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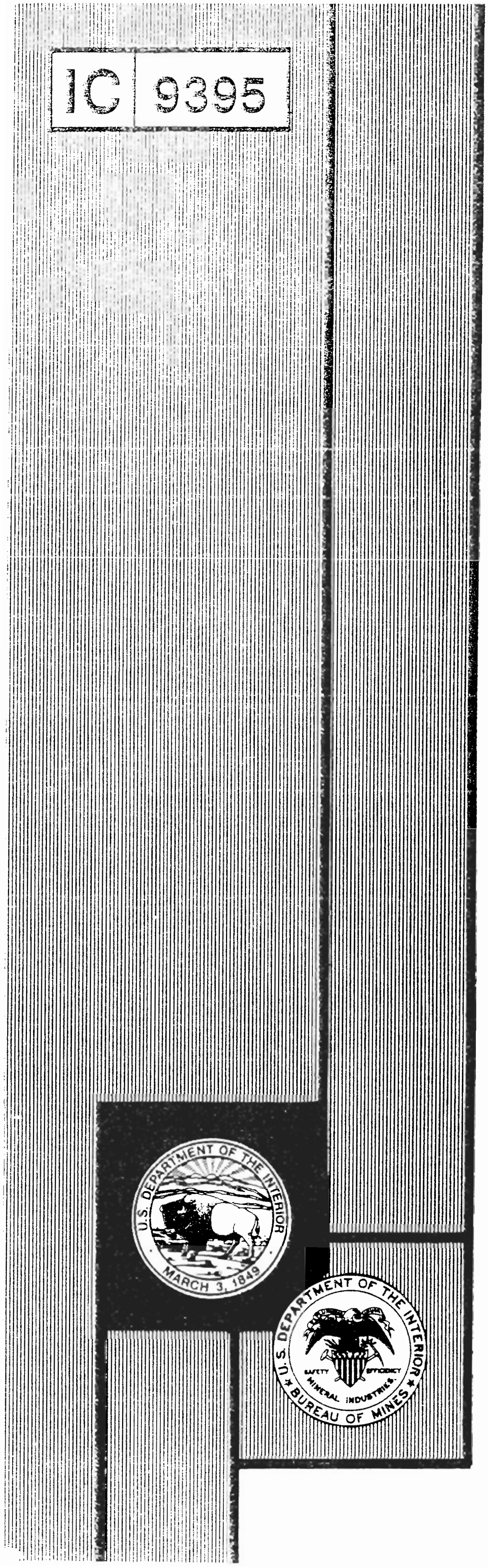

Methane Control for Underground Coal Mines

By William P. Diamond

UNITED STATES DEPARTMENT OF THE INTERIOR

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ILLUSTRATIONS

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

bbl/min	barrel per minute
Bcf	billion cubic feet
cfd/ft	cubic foot per day per foot (of hole length)
cm	centimeter
cm^3/g	cubic centimeter per gram
ft	foot
ft^3/min	cubic foot per minute
ft^3/st	cubic foot per short ton
gal	gallon
gpm	gallon per minute
h	hour
in	inch
kg	kilogram
kPa	kilopascal
lb	pound
m	meter
m^2	square meter
m^3	cubic meter
Mcf	thousand cubic feet
Mcfd	thousand cubic feet per day
m^3/d	cubic meter per day
$(m^3/d)/m$	cubic meter per day per meter (of hole length)
MMcf	million cubic feet
MMcfd	million cubic feet per day
m^3/min	cubic meter per minute
m^3/s	cubic meter per second
pct	percent
psi	pound per square inch
psig	pound per square inch, gauge

METHANE CONTROL FOR UNDERGROUND COAL MINES

By William P. Diamond[1]

ABSTRACT

Ventilation has long been the primary means of controlling methane emissions in underground coal mines. However, as mining has progressed into gassier areas of U.S. coal basins, supplemental means of methane control have become of interest, if not a necessity, for continued safe and productive mining operations. This paper describes the history and technology of methane drainage in the United States and other countries. The methane drainage technology developed in European countries is a valuable resource since their longer history of mining has already forced mine operators to deal with methane emission problems only now being experienced in the United States. Methods for assessing the need for methane drainage and the data required for planning and implementing an appropriate system are reviewed. The effectiveness of the various technologies for reducing methane emissions underground and/or the in-place gas content of individual coalbeds is illustrated with case studies. In addition to the safety and productivity gains to be realized from methane drainage systems, the potential for commercialization of coalbed methane is discussed.

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INTRODUCTION

Methane emissions can adversely affect both the safety and the productivity of underground coal mines. Since the first documented major U.S. coal mine explosion in Virginia in 1839, several thousand fatalities have occurred owing to explosions where methane was a contributing factor (*91*).[2] Ventilation has been the primary means of controlling methane in coal mines for many years. However, as mines began operating in deeper and gassier coalbeds, supplemental means of methane control became of interest to mine operators.

The shift to mining gassier coalbeds is quite evident in figure 1, which charts the gas emissions from coal mine ventilation systems from 1971 to 1988. The volume of methane and the number of operating mines remained rather stable through the early to middle 1970's (*44, 46*), but as of the 1980 and 1985 surveys (*35-36*), methane emissions increased substantially, while the number of mines declined in 1985.

The decline of methane emissions in 1988 (fig. 1) is at least partly due to the increased use of methane drainage technology, especially in the Black Warrior Basin of Alabama. Methane emissions from Alabama coal mines decreased by 17 pct, from 2.3 to 1.9 × 10^6 m^3/d (82.4 to 68.4 MMcfd), between 1985 and 1988 (*10*). During this same time, the annual production and capture of coalbed methane for commercial sale increased 130 pct, from 245 to 563 × 10^6 m^3 (8,648 to 19,865 MMcf) (*62*). Approximately 90 pct of this commercial production was from methane drainage installations located on mine property.

This paper describes the various methane control technologies available to the coal industry. Methodology and data requirements necessary to select and design optimum methane drainage systems are discussed, along with the advantages and disadvantages of the systems. Examples of gas production rates and the effects of the various methane drainage technologies on mine emissions from experimental and larger scale programs are included.

HISTORY OF METHANE DRAINAGE

Bromilow and Jones (*6*) reported on the early history of methane drainage in Europe, where coal mining has a much longer history than in the United States. The first attempts to isolate and pipe gas from a coal mine in Great Britain occurred in 1733 at the Haig Pit, Whitehaven, England. In 1844, following an explosion at another colliery, investigators concluded that gas accumulations in the gob (caved and fractured zone above an extracted longwall panel) had caused the explosion. The investigators recommended that pipes should be used to drain the gob and carry the gas up the shaft to the surface. The recommendations were reviewed by a committee of mining engineers, but were dismissed as impractical.

In-mine cross-measure holes were used in North Wales in the late 1800's to drain gas from overlying virgin coalbeds. The first successful large-scale use of cross-measure holes took place in the early 1940's at the Mansfield Colliery, Ruhr, Germany. The first recorded successful use of a vertical borehole to drain gas from virgin coal occurred at this same mine in 1943 (*79, 104*).

