurement of desorbed gas, the coal sample will usually still contain gas. To complete the gas determination procedure, the amount of residual gas must be measured. The procedure recommended by the Bureau is to crush the coal in a sealed ball mill. The ball mill constructed for crushing coal was fabricated from a piece of 0.64-cm (1/4-in) wall, 17.78-cm (7-in) diameter steel pipe. A steel plate was welded to the bottom, and a lid was fitted to the top. At the top, a short section of pipe with 2.54-cm (1-in) wall thickness was welded inside the 17.78-cm (7-in) pipe to provide sufficient surface area for machining a groove for an O-ring seal and for bolt holes to secure the lid.

The ball mill is tumbled on a roller machine for approximately 1 hr to crush the coal. The mill is allowed to cool to room temperature, and the volume of gas released is then measured by the water displacement method. The crushed powder and any uncrushed lumps are weighed separately. The volume of gas released is attributed only to the crushed powder. A set of residual gas data and calculation procedure follows:

Weight of crushed powder--735 g

Weight of uncrushed lumps--45 g

Volume of gas bleed off--1,082 cm^3

$$\text{Residual gas calculation} = \frac{\text{gas bleed off, cm}^3}{\text{weight of sample crushed to powder, g}}$$

$$= \frac{1{,}082\ \text{cm}^3}{735\ \text{g}}$$

$$= 1.5\ \text{cm}^3/\text{g}\ (24.02 \times 10^{-3}\ \text{ft}^3/\text{lb},\ 48\ \text{ft/ton}).$$

Theoretically, it is possible to crush a coal sample in the ball mill at any point after collection and to obtain the total gas content (excluding lost gas) of the sample. This procedure is generally not considered appropriate if maximum information from the sample is desired. By crushing the sample before the desorption process is complete, it is impossible to obtain the relative amounts of desorbed and residual gas. This distinction is important because the actual residual gas, which will not desorb from the sample while sealed in the canister, probably represents gas that will not flow to a methane drainage borehole and possibly represents gas that will not be emitted into a mine atmosphere. It is true that during the process of mining coal, the coal is broken up into variously sized pieces; however, the majority of these pieces will not usually duplicate the very fine powder that the ball mill produces in the residual gas procedure.

The total gas content of a particular sample is the volume of lost gas and desorbed gas divided by the total sample weight plus the residual gas content. The calculation procedure and sample data set follow:

Lost gas--240 cm^3

$$\text{Total gas} = \frac{\text{lost gas + desorbed gas}}{\text{total sample weight}} + \text{residual gas}$$

$$= \frac{240\ cm^3 + 3{,}246\ cm^3}{780\ g} + 1.5\ cm^3/g$$

$$= 4.5 + 1.5$$

$$+ 6.0\ cm^3/g\ (96.10\times10^{-3}\ ft^3/lb,\ 192\ ft^3/ton)$$

Auxiliary Test Procedures

Proximate, ultimate, and Btu analyses are obtained on the crushed powder from the residual gas test. These test results can be used to further evaluate the gas content results on a practical and theoretical basis.

Because the gas content is presented on a volume-to-weight ratio, the presence of noncoal material, primarily shale and pyrite (which adds weight but not gas storage capacity), can produce seemingly erroneous data. Thus two samples from the same coalbed core may have gas contents varying by several cubic centimeters per gram if one sample contains appreciably higher noncoal material. The coal analysis will help determine if noncoal material is influencing the total gas content.

Evaluation of the influence of depth of burial on the gas content is preferably done on a clean coal, thus removing the noncoal material variable from the evaluation. However, because coalbeds do contain noncoal material, the actual in-place methane in a particular volume of coal should be related to the as-received coal data.

Theoretically, the gas content of coal is influenced by the rank of the coal, with higher ranks generally having higher gas contents. The coal analysis can be used to determine the apparent rank of the coal by ASTM Standard D388 (2) for evaluation of the rank parameter. Coal petrography, specifically vitrinite reflectance measurements, can also provide a measurement of coal rank. Determining the microscopic constituents of the coal (macerals) may also be useful in investigations of the factors influencing the methane content of coalbeds. Adsorption isotherm tests (18) will give data on the theoretical storage capacity of a sample, and along with the other analytical tests, can be an important tool for evaluating the direct method test results.

Gas samples should be obtained periodically during the desorption testing of coal samples. Gas compositional analysis will provide information on the gas quality, including the presence of gases other than hydrocarbons. Ethane, propane, and butane are common hydrocarbons found in small amounts (generally less than 2 pct combined) in coalbed gas. Carbon dioxide (occasionally in amounts as high as 15 pct) is a common, potentially undesirable, component of coalbed gas which has been found at the higher levels primarily in a relatively small area of the Pittsburgh Coalbed in Pennsylvania and West Virginia, and in several western coals. Several publications (17, 19, 29) discuss the origin and composition of coalbed gas.

Geologic Considerations

Variations in Gas Content

The gas content of individual coalbeds has been observed to increase as the depth of the coalbed increased (9-10, 13-14, 25, 27, 30). A coalbed contains more gas at greater depths primarily owing to the increase in reservoir pressure, which allows the coal to "hold" more gas, if it is available. Figure 10 illustrates increasing gas content with increasing depth for the Mary Lee Coalbed in Alabama. It is important to note that this graph is only for the Mary Lee Coalbed and should not be used to estimate the gas content of any other coalbed or coal region.