In the United States, the potential for using boreholes (horizontal and vertical) to drain gas from coal in advance of mining was recognized in the early 1900's (*13*). Lawall and Morris (*56*) reported on an attempt to drain gas from the Pocahontas No. 4 Coalbed, West Virginia, by drilling short (4.6- to 31.1-m [15- to 102-ft]) horizontal holes into the ribs. Measured gas pressures and flow rates were variable, but generally low. The maximum flow measured was about 453 m^3/d (16 Mcfd) from a 8.9-cm (3.5-in) diameter, 21.6-m (71-ft) long hole. The hole had a maximum shut-in pressure of 207 kPa (30 psi). Ranney (*86*) reported on the "sorption" of gas in coal and the need to "upset" the equilibrium conditions by reducing the pressure to release the gas. He proposed that, for mine safety, a vacuum could be applied to a coalbed by drilling long horizontal holes spaced 244 m (800 ft) apart. He further stated that it was possible to drill horizontal holes 1,219 to 1,524 m (4,000 to 5,000 ft), control the elevation of the

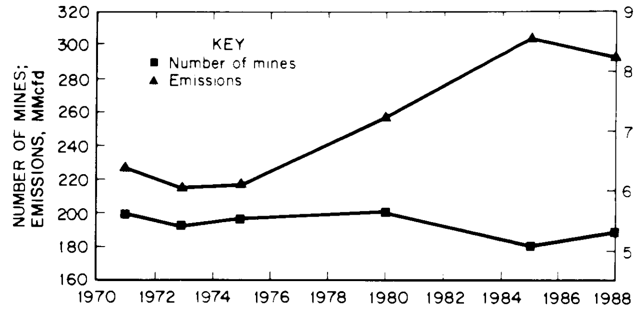

Figure 1.—Daily U.S. gas emissions and number of contributing mines, 1971-88 (*102*).

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

hole at any depth, and follow the contours of the coalbed. Unfortunately, he did not offer research results and details about the drilling equipment and procedures that could accomplish his claims. He stated, however, that it was the same technology used to drill horizontal oil wells.

The first attempt to remove gas produced from underground methane drainage systems to the surface by use of pipelines is reported to have occurred in Great Britain about 200 years ago, and the practice became widely used throughout the coalfields of Europe in the 1940's (*6*). The first known similar system in the United States was a component of a cross-measure methane drainage system designed to drain gas from the gob at an advancing longwall mine in Colorado (*87*).

In the early 1930's, in the United States, a 26-m (85-ft) deep, 7.6-cm (3-in) diameter corehole was used to successfully drain gas from "broken sandstone" above a mined-out section in the Pocahontas No. 5 Coalbed, Virginia (*12*). The coalbed was at a depth of approximately 52 m (170 ft). Four similar coreholes were eventually completed and were estimated to have produced at a combined rate of nearly 25 × 10^3 m^3/d (900 Mcfd). The holes reduced in-mine methane concentrations on the continuous miner sections from 1.5 to 0.3 pct. These holes were similar in concept to the gob gas ventholes used today to drain gas from longwall mining operations.

Tilton (*100*) noted the production of gas from vertical wells penetrating the Pittsburgh Coalbed in West Virginia. The initial well was completed in 1905 to gas reservoirs below the Pittsburgh Coalbed. In 1931, prior to abandonment of the well, gas was "discovered" in the Pittsburgh Coalbed, and the well was recompleted to that zone. In 1949, 22 additional wells were drilled to the coalbed, with 34 × 10^6 m^3 (1,217 MMcf) of gas produced through 1984 (*101*).

The first vertical wells in the United States designed specifically to remove gas directly from a coalbed were drilled in 1952 at a mine on the Pennsylvania-West Virginia border (*92*). The first well was a dual completion in the Sewickley Coalbed at a depth of about 113 m, (370 ft) and the Pittsburgh Coalbed at a depth of 140 m (458 ft). The well was completed so that gas could be produced and monitored separately from each coalbed. The Pittsburgh Coalbed produced up to 1.1 × 10^3 m^3/d (40 Mcfd) of gas when the water level was kept low by bailing through the tubing string. No measurable gas was produced from the Sewickley Coalbed owing to the completion design, which precluded removing water from the zone.

A second well at the same mine site was equipped with a downhole water pump and a vacuum pump on the surface to draw gas from the coal. Maximum gas production reached 453 m^3/d (16 Mcfd). After 10 months of low gas production, an attempt was made to increase production by "shooting" the well with nitroglycerin. This was the first documented attempt to stimulate a coalbed gas drainage well. The stimulation was unsuccessful, with post-stimulation production reaching only 85 m^3/d (3 Mcfd). The first known hydraulic stimulation of a coalbed occurred at this same mine in 1959 (*92*). Prior to stimulation, maximum gas production was 28 m^3/d (1 Mcfd) from the Pittsburgh Coalbed at a depth of 140 m (460 ft). The coalbed was stimulated with 38 m^3 (10,000 gal) of water. Fluorescein dye was added as a tracer for future underground evaluation of the stimulation. Treatment rate was 0.5 to 0.8 m^3/min (3 to 5 bbl/min), and a maximum pressure of 4,137 kPa (600 psig) was reached. The pressure of 4,137 kPa (600 psig) remained constant throughout the treatment; this was interpreted to suggest that a "true" fracture had not been created, but existing fractures had been "washed-out" or "flushed." Maximum gas production after stimulation was 4.2 × 10^3 m^3/d (150 Mcfd). Average production for 50 days after stimulation was 1.4 × 10^3 m^3/d (50 Mcfd).

The potential value of coalbed methane as a recoverable resource was recognized many years ago. In 1934, Lawall and Morris (*56*) calculated that two mines operating in the Pocahontas No. 4 Coalbed, West Virginia, were liberating approximately 0.37 × 10^6 m^3/d (13 MMcfd) of gas; based on a price of $0.10/28.3 m^3 (1 Mcf), its value was $1,300/d. Burke and Parry (*7*) in 1936 noted that the presence of gas in coal mines required the use of "costly ventilation," but that the gas may have "considerable intrinsic value, and its recovery might conceivably be a profitable undertaking." Ranney (*86*) estimated in 1941 that approximately 14.2 × 10^6 m^3/d (500 MMcfd) of natural gas was being "wasted" from U.S. coal mines. He thought it surprising that, in view of the 275 miner deaths in 1940, no thought was given to recovering the gas from coal in advance of mining to enhance mine safety. He recognized, however, that anyone suggesting that this gas be recovered and used would be considered "visionary or crazy." In 1943, Price and Headlee (*83*) concluded that technology developed by the petroleum and gas industry could be adapted for the economic recovery of coalbed gas.

ESTABLISHING THE NEED FOR METHANE DRAINAGE

A mine-safety-related methane drainage program requires substantial capital expenditure and certainly should not be undertaken if it is not needed to maintain a safe and productive underground working environment. At an existing mine, the most obvious indicator of need is difficulty in maintaining methane concentrations at the working face or in the return air below the maximum level allowed by the requisite regulatory authority. An example that illustrates the effect of high methane concentrations on mine operations was reported by Kline (*51*). A mine operating in the Pocahontas No. 3 Coalbed, Virginia, lost over 333 h of production time owing to gas delays on a longwall panel. The capital cost of installing larger capacity fans or additional ventilation shafts to increase the volume of ventilation air made methane drainage an attractive and cost-effective alternative. Kline (*51*) reported that if the gas removed by the various methane drainage techniques were added to the volume emitted into the mine, the resulting methane volume would be "well beyond our capacity for dilution."

Ideally, a property should be evaluated for its methane emission potential during the preliminary exploration and mine planning phase of mine development (*15-16, 85*). This approach offers a distinct advantage over the common practice of waiting until a methane emission problem has become acute before methane drainage is considered. If a premining course of action is taken, the necessary geologic, engineering, and reservoir data can be obtained early so that various methane drainage options can be evaluated for their effectiveness relative to the site-specific conditions (*60*). This allows the inclusion of a methane drainage system, if it is needed, into the original mine design.

Retrofitting a methane drainage system into existing mining operations, while feasible, generally limits options, especially if the methane problem has already become acute. This course of action will probably result in higher costs for the system itself, in addition to the cost of any loss of coal production. Methane drainage prior to mining has the additional advantage of potentially providing revenue to the mine at a time when no revenue is being generated from coal production. The primary advantage to the mine, however, would be the mining of coal with a reduced gas content, which over the long run allows for safer and more productive mining conditions.

Assessment of the need for methane drainage prior to mine development generally requires both an empirical and a theoretical approach. If there are active mines in the general area with similar geologic conditions and coal characteristics, a review of gas problems in those mines provides the best insight into the level of gas emissions to be expected at the new location.