Even though the gas content of a coalbed increases with depth, this does not mean that all deep coalbeds are necessarily gassy. Many coalbeds in the Eastern United States contain appreciable gas (>5 cm^3/g [160 ft^3/ton]) at depths of 305 m (1,000 ft) (8). However, many coalbeds in the western United States at depths of 305 m (1,000 ft) contain little gas (<2 cm^3/g [64 ft^3/ton]). The reason for these variations in gas contents of coalbeds at similar depths are in many cases due to differences in the rank of the coal. Coal rank (table 5) is a measure of the stage of coalification that a coal deposit has reached. The coalification process progressively transforms the original plant material into higher ranks of coal, depending primarily on temperature and time and to a lesser extent on pressure (29). Methane is generated throughout the coalification process in varying amounts, with an increased yield of methane associated with reduction of hydrogen, which begins at approximately 29 pct volatile matter content in the medium-volatile bituminous coal range (29). Owing to the influence of the coalification process, it is therefore possible to have deep coalbeds that have not gone through the stages that produce high volumes of methane and that do not have high gas contents.

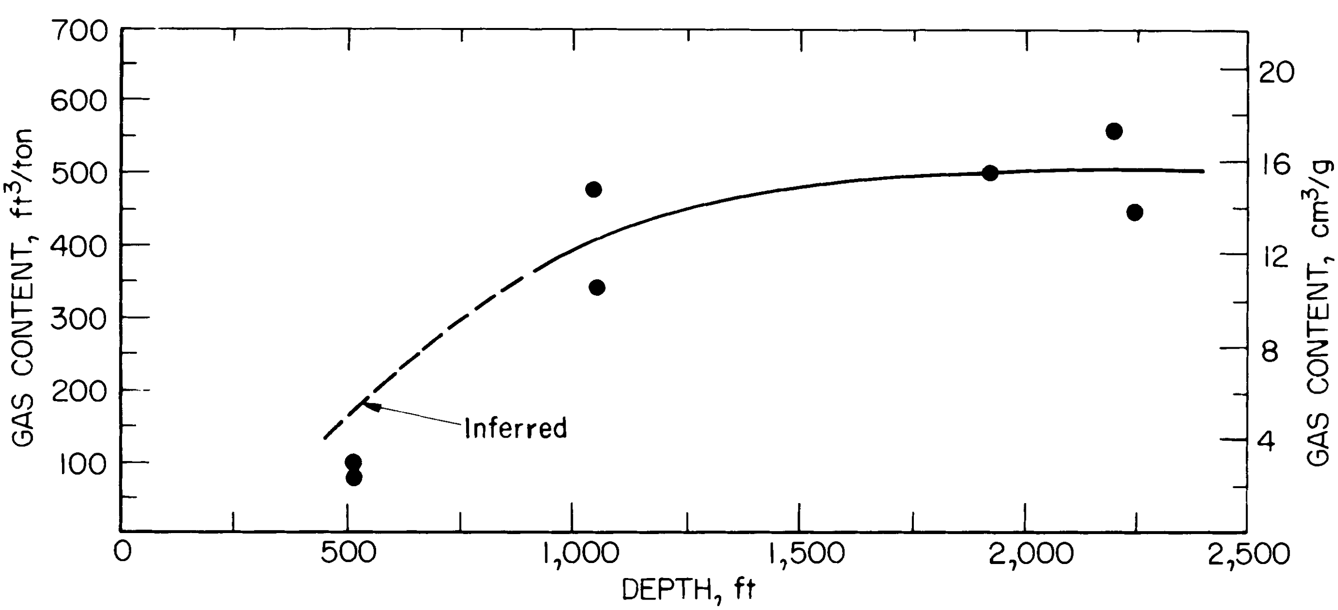

FIGURE 10. - Gas content versus depth for the Mary Lee Coalbed, Alabama.

TABLE 5. - Classification of coal by rank (2)

Group	Fixed carbon limits, pct (dry, mineral-matter-free basis)		Volatile matter limits, pct (dry, mineral-matter-free bases)		Calorific value Btu/lb (moist, mineral-matter-free basis)	
	Equal to or greater than--	Less than--	Greater than--	Equal to or less than--	Equal to or greater than--	Less than--
CLASS I.--ANTHRACITIC						
Meta-anthracite........	98	...	...	2	...	...
Anthracite.............	92	98	2	8	...	...
Semianthracite.........	86	92	8	14	...	...
CLASS II.--BITUMINOUS						
Low-volatile bituminous coal.......	78	86	14	22	...	...
Medium-volatile bituminous coal.......	69	78	22	31	...	...
High-volatile A bituminous coal.......	...	69	31	...	14,000	...
High-volatile B bituminous coal.......	...	...	...	...	13,000	14,000
High-volatile C bituminous coal.......	...	...	...	...	11,500	13,000
CLASS III.--SUBBITUMINOUS						
Subbituminous A coal................	...	...	...	...	10,500	11,500
Subbituminous B coal................	...	...	...	...	9,500	10,500
Subbituminous C coal................	...	...	...	...	8,300	9,500
CLASS IV.--LIGNITIC						
Lignite A..............	...	...	...	...	6,300	8,300
Lignite B..............	...	...	...	...	...	6,300

The graph (fig. 10) that is a plot of direct method gas contents versus depth of samples from the Mary Lee Coal Group is also influenced by rank variations of the coalbeds. Figure 11 shows the distribution of coal rank and depth in the basin. In general, the rank increases with depth; however, this relationship is variable and does not precisely correlate throughout the area. Because of the high numbers of samples that would be needed for direct method testing to document the change in gas content with rank in a coal basin and the relative ease of mapping the changes in depth and obtaining samples from a variety of depths for gas content determinations, the relationship of gas content to depth for coalbeds is most commonly presented. The Bureau of Mines is currently conducting research to document and relate the influence of coal rank as well as depth on gas content.

Coalbed Discontinuities

There are many geologic features that disrupt the continuity of a coalbed. They can be stratigraphic in origin and characterized by an interruption in sedimentation, either nondeposition or erosion, such as a sand channel; or they can be structural in origin and characterized by a surface separating two unrelated groups of rock, such as a fault (1). Discontinuities are an important consideration in evaluating the gas drainage potential of coalbeds. The presence of discontinuities can cause serious problems in the drilling and completion of both vertical and horizontal gas drainage

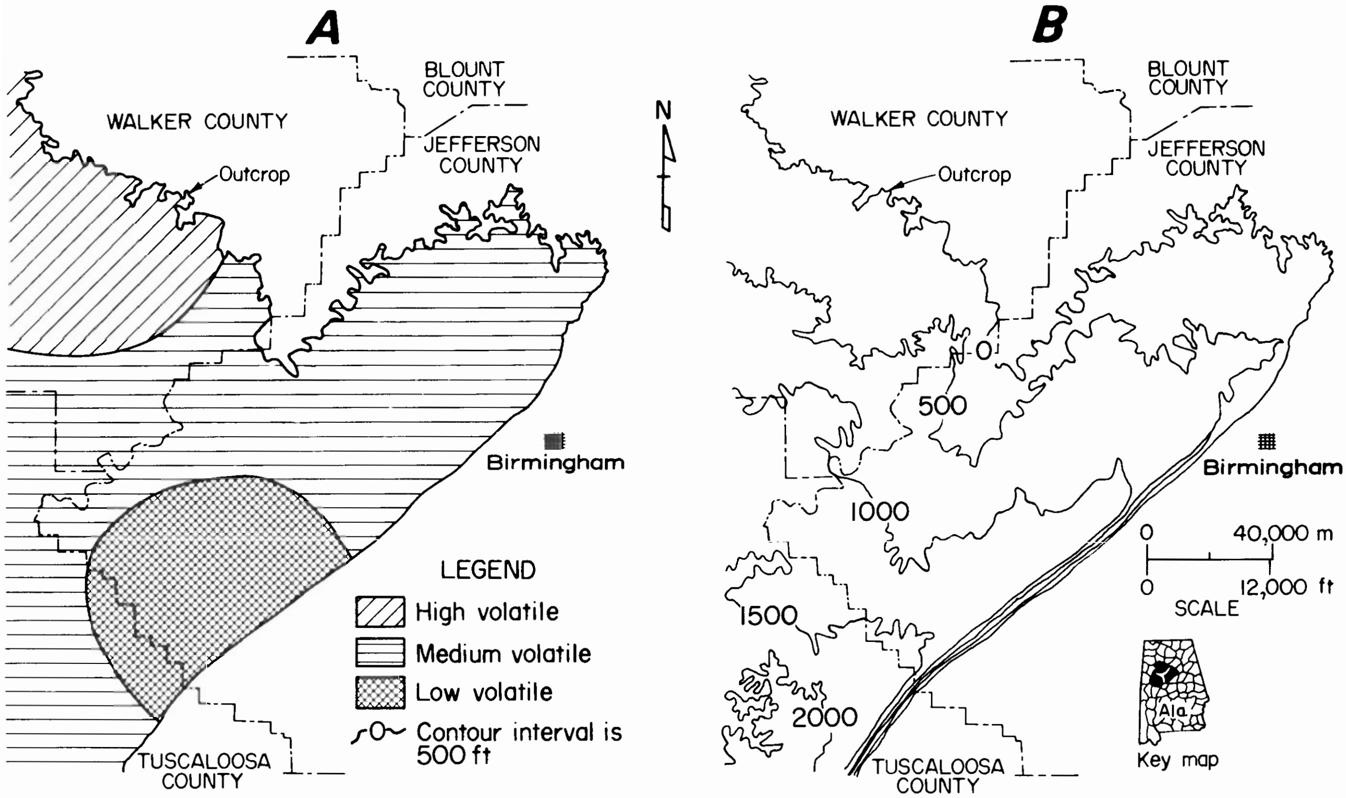

FIGURE 11. - *A*, Map of rank distribution, and *B*, depth distribution of the Mary Lee Coalbed, Alabama.

boreholes as well as influencing the flow of gas (decreasing, or in some cases increasing, production as previously discussed) to the boreholes.