A direct measurement of the site-specific gas in place for the coalbed to be mined can be helpful for assessing the relative gassiness of the coalbed. The gas content of surrounding strata, including other coalbeds, should also be measured to determine the number, location, and possible influence on mining of these additional gas-bearing zones. The gas content values are an important variable required for gas production simulations using the various available coalbed gas reservoir models. Gas content testing is a relatively simple procedure that utilizes samples of coal from exploration coal cores (*20*). The direct-method procedure requires that the coal sample to be tested be sealed in a desorption canister as soon as it is retrieved from the corehole to minimize the amount of gas lost before gas content testing begins. Gas is periodically bled from the container and measured, after which the results are corrected to standard temperature and pressure. After a period of desorption that may last several months, the total cumulative volume of gas desorbed is determined.

Properly conducted direct-method testing of coal cores provides relatively accurate estimates of in-place gas contents for most mine planning purposes at a reasonably low cost. A modified-direct-method (MDM) procedure provides an increased level of accuracy, but at a higher level of instrumentation sophistication, procedural complexity, and cost (*103*). This methodology measures the pressure of the gas desorption in the sealed container and uses the ideal gas law to calculate the volume of gas desorbed from the coal sample. The MDM is particularly useful for samples (both coal and other rock types) with low gas contents and for samples with unusually high percentages of other gases besides methane.

Gas content values can be compared with any available data from surrounding mine properties, or other areas of similar geologic conditions and mining methods. The severity of mining problems associated with known levels of in-place gas contents can then be compared with the test results from the new area of interest. A listing of gas content values for approximately 1,500 coal samples from more than 250 coalbeds in 17 States is included in Diamond (*20*).

Gas content data on individual coal samples can be used along with auxiliary data on coal rank and/or depth to construct curves for estimating in-place gas contents (*16, 19, 23, 42-43, 49, 67-68, 94*). These curves can be used to estimate gas content values only if the rank and/or depth are known for a particular coalbed of interest (fig. 2). The curves are best used for estimating in-place gas volumes in regional studies. They should be used with caution for a relative small, mine-size area, where "abnormal" conditions may exist. The curves may be used in preliminary assessments of small areas but should not be considered a substitute for site-specific gas content determinations.

Unfortunately, it is not possible to cite a definitive threshold in-place gas content value above which methane drainage would be required or recommended. Numerous geologic and mining factors in addition to the in-place gas content influence methane emissions into a mine. Methane drainage has been practiced by coal companies in the low-volatile, Pocahontas No. 3 Coalbed, Virginia, at depths of 380 to 790 m (1,250 to 2,600 ft), where gas contents approach 18.8 cm^3/g (600 ft^3/st) (*51*); and in the high-volatile A, Pittsburgh Coalbed, Pennsylvania and West Virginia, at depths up to 305 m (1,000 ft) (*61, 85, 99*), where gas contents are commonly only about 4.7 to 6.3 cm^3/g (150 to 200 ft^3/st) (*20*). Large patterns of vertical boreholes have been successfully used for methane drainage in advance of mining in the medium- to low-volatile Mary Lee-Blue Creek Coalbeds, Alabama, where gas contents are approximately 14.0 to 19.0 cm^3/g (450 to 600 ft^3/st) at depths ranging from 305 to 610 m (1,000 to 2,000 ft) (*17*).

Insight into the selection and configuration of appropriate methane drainage techniques can be gained from simulations using computer-based reservoir and production models. The models can best be used to evaluate the potential effectiveness of the various technologies available, alternate configurations of well patterns, and the time factor between when holes are put on production versus mine development. Most of the available models are designed to simulate the production of gas from vertical wells drilled into virgin coal reserves (*50*). However, several of the models have been adapted to include horizontal holes drilled from underground workings, as well as the influence of adjacent mine workings (*41, 60, 88, 90, 97*).

A comprehensive mine simulator, combining the variables of mining operations and coalbed reservoir and production simulators, that could predict minewide ventilation and/or methane drainage requirements does not currently exist. It is, therefore, not possible to predict the need for methane drainage by utilizing a theoretical analytical technique. Most mining companies wait until methane emission problems are encountered before methane drainage is considered owing to the difficulty in predicting the need for methane drainage.

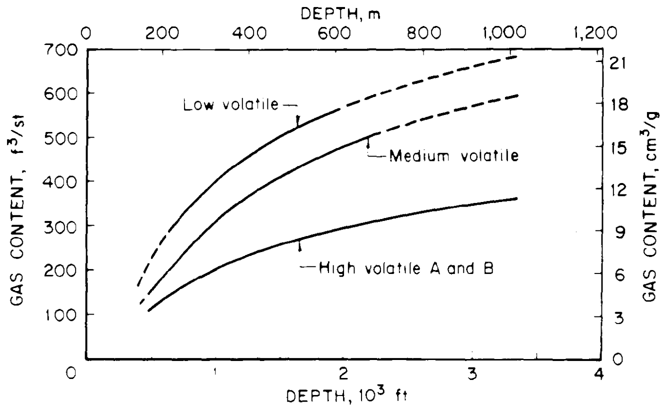


Figure 2.—Gas content versus depth and coal rank, Black Warrior Basin, Alabama (*67*).

Another aspect of methane drainage to consider when evaluating the need for such technology is the potential for on-site utilization or commercial sale of the produced gas. The capture and utilization of coalbed gas does require additional effort beyond venting the produced gas at the surface. Gas gathering and metering systems and, depending on the ultimate use and quality of the gas, compression and gas treatment facilities may have to be constructed. Gas sales contracts and perhaps gas ownership and/or royalty agreements must be negotiated. In spite of the extra effort required, gas utilization or sales can offset the cost of methane drainage and perhaps produce a profit (*27, 105*). To illustrate the production potential, coalbed methane wells in the Black Warrior Basin of Alabama produced 2.6 × 10^9 m^3 (91.8 Bcf) of gas in 1992 (*38*). Cumulative production from coalbed methane wells in the basin was nearly 8.2 × 10^9 m^3 (290 Bcf) through 1992, with about 55 pct of the production being located on mine property.

ESTABLISHING A GEOLOGIC FRAMEWORK

Once the need for methane drainage has been determined, a geologic framework must be established for the site. A site-specific (minewide) geologic framework is essential to help provide a basis for picking drilling sites and designing the drilling and completion programs for individual methane drainage holes. Additionally, the mine development plan must be taken into account when finalizing drilling locations.

GENERAL MAPPING REQUIREMENTS

Two basic types of maps are required for methane drainage planning: isopach and structure. Coal isopach maps should be constructed for all coalbeds (and any other gas-bearing strata) that may contribute gas to the mining operation and which may be considered for methane drainage. Coal thickness is a critical consideration. In vertical wells, maximum coal thickness or surface area exposed to the wellbore is advantageous for optimum gas and water production. In horizontal holes, the thicker the coalbed and the more uniform the structural dip, as determined from a structure map, the easier it is to keep the well path in the coalbed. Structure maps that depict changes in elevation of individual stratigraphic units, such as coalbeds, are also used in conjunction with surface elevation (topographic maps) to provide an estimate of depth to the coalbed and other relevant strata for the design of the drilling and completion programs of vertical methane drainage wells.

COALBED DISCONTINUITIES

The data and trends portrayed on the geologic maps can be used to delineate or forecast the presence of coalbed discontinuities, in particular "wants," sand channels, and structural faults that can disrupt the continuity of the coalbed. Coalbed discontinuities should be avoided since they commonly cause drilling and production problems. If a vertical methane drainage well, such as well *A*, figure 3, penetrates a sand channel, the well may not produce appreciable gas. Well *B*, figure 3, has encountered the targeted coalbed, but has been drilled into an area between a clay vein and a fault. If the clay vein and fault are impermeable and their boundaries define a small drainage area, well *B* may only influence that small area, thus reducing the benefit for the cost expended. Well *C*, figure 3, has penetrated a fault plane that has displaced the targeted coalbed. Unless the fault plane is a conduit for gas migration, well *C* will probably not be productive. Well *D*, figure 3, encountered a mine void in an overlying coalbed. Technically not a coalbed discontinuity, the void, however, disrupts the continuity of the strata. The mine void will most likely result in drilling problems and may cause abandonment of the well before the target coalbed is reached.