An ideal coalbed from both a mining and a gas drainage standpoint would be of uniform thickness with no interruptions (fig. 12*A*). This is seldom the case, as many coalbeds exhibit various types of stratigraphic discontinuities as shown in figure 12*B*. A horizontal gas drainage borehole drilled into this coalbed would probably encounter great difficulty both in drilling and in staying in the coalbed. A vertical borehole (resource confirmation corehole or production hole) would also experience problems in sample

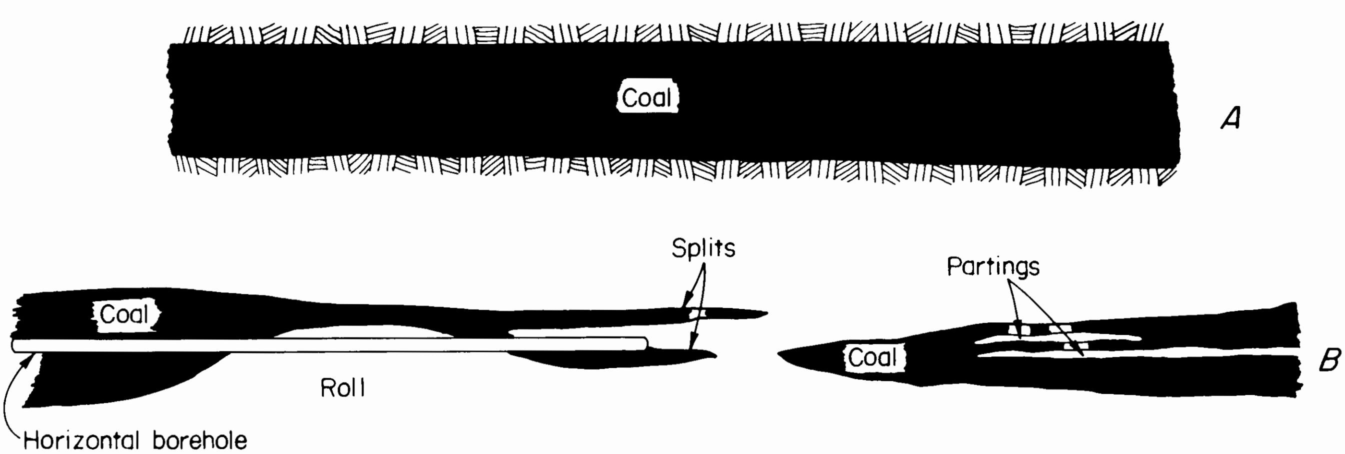

FIGURE 12. - *A*, Section view of ideal coalbed, and *B*, effect of coalbed discontinuities on horizontal gas drainage boreholes.

recovery and gas flow if areas of thin or absent coal were encountered, as at the "roll" or in the area of the "splits."

Boreholes drilled in an area of extensive partings (fig. 12*B*) could encounter gas flow problems. A horizontal hole drilled completely above or below an extensive parting that effectively separates a coalbed into separate reservoirs may drain methane only from that portion of the coalbed actually drilled. The other portion of the coalbed would remain undrained, and the gas would still be a hazard to future mining or would be unavailable for commercial production. A stimulation treatment in a vertical hole drilled into an area with an extensive parting may not completely stimulate both portions of the reservoir. If the treatment did not efficiently penetrate above and below the parting, the gas flows could be reduced with the same potential consequences as described for the horizontal holes.

Impermeable discontinuities that completely disrupt a coalbed are particularly troublesome for gas drainage drilling activities. Figure 13 illustrates several geologic situations that can adversely affect drilling. Borehole A has been drilled into a sand channel and completely missed the coalbed. If this was a resource confirmation core hole, no coal would have been obtained for direct method gas content testing. If borehole A was for gas drainage, it would probably be ineffective unless gas had migrated (or would migrate) from the coal to the sand channel and was trapped. Clay veins are generally smaller than the sand channels, however, if they are encountered, they can cause equally serious problems.

Borehole B (fig. 13) has encountered a full section of the coalbed; however, it is bounded by a clay vein and a fault. This situation can be bad or good for gas production, depending on the size of the "cell" that borehole B has intercepted. If the bounded area is small, a limited amount of coalbed reservoir will be available to feed gas into the borehole, therefore, its production potential is low. If borehole B has penetrated a larger "cell" or is not completely bounded by discontinuities, the situation may enhance gas production. A bounded coalbed reservoir of this type will potentially have a faster pressure drawdown

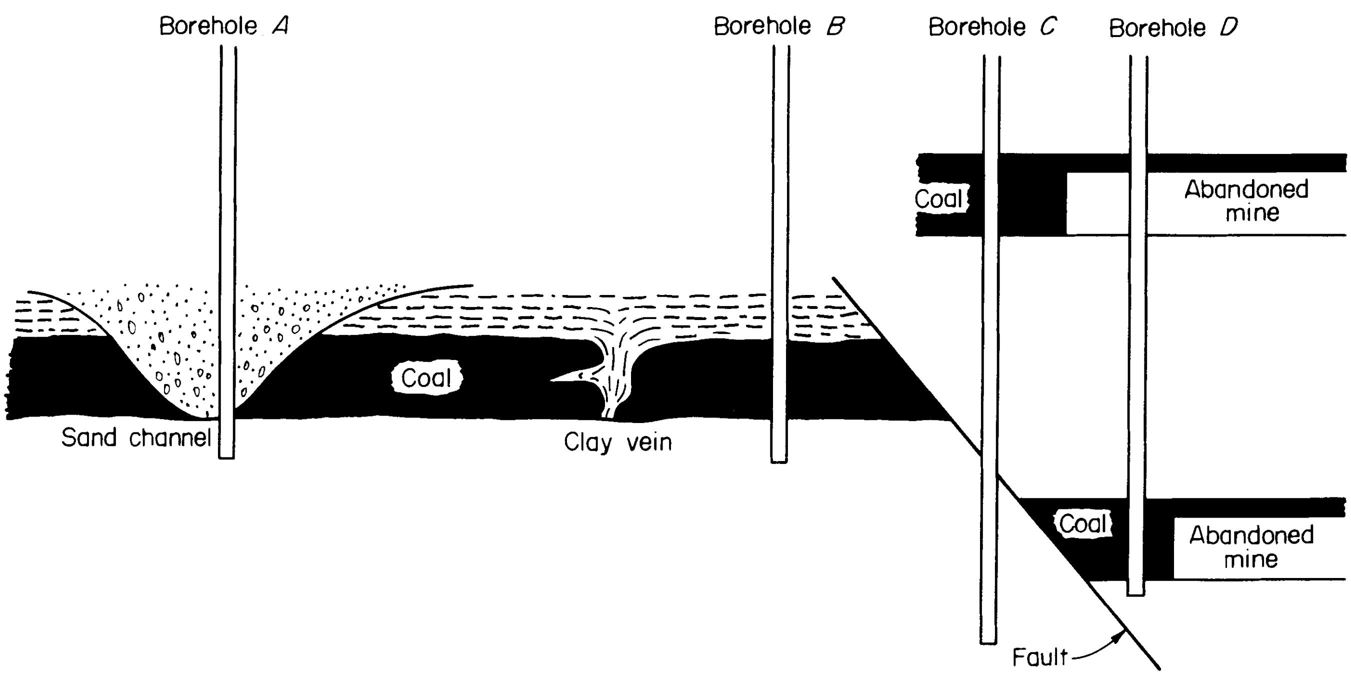

FIGURE 13. - Section view of effect of coalbed discontinuities on vertical gas drainage boreholes.

when dewatering is initiated, and higher gas saturations and production rates should follow as has been observed at a vertical borehole methane drainage pattern in Alabama (3, 23).

Borehole C (fig. 13) has completely missed the coalbed by intercepting a fault; therefore, there are no samples or gas production from the coal. Borehole D, which was to be a commercial well, has intercepted the coalbed; however, it is very near an abandoned mine. An abandoned mine is not a natural coalbed discontinuity, but it does interrupt the coalbed reservoir and can have serious consequences. It is quite likely that in addition to a portion of the coalbed reservoir having been removed by mining, a significant amount of the gas originally in the remaining coal migrated to the mine openings and is no longer available for production from a borehole. Abandoned mines above the target coalbed must also be considered, since if a void is encountered, all of the drilling fluids and the hole may be lost. If the hole could be saved, expensive remedial actions such as casing through the mine opening might be required.

All of the geologic situations described in figure 13 would also have serious effects on horizontal drilling activities (11). Sand channels are particularly troublesome because of their large size and slow rate of penetration with the horizontal drilling equipment. Intercepting an abandoned mine with a horizontal borehole could be hazardous if the mine was full of water (or gas) which flowed uncontrolled into the mine workings from which the hole was being drilled.

Since coalbed discontinuities can seriously affect the successful completion of resource confirmation core holes as well as vertical and horizontal methane drainage boreholes, they should be evaluated as part of the feasibility studies for a specific project area or drill site. While it is not possible to precisely locate all discontinuities (especially the smaller ones) before drilling a particular site, basic geologic mapping techniques can project probable areas of occurrence if sufficient data are available. It is also possible to estimate the probability of encountering coalbed discontinuities by statistically evaluating data from mines in adjoining areas (12). Impermeable coalbed discontinuities are also important from a mine ventilation standpoint since they can isolate large volumes of gas that can be liberated suddenly in high volumes when penetrated by a mine entry.

Multiple Coalbed Reservoirs

Multiple coalbed reservoirs can be attractive for a resource recovery program using vertical boreholes; however, their thickness and distribution must be amenable to efficient well completion practices. Completions of multiple coalbed reservoirs may also have applications in mining when more than one coalbed is to be mined or where gas from surrounding coalbeds may migrate to the workings in the coalbed being mined.

In general, it is preferable to have the coalbed completely exposed (open-hole completion) to the wellbore for the most efficient gas production (23). The completion of multiple coalbeds, if they are distributed over a large interval in the well, can necessitate the installation of casing through the upper coalbeds, which is less desirable. In well A (fig. 14) two thick coalbeds have been encountered at the bottom of the hole. Assuming that both coalbeds have sufficient gas to warrant completion, both could probably be completed open hole with the casing set above the upper coalbed. Depending on the actual distance between the two coalbeds and the competence and condition of the intervening rock unit, each coalbed could be stimulated separately or at the same time. Separate treatments would be desirable to increase the probability of getting a good stimulation treatment in each coalbed. If both coalbeds were treated at the same time, there would be a chance that the treatment would only enter one of the coalbeds, in spite of treatment designs to avert that