Coalbed discontinuities also adversely affect the drilling and production of gas from horizontal boreholes. Hole *A* in figure 4 has encountered a "roll" that will probably cause drilling problems when the harder, noncoal material is penetrated. Production of gas from this hole will most likely be adversely affected owing to the reduction in hole length caused by encountering splits and the eventual pinch-out of the gas reservoir. Hole *B*, figure 4, has encountered a sand channel and a fault that has displaced the coalbed, resulting in similar drilling and production problems.

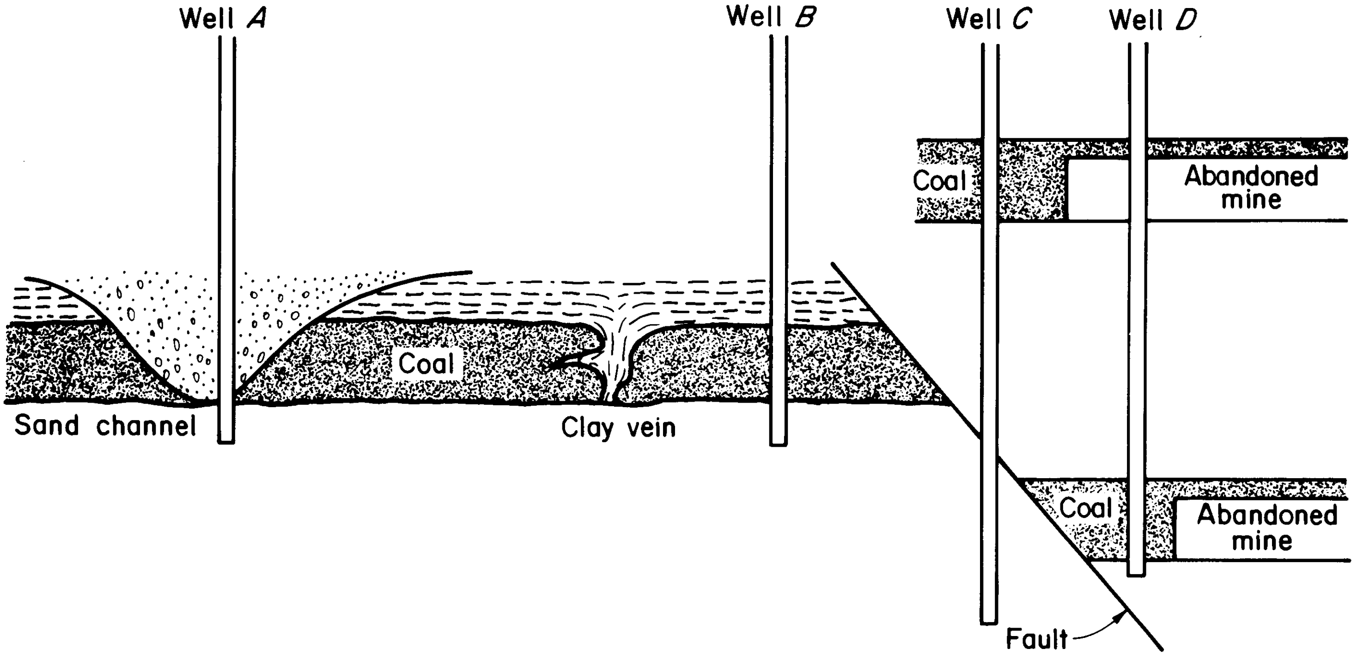


Figure 3.—Schematic section view of effect of coalbed discontinuities on vertical methane drainage wells (*16*).

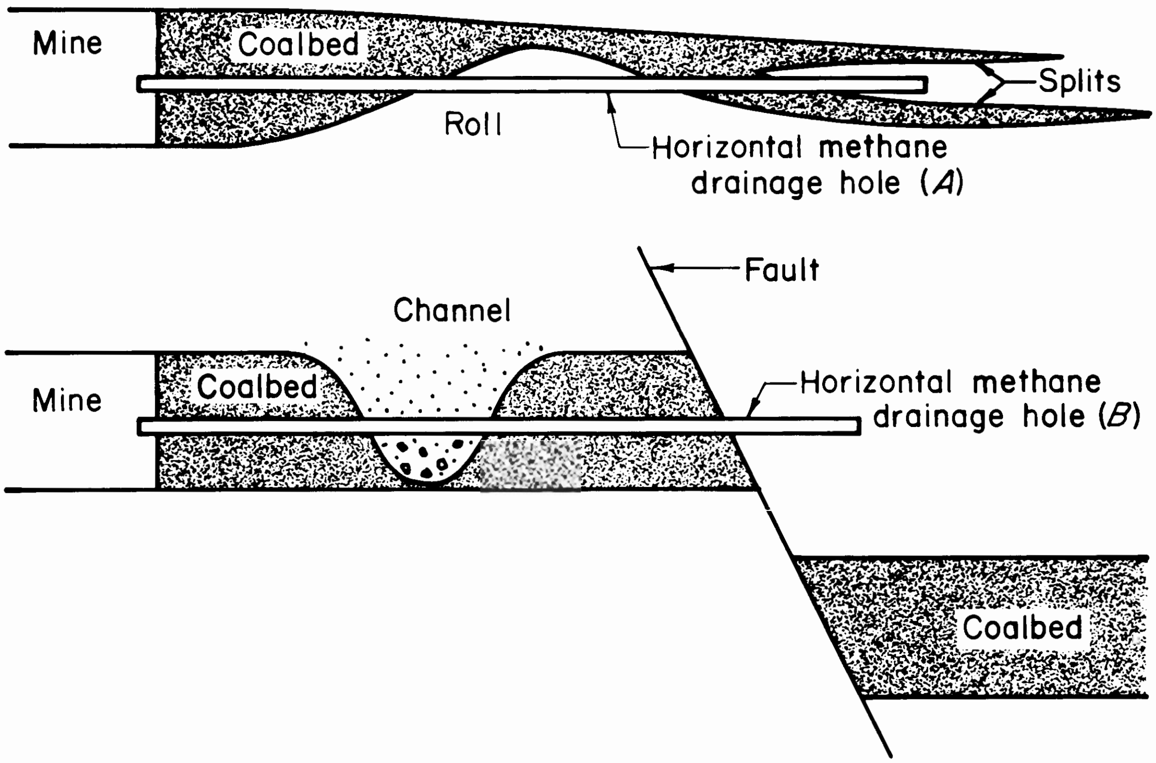


Figure 4.—Schematic section view of effect of coalbed discontinuities on horizontal methane drainage boreholes.

The occurrence of coalbed discontinuities obviously presents potential mining problems, in addition to being a concern for the most advantageous placement of coalbed gas drainage wells. If mine workings are available for underground mapping, geologic trends, including faults, clay veins, and sand channels, may be projected into adjoining unmined areas. A geologic and statistical methodology has been developed that uses data from mined-out areas to estimate the probability of encountering coalbed discontinuities with vertical drilling grids of various spacings (*39*).

MULTIPLE GAS RESERVOIRS

A geologic consideration that should be addressed early in the planning stages of a methane drainage program is an evaluation of additional gassy coalbeds surrounding the coalbed to be mined. Gas from overlying coalbeds can be a particular problem, especially if the beds occur in strata over a longwall panel. As the longwall panel is extracted, unsupported overburden collapses behind the temporary roof support of the shields. Gas enters the mine atmosphere from overlying coalbeds exposed directly to the caved zone (gob), or may migrate through fractures into the gob or to the mine through the roof near the face (fig. 5). Diamond, (*25*) found that coalbeds as much as 61 m (200 ft) above an extracted longwall panel contributed gas to the gob. Gas also migrates into mine workings developed in room-and-pillar sections through fractures in the roof and floor that connect to other gassy coalbeds. An effective methane drainage strategy for multiple gas-bearing coalbed reservoirs may require several gas drainage techniques. This could include multiple-zone completions in vertical wells drilled in advance of mining, as well as postmining gob gas drainage.