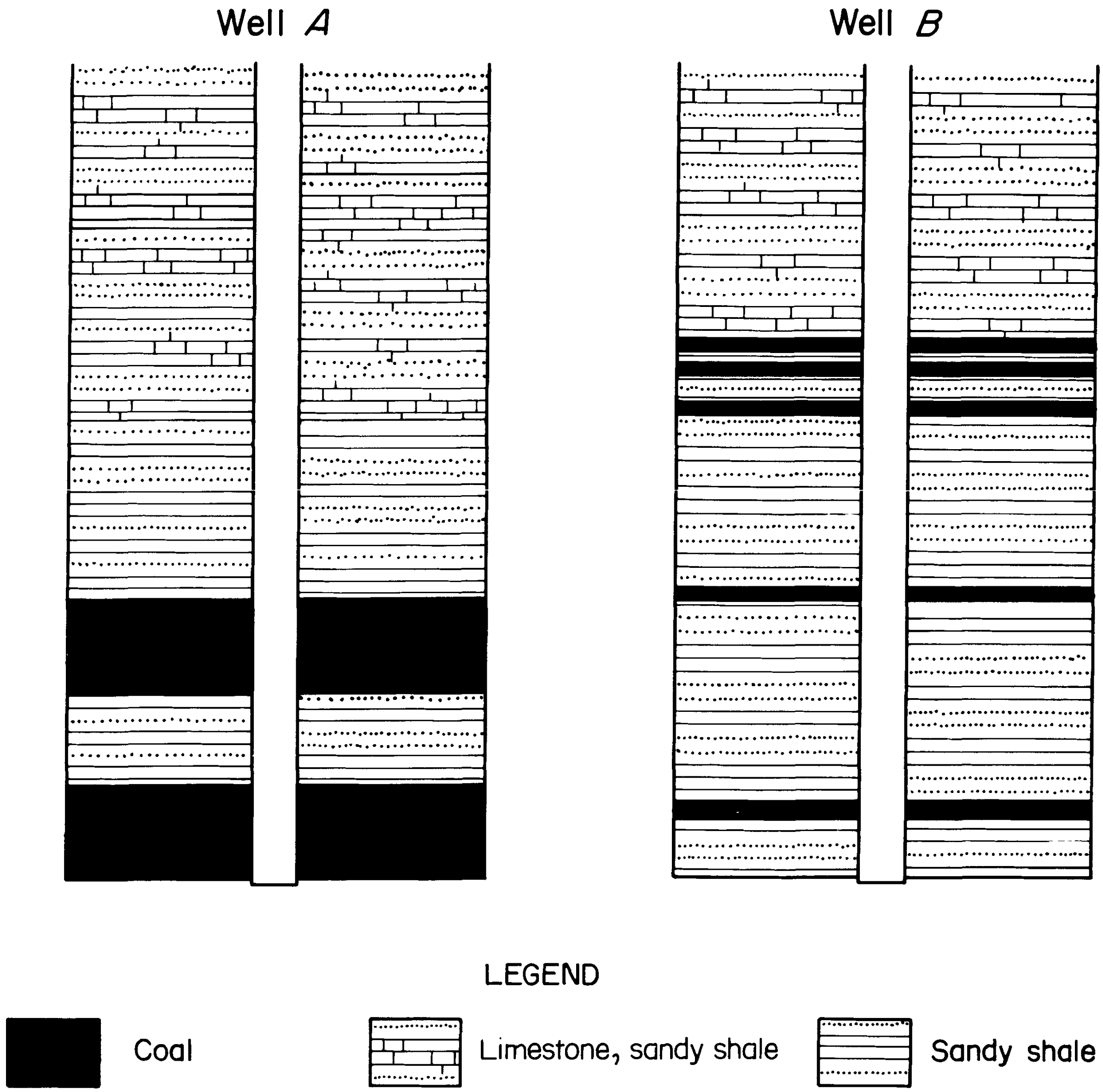

FIGURE 14. - Examples of multiple coalbed reservoirs.

situation. A good stimulation treatment is critical for efficient production of methane from a coalbed (23). The additional cost for separate treatments must be balanced against the potential for incomplete stimulation of coalbeds in a zone treatment.

Well B (fig. 14) represents an undesirable situation involving multiple coalbeds. Instead of one or more thick coalbeds being encountered, all of the coalbeds are thin, and they are spread over a large interval in the well. Even though collectively all of the coalbeds in well B may contain a volume of gas equal to or greater than that of a single thick gassy coalbed, the completion cost will probably be high and the production potential low. If the interval containing the coalbeds is large and the rock between the coals is subject to deterioration and sloughing, the upper coalbeds would have to be cased to prevent the hole from filling in.

When casing is installed through a coalbed that is to be completed for production, communication between the coalbed reservoir and the wellbore must be established either using conventional perforations or preferably by slotting (6, 28). The perforations or slots must be precisely located at the coalbed interval to have a reasonable chance of a successful completion. The thinner the coalbed, as in well B (fig. 14), the greater the chance of missing the coalbed when an attempt is made to perforate or slot.

The coalbeds in well B (fig. 14) would probably have to be completed with three separate stimulation treatments. The upper three coalbeds would be grouped as a zone, and the bottom two coalbeds would be stimulated individually. The production potential of the coalbeds in well B would probably not justify the high cost of this completion program, or even the cost of the well itself.

REGIONAL CONSIDERATIONS

Regional considerations for coalbed gas potential are essentially an expansion and correlation of information gained from site-specific evaluation procedures. The regional considerations, like the site-specific considerations, have both mine safety and resource production potential applications (7).

Calculation of an Area's In-Place Gas Volume

A calculation of the in-place gas volume in an area and mapping of the gas distribution are primary regional considerations. To calculate the in-place gas volume, the following are needed: A means of estimating the gas content that is related to mappable parameters (direct method gas contents versus depth, fig. 10), and maps of the parameters (depth of the coalbed in the area, and coal thickness, fig. 15).

Once the appropriate maps have been constructed and gas contents from coal samples versus depth have been graphed, the actual calculation of the in-place gas volume is quite simple. The data from the Mary Lee Coal Group in the Warrior Basin of Alabama will be used as an example. The overburden map (fig. 15) has been drawn with a 152-m (500-ft) contour (depth) interval. The coal isopach (thickness) map has been superimposed on the overburden map so that the volume of coal in each 152-m (500-ft) depth interval can be calculated.