FRACTURE ANALYSIS

Fractures, both in the coalbed (cleat) and in surrounding strata (joints), can have a significant influence on the flow of gas to methane drainage boreholes and mine entries. Once gas has desorbed from the micropore structure of coal, its flow to a wellbore or mine entry is first governed by Fick's law of diffusion (concentration gradients) until the gas molecules reach the cleat, at which point Darcy flow is the controlling influence (fig. 6). In water-saturated coalbeds, the Darcy flow of gas through the cleat system is controlled by the degree of pressure

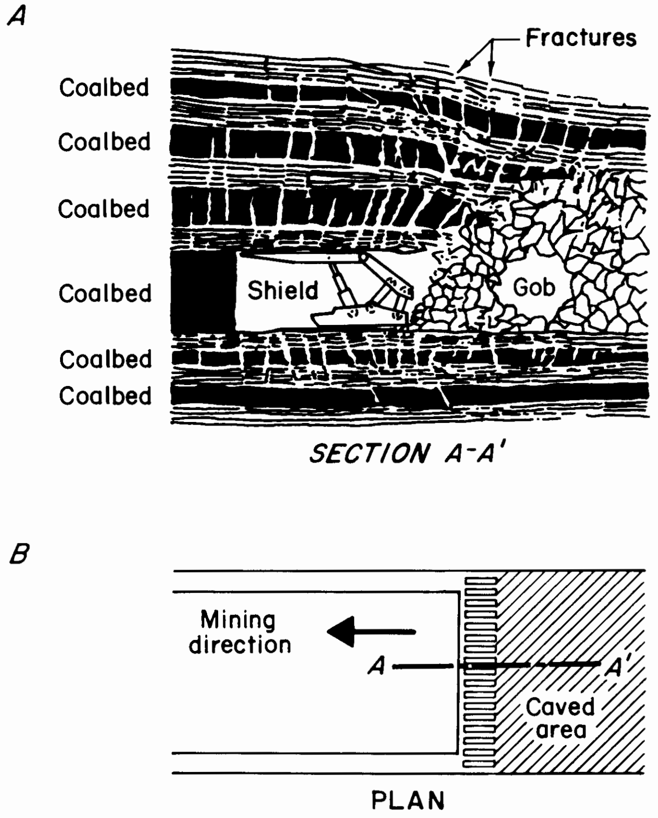


Figure 5.—Schematic section view of longwall mining with gob gas conduits (*A*) and plan view of longwall panel (*B*) (*9*).

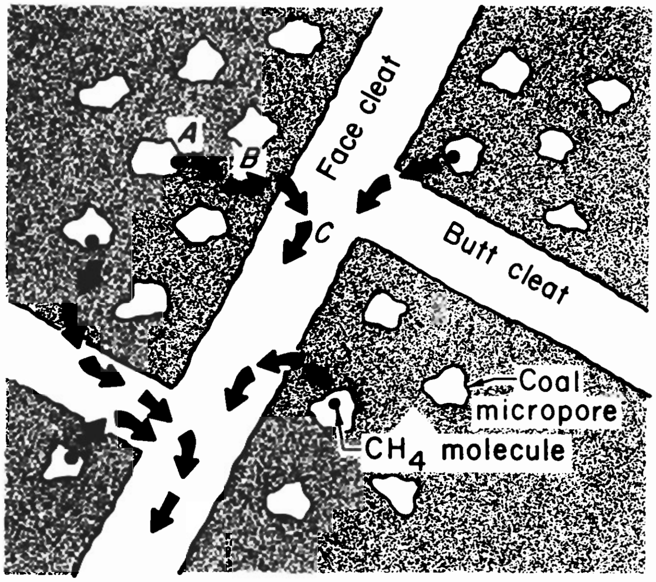


Figure 6.—Schematic plan view of desorption of methane from coal micropore (*A*), diffusion through coal matrix (*B*), and Darcy flow through cleat (*C*).

reduction from dewatering. Dewatering is controlled by the permeability of the cleat and the conductivity of horizontal holes drilled into the coalbed or sand-filled fractures from stimulated vertical wells. Some coalbeds may not be water saturated, and gas production may be initiated without dewatering.

Generally two vertical cleats, face and butt, oriented at approximately 90° to each other, occur in coalbeds (*65*). The face cleat is the dominant fracture, generally extending for a meter or more (several feet) laterally and cutting through bedding. The butt cleat is usually less well developed and has a short lateral extent. A butt cleat commonly terminates against a face cleat and does not extend as high vertically to cut across as many horizontal layers in the coalbed. The relative dominance of the face cleat over the butt cleat varies depending on the geologic processes that have created or influenced the physical character of the coalbed over the millions of years of geologic history since it was deposited. Water and gas flow should be enhanced in the face cleat direction owing to the differences in physical character and associated permeability between the face and butt cleat. Fluids and sand proppant from stimulation treatments in vertical wells have also been shown to preferentially invade and advance along the face cleat (*24*).

Cleat orientation can be measured directly with a compass in an active mine or can be projected from measurements in nearby mines. If active mines in a coalbed of interest are not available, it is possible to estimate cleat orientations from mines in other coalbeds or from surface outcrops. In some cases, subsurface cleat orientations can be interpreted from fracture trends in other rocks exposed at the surface, or lineaments from areal photography (*21, 66*). Where no other data are available, an oriented core sample can be used to determine cleat direction (*4*).

The presence, orientation, and frequency of fracturing as measured at the surface may be indicative of similar fracture characteristics in the subsurface. Attempts have been made in several producing areas to place vertical coalbed gas drainage wells near fracture zones to take advantage of the expected increased permeability. Briscoe (*5*) reported that a significant increase in gas production was achieved in the Black Warrior Basin of Alabama when vertical wells were drilled near fracture systems. Wells located within 61 m (200 ft) of fracture zones obtained 25 pct greater gas production and 50 pct greater water production than wells in unfractured areas. Additionally, Briscoe (*5*) showed that the position of wells relative to the regional dip of the coalbed influenced production. Updip wells dewatered and produced gas before the downdip wells. A similar relationship was found in West Virginia, where wells drilled on structural highs that encountered the Pittsburgh Coalbed above the gas-water contact produced gas. Wells drilled below the gas-water contact were not productive (*78*).

METHANE DRAINAGE TECHNOLOGY

Numerous methane drainage techniques have been developed, both in the United States and abroad. The multiple techniques are the result of variations in a few standard practices that have evolved as a consequence of site-specific geologic conditions and mining methods that exist throughout the world. Methane drainage practices in the United States are generally different from those commonly used elsewhere. For the most part, European coal basins are more tectonically disturbed than those in the United States; consequently strata are more steeply dipping. Because of the steep dips, mining methods are different from those used in the United States (fig. 7). European coal basins also contain more numerous, thick, minable, gassy coalbeds that are stratigraphically closer together. This has resulted in the need to drain gas from multiple-coalbed gas reservoirs. Also, owing to the long history of coal mining in Europe, most of the shallower, less gassy coalbeds have already been mined. This has resulted in mining at greater depths, where the gas content of the coal is generally higher. The long historical habitation of many of the European coal regions and the cultural development on the surface have restricted much of the methane drainage technology to underground methods. The U.S. coal mining industry is now reaching a development stage where some of the European problems are being encountered, and their methods of methane drainage will be increasingly adapted to U.S. conditions.

The various methane control technologies can be grouped in several ways for discussion purposes. In this paper, they are generally grouped as either underground or surface technologies.