For estimation purposes, the gas content of the median depth of each 152-m (500-ft) overburden interval (fig. 10) is used in the calculation as the average gas content of the interval. The gas content of the median depth of each interval is multiplied by the volume of coal in the interval to obtain the in-place gas volume. As an example, the gas content of the median depth of the 305- to 457-m (1,000- to 1,500-ft) Mary Lee overburden interval is 14.0 cm^3/g (448 ft^3/ton), and the coal volume is 1,421 trillion kg (1,566 billion tons), which when multiplied yields 19.9 billion m^3 (702 billion ft^3) of gas for the interval. Similar calculations are made for each interval (table 6), and the total in-place volume (52.3 billion m^3 [1.8 trillion ft^3] for the Mary Lee Group) can be determined.

TABLE 6. - In-place gas volume for the Mary Lee Coal Group, Alabama

Overburden		Average gas content		Gas in place	
m	ft	cm^3/g	ft^3/ton	Billion m^3	Billion ft^3
0-152	0- 500	0.5	16	0.8	28
152-305	500-1,000	9.2	294	15.0	530
305-457	1,000-1,500	14.0	448	19.9	702
457-610	1,500-2,000	15.5	496	11.9	419
610-762	2,000-2,500	15.7	502	4.7	165
				52.3	1.8 million

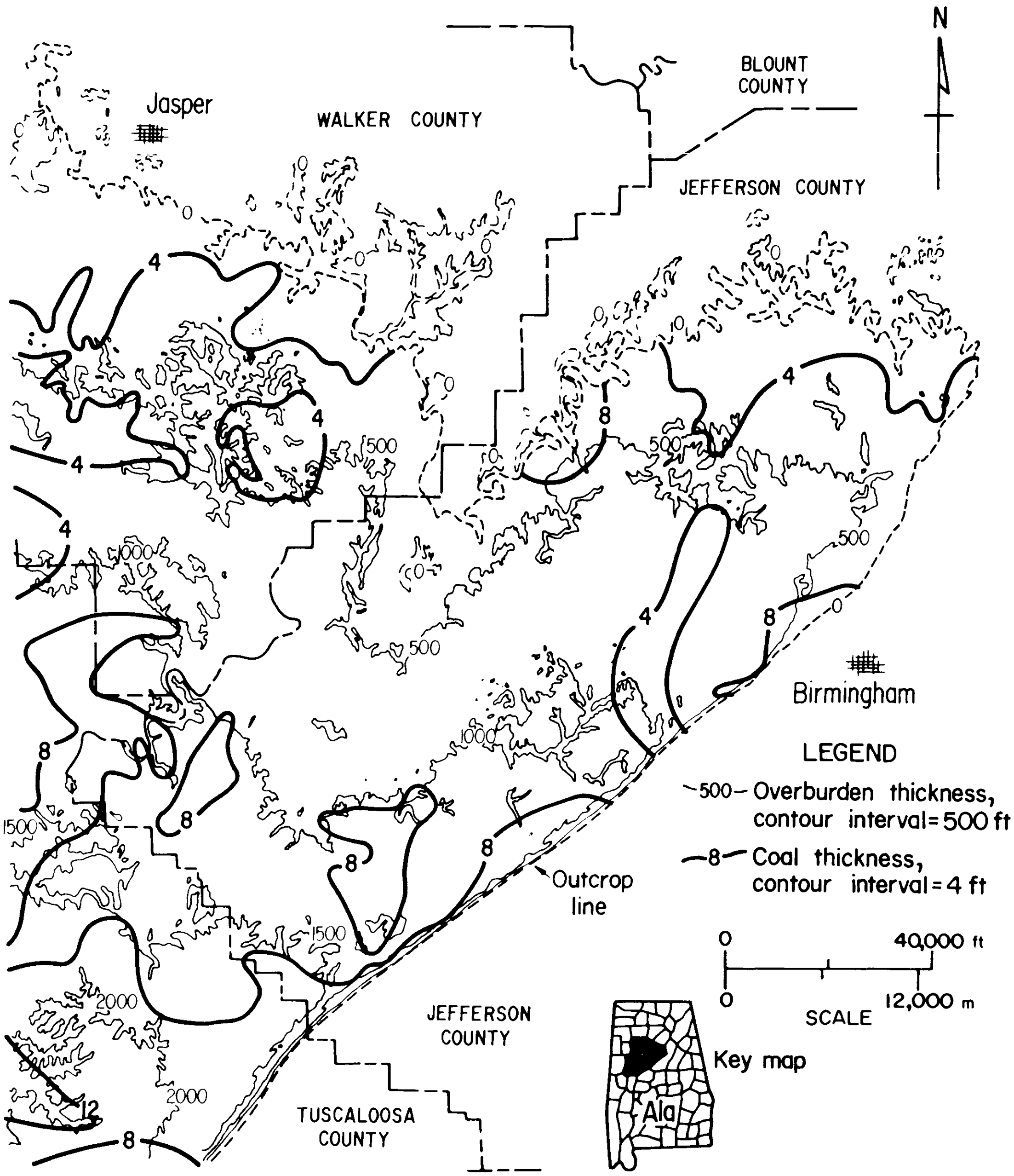

FIGURE 15. - Isopach of the Mary Lee Coal Group superimposed on the overburden isopach.