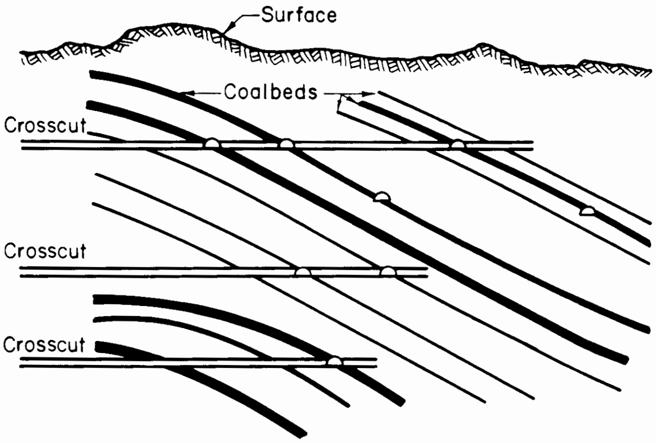


Figure 7.—Schematic section view of typical European coal basin and mining method (9).

UNDERGROUND METHANE DRAINAGE

Horizontal Boreholes - In-Mine

Most underground methane drainage technologies entail the drilling of horizontal boreholes into the coalbed being mined. In the United States, horizontal boreholes are the most commonly used technique to drain gas directly from the coalbed to be mined. Holes drilled from underground workings are also a common methane drainage technique outside the United States; however, many of the holes are not drilled into or even from the coalbed to be mined. Horizontal boreholes have two distinct advantages over other options. First, in most applications in the United States, the entire length of the hole is drilled into the gas reservoir and is productive. In contrast, a vertical well may have to be drilled 305 m (1,000 ft) or more to reach a 1.5-m (5 ft) thick coalbed and then have only 1.5 m (5 ft) of the hole in the reservoir. Second, a horizontal borehole can be drilled perpendicular to the face cleats to maximize the drainage of gas by intercepting the greatest number of these primary conduits of gas flow (fig. 8).

A major disadvantage of horizontal boreholes is that they must be drilled in the very restrictive underground

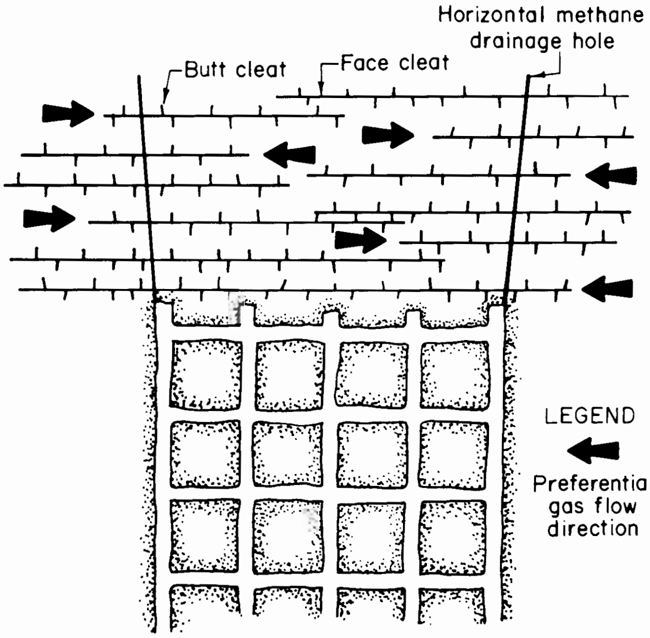


Figure 8.—Schematic plan view of horizontal methane drainage boreholes drilled to preferentially intercept face cleat.

environment. Commonly, the size of the working area can be quite small, transporting people and materials to the drill site can be cumbersome, and stringent safety regulations must be obeyed. The successful use of horizontal boreholes underground also requires close coordination between the mining plan and the methane drainage plan. Neither operation must hinder the other, in terms of logistics and in completing their respective activities so as to not impede the other's progress.

Underground horizontal boreholes can be used to control methane emissions in two general ways: draining gas from a block of coal to be mined, or shielding active mining areas from migrating gas. The drainage of gas can be either in advance of mining or during mining as part of the mining cycle. Shielding can be accomplished either by intercepting the gas before it enters the mine atmosphere or by diverting the migrating gas from the active face area. Optimum placement of the holes can also provide a combination of control functions.

Horizontal boreholes drilled from existing underground mine workings can be used for long-term methane drainage in advance of mining. In the mid-1970's, two horizontal boreholes were drilled in the Upper Sunnyside Coalbed, Utah, from a set of entries abandoned for more than a year due to high methane emissions (fig. 9). The two holes were drilled 131 and 137 m (430 and 450 ft) into the coalbed. Combined production from the two holes averaged over 4.0 × 10^3 m^3/d (140 Mcfd), or 15 $(m^3/d)/m$

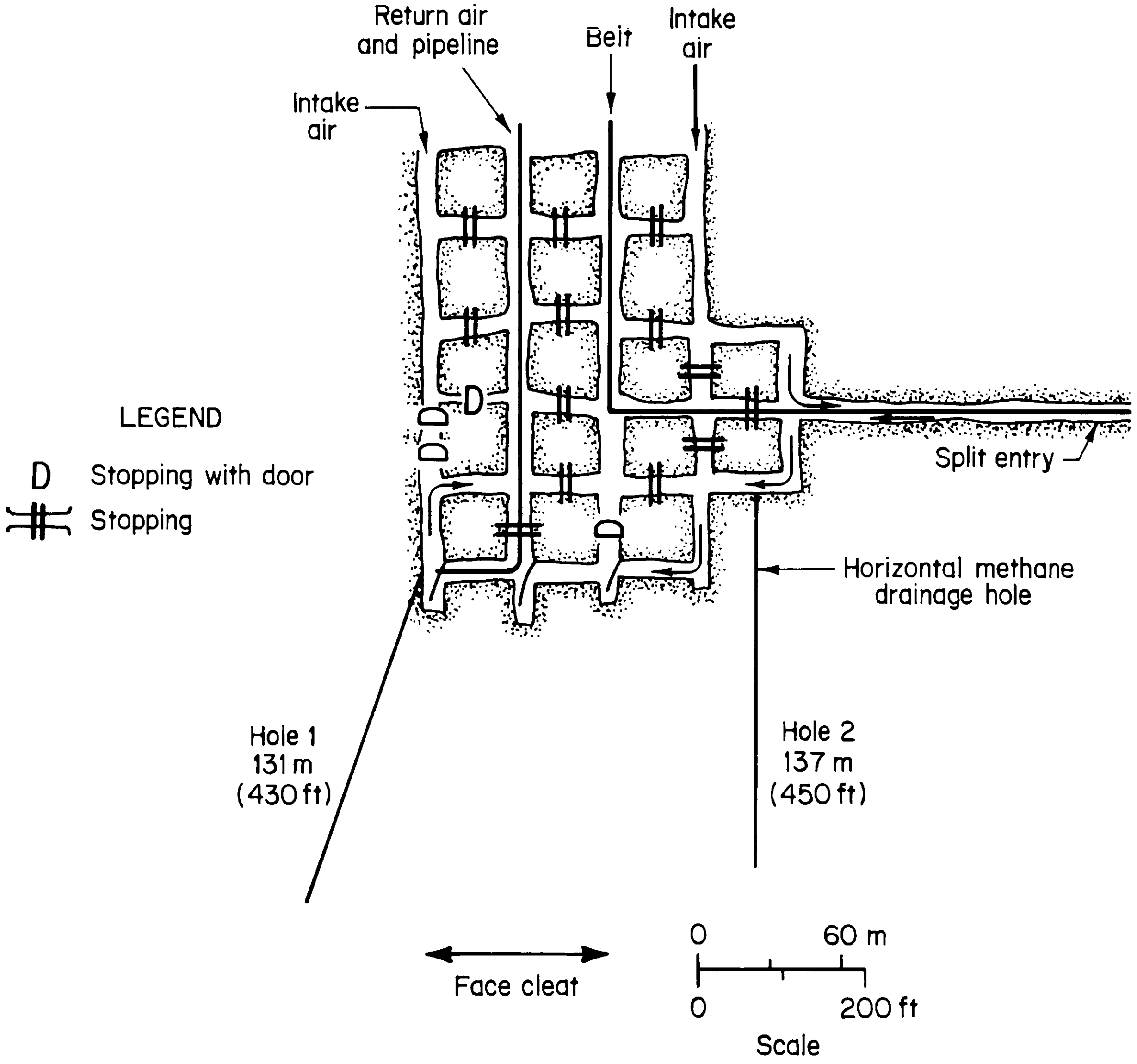


Figure 9.—Plan view of horizontal methane drainage boreholes, Sunnyside Coalbed, Utah (*80*).

(160 cfd/ft) of hole, for 6 months. In 9 months, the two holes produced over 0.99 × 10^6 m^3 (35 MMcf) of gas, and face emissions were reduced by 40 pct. This enabled mining to resume in the area (*80*).

In the late 1970's, four long horizontal boreholes were drilled into the Pittsburgh Coalbed, Pennsylvania, from a section of a mine that had been abandoned for 2.5 years due to high gas emissions. The length of the holes ranged from 299 to 764 m (982 to 2,505 ft) (fig. 10). The combined initial flow rate of each hole was 16.4 × 10^3 m^3/d (580 Mcfd), or 9.3 $(m^3/d)/m$ (100 cfd/ft) of hole. Production decreased to 6.6 × 10^3 m^3/d (234 Mcfd), or 3.7 $(m^3/d)/m$ (40 cfd/ft) of hole, after 2.7 years of production (fig. 11) (*84*). Cumulative production for the four holes was 7.2 × 10^6 m^3 (255 MMcf). Gas production from the holes was lower than expected for the Pittsburgh Coalbed, apparently owing to the presence of a sandstone channel and clay veins that effectively isolated this area from the rest of the gas reservoir. The 2.5-year idle period prior to the drilling of the holes also allowed gas from this isolated area to drain into the mine workings, lowering the volume of gas to be drained.

This project in the Pittsburgh Coalbed was unique at the time for the United States for two reasons. In previous horizontal drilling projects, the primary gas problem was emissions at the active face. Gas produced by horizontal boreholes drilled near the face was vented underground to an area where sufficient air was available to dilute the methane concentration below the allowable limit. In this case, a 15.2-cm (6-in) diameter steel underground pipeline was included in the methane drainage system to carry the produced gas to the surface through a vertical borehole drilled into the mine. Also unique to this installation was a demonstration project to utilize some of the gas production to produce electricity from a turbine generator to power a ventilation fan (*84*).

In the late 1970's, a 308-m (1,010-ft) horizontal borehole was drilled to drain gas from the Mary Lee Coalbed, Alabama (*81*). The hole was drilled from a set of old workings into an adjacent area that was to be mined in the next year (fig. 12). The hole initially produced gas at a rate of 5.7 × 10^3 m^3/d (200 Mcfd), or 18.6 $(m^3/d)/m$ (200 cfd/ft) of hole, and declined to 1.8 × 10^3 m^3/d (65 Mcfd), or 6 $(m^3/d)/m$ (65 cfd/ft) of hole, a year later just prior to being mined through. Total gas production from the hole was 1.1 × 10^6 m^3 (40 MMcf). Methane emissions at the face were reduced by as much as 60 pct after the initiation of methane drainage (fig. 12).

Probably the most significant advance in underground horizontal drilling was the shift from rotary drilling equipment to the use of in-hole motors. In the first controlled direct comparison of the drilling techniques, Kravits (*53*) found that the in-hole motor provided greater control of the horizontal and vertical trajectory of the hole and at the same time increased drilling productivity and lowered the drilling cost per foot of hole. Another improvement in horizontal drilling technology has been the development of downhole directional surveying systems to replace the time-consuming single-shot survey tools that must be pumped down the hole and retrieved for each survey (*52, 98-99*).

With the increased use of longwall mining in the United States, many mines are experiencing unprecedented methane emission problems. Methane emissions associated with longwall mining are of particular concern because they can occur at any time in the mining cycle. Methane emissions can be encountered during the driving of development entries with continuous miners, progressing to emissions at the active longwall face, and continuing through the accumulation of methane in the gob and finally into the bleeder entries. These potential methane emission problems may require the use of several types of methane drainage systems, including several applications of horizontal boreholes.

Long (>305-m [>1,000 ft]) horizontal boreholes drilled in advance of driving the development entries for longwall panels can be utilized to drain methane as discussed previously, and/or they can be used to shield development entries from the flow of gas from the surrounding virgin coal reserves. Figure 13 illustrates an application of long horizontal boreholes (*A*) placed for general methane reduction in virgin blocks of coal prior to mining, and which also (*B*) provide a shielding benefit to development entries as they are advanced, as well as after completion.

If sufficient time is available, a developed panel in a gassy coalbed may degasify naturally into the surrounding entries prior to longwall mining. However, in many mining operations, continuous miner sections for the driving of development entries are barely able to keep pace with the longwall. Consequently, sufficient time may not be available to provide a significant reduction in the gas volume within the longwall panel. This situation has become increasingly serious over the past several years, as more efficient longwall equipment and larger panels have been utilized to increase productivity. Aul and Ray (*2*) observed that between 1983 and 1990, longwall productivity increased by 200 to 400 pct, accompanied by a 200- to 300-pct increase in methane emissions at several mines operating in the Pocahontas No. 3 Coalbed, Virginia. The mines are operating at depths ranging from 366 to 732 m (1,200 to 2,400 ft), with gas contents as high as 18.8 cm^3/g (600 ft^3/st). Methane emission rates at these mines averaged between 0.48 and 0.68 × 10^6 m^3/d (17 to 24 MMcfd) in 1990.

Owing to the increase in methane emissions, methane control systems at these mines had to evolve to keep pace

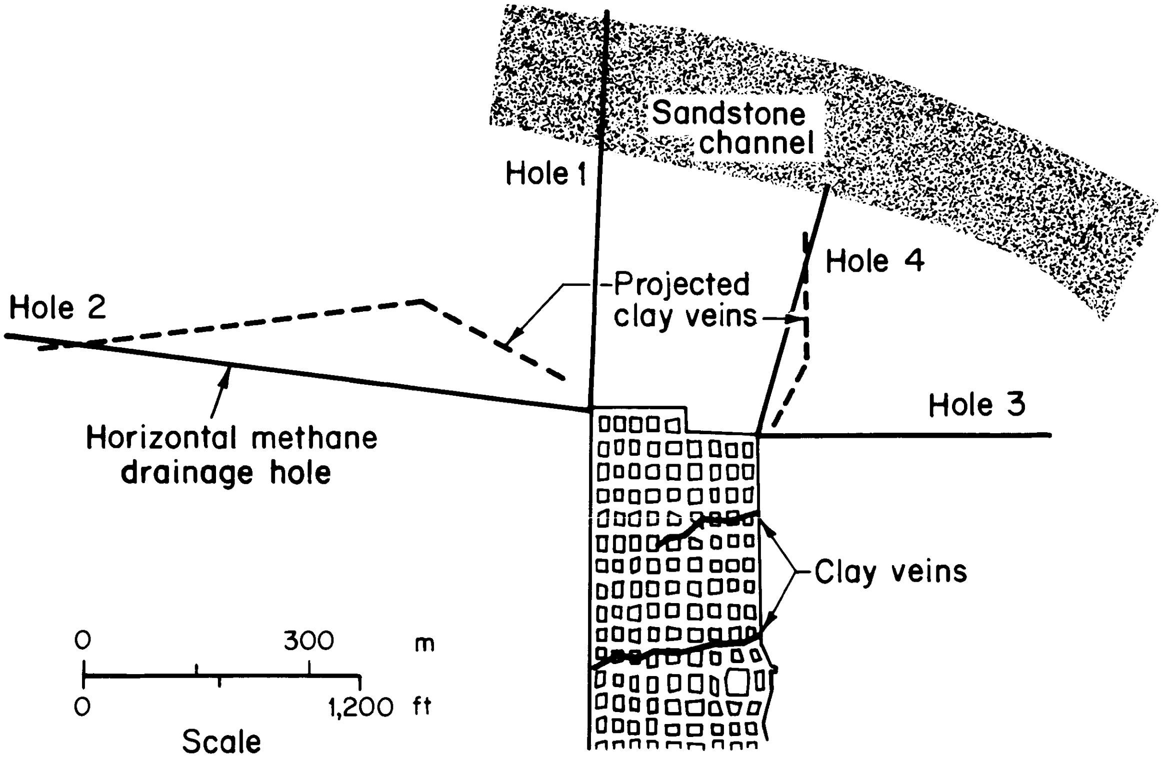


Figure 10.—Plan view of horizontal methane drainage boreholes, Pittsburgh Coalbed, Pennsylvania (*84*).