The gas content information can be used in conjunction with the regional overburden map to delineate areas of high in-place gas volumes (potentially bad for mining, good for commercial production) and low in-place gas volumes (potentially good for mining, bad for commercial production). Since the gas content of coal increases with depth, the deeper parts of the Warrior Basin, as delineated on the overburden map, have the highest potential for large volumes of in-place gas. At a depth of 610 m (2,000 ft), every 2.6 km^2 (square mile) of Mary Lee coal, 1.8 m (6 ft) thick, would contain approximately 85 million m^3 (3 billion ft^3) of in-place gas. This volume of gas would probably be attractive for its resource production potential, but it would be a tremendous volume of gas to encounter in a mining operation. The gas content at a depth of 610 m (2,000 ft) from figure 10 is approximately 15.7 cm^3/g (502 ft^3/ton), which when plotted on the graph of expected mine emissions (fig. 3) yields an estimate of over 96 m^3 (3,400 ft^3) of gas emissions from all sources (roof, floor, ribs, and pillars in addition to that actually contained in the volume of coal mined at the face) for each 907 kg (ton) of coal production. If possible, it would be preferable from the standpoint of the potential methane hazard (which of course is not the only consideration for locating a mining operation) to locate in the areas of lower in-place gas volumes.

The general regional estimates of in-place gas volumes, as calculated by the procedure described above, can be a valuable indicator of areas to be seriously considered for commercial gas production. Previous studies (4, 9-10, 14, 16, 25, 30-31) have estimated the in-place gas volumes for several of the gassiest coalbeds and coal-bearing formations in the United States (table 7), and several estimates of the in-place coalbed gas volumes for the entire United States have been made (table 1). These estimates are only valuable if used with an understanding of their true meaning and significance. It is very important to realize that these values are for in-place gas volumes and do not represent the volume of gas that can physically and/or economically be recovered from coalbed gas drainage systems.

The percentage of in-place gas that can physically be removed from a coalbed is presently unknown and will probably be different for each coalbed and even for different areas of the same coalbed. It is probable that the volume of gas that is residual gas in the direct method test will probably not flow to a wellbore and perhaps will not flow into a mining operation. Economically, it is unlikely that gas that is at low concentrations, as in the shallow portions of coal basins and in the low-rank coals, will ever be captured for utilization.

TABLE 7. - In-place gas volumes of selected U.S. coalbeds

Coalbed or formation, and State	Area		In-place gas volume	
	km^2	mi^2	Billion m^3	Trillion ft^3
Mesaverde Fm. (32), (Southern Piceance Basin), Colorado...	4,079	1,575	887.0	31.3
Mesaverde Fm. (4), (Sandwash Basin) Colorado.............	1,072	414	396.7	14.0
Mary Lee (10), Alabama.......	2,161	835	52.3	1.8
Vermejo Fm. (31), Colorado...	464	179	44.2	1.56
Pittsburgh (9), Pennsylvania and West Virginia...........	3,367	1,300	42.5	1.5
Fruitland Fm. (16), Colorado.	715	276	39.6-283.2	1.4-10.0
Lower Hartshorne (14), Oklahoma....................	1,554	600	31.1-42.5	1.1-1.5
Upper Freeport (30), Pennsylvania................	1,295	500	5.7-11.3	0.2-0.4
Beckley (25), West Virginia..	518	200	2.8	.1

Additional Regional Considerations

The other regional considerations for coalbed gas drainage activities are primarily related to geologic factors for selection of areas within a region for site-specific evaluation of proposed commercial gas recovery projects. The thickness of coalbeds can vary on a regional basis as well as locally, as discussed previously. The thicker the coalbed, the larger the reservoir for gas storage. Also, various coalbeds can appear and disappear independently of each other throughout a region. This is important if multiple zone completions of vertical wells are anticipated. For commercial ventures it is necessary to pick an area for potential development that has the optimum balance of gas content, coal thickness, and number and distribution (vertical thickness of producing zone and distance between individual coalbeds) of producible coalbeds if multiple completions are planned.

Regional trends of water-bearing sands (water sands) should also be considered to determine where such sands may be in close association with coalbeds from which gas is to be extracted by vertical wells. If water sands are present, high volumes of extraneaous water may be produced, perhaps indefinitely, without dewatering the coalbed, and with little if any gas production. The type and cost of completion procedures for vertical wells can be seriously affected by the presence of water sands in a prospective producing zone.

CONCLUSIONS

Coalbeds can contain appreciable quantities of methane, the removal of which may be desirable for mine safety and/or energy resource utilization purposes. The direct method test can be used to determine the gas contents of coalbeds at specific sites of future mining operations or potential resource recovery and utilization systems. Geologic evaluation, including a determination of the potential of encountering coalbed discontinuities, is an important consideration when locating methane drainage drilling sites. Maximum information can be obtained from a resource confirmation exploratory hole if a continuous wire line core is obtained. If wire line coring is not possible, a twinned-hole approach is the second choice.

Regional considerations influencing the gas potential of coalbeds are primarily related to the calculation of the total in-place gas for a coalbed (or group of coalbeds) in an area. Caution must be used not to confuse the in-place gas volumes with recoverable volumes. The distribution of the gas volumes in a region can be used to delineate areas of high in-place gas volumes where mining may be adversely affected but resource recovery and utilization may be enhanced. Regional mapping of geologic trends such as coal thickness, number of coalbeds, and water sands can aid in delineating areas with the highest potential for commercial production of methane from coalbeds.

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