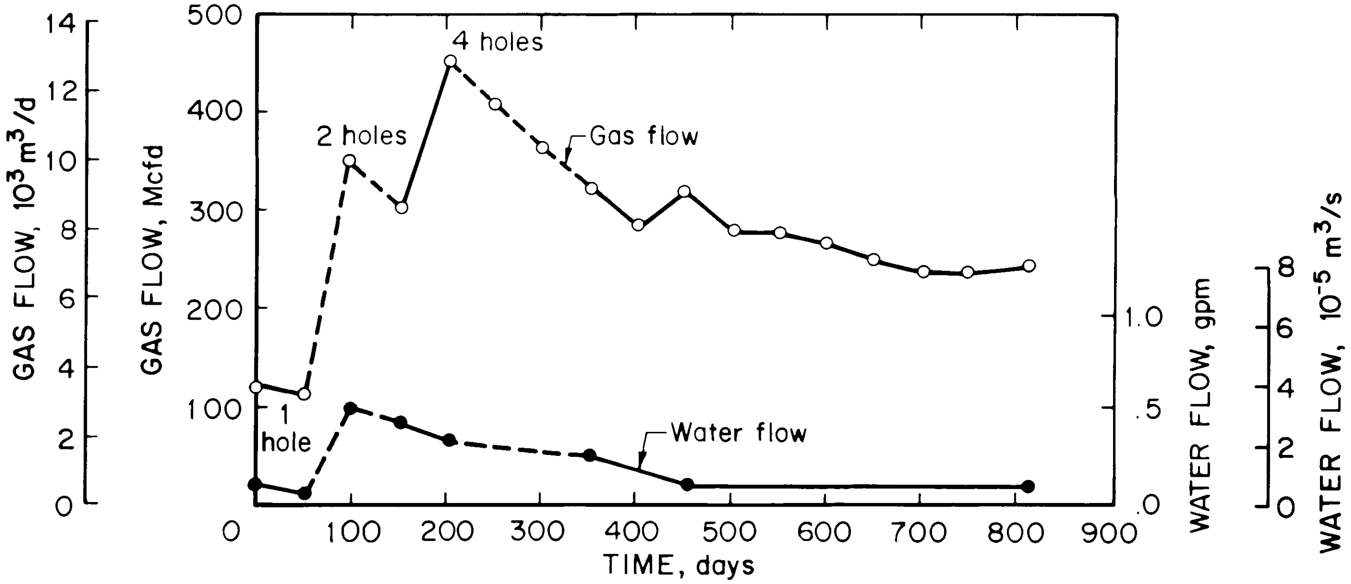


Figure 11.—Daily gas and water flow rates from horizontal methane drainage boreholes, Pittsburgh Coalbed, Pennsylvania (*84*). Dashed portions of curves represent interval when holes were shut in.

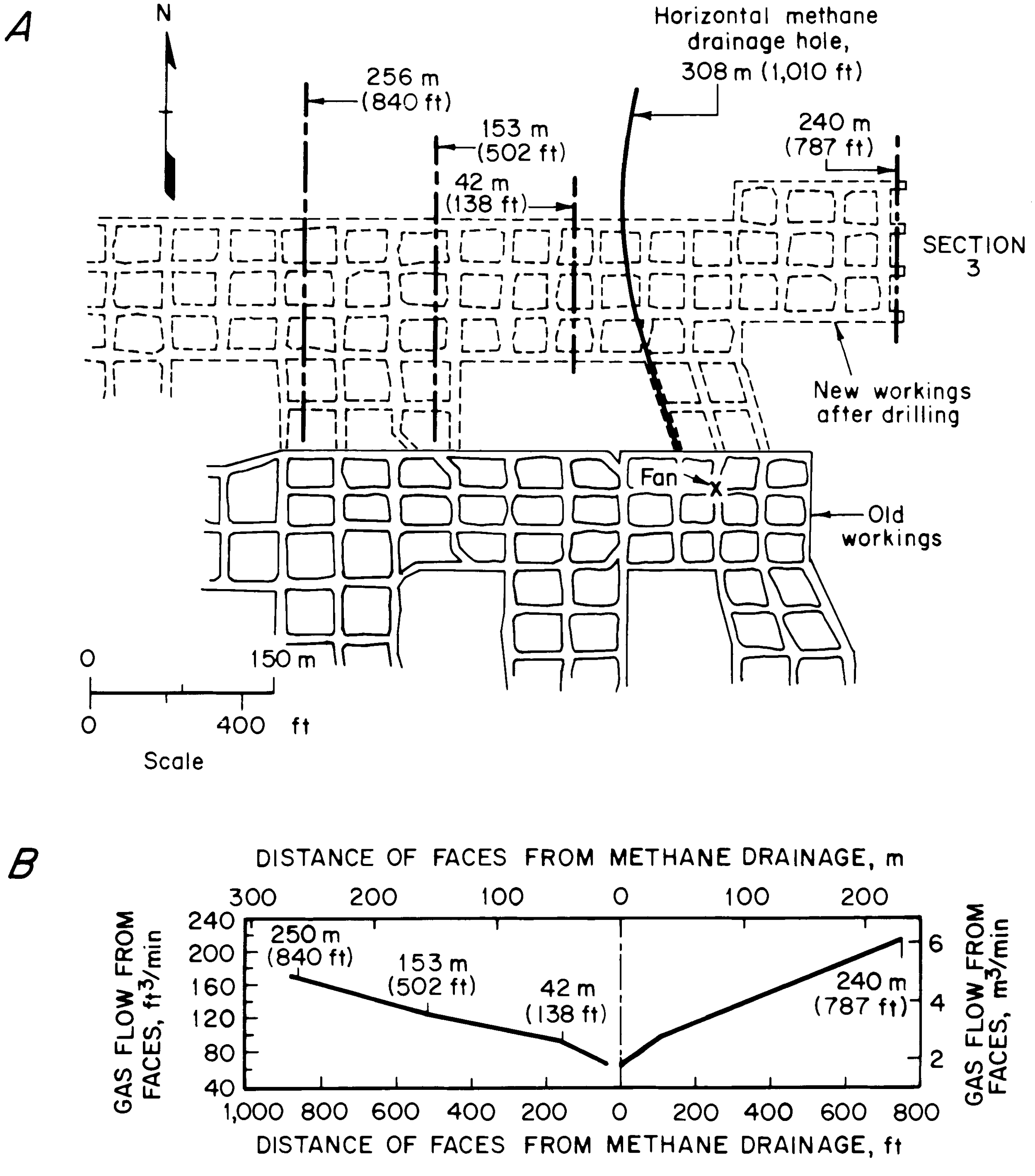


Figure 12.—Plan view of horizontal methane drainage borehole (*A*) and gas flow in relation to mine advance (*B*), Mary Lee Coalbed, Alabama (*81*).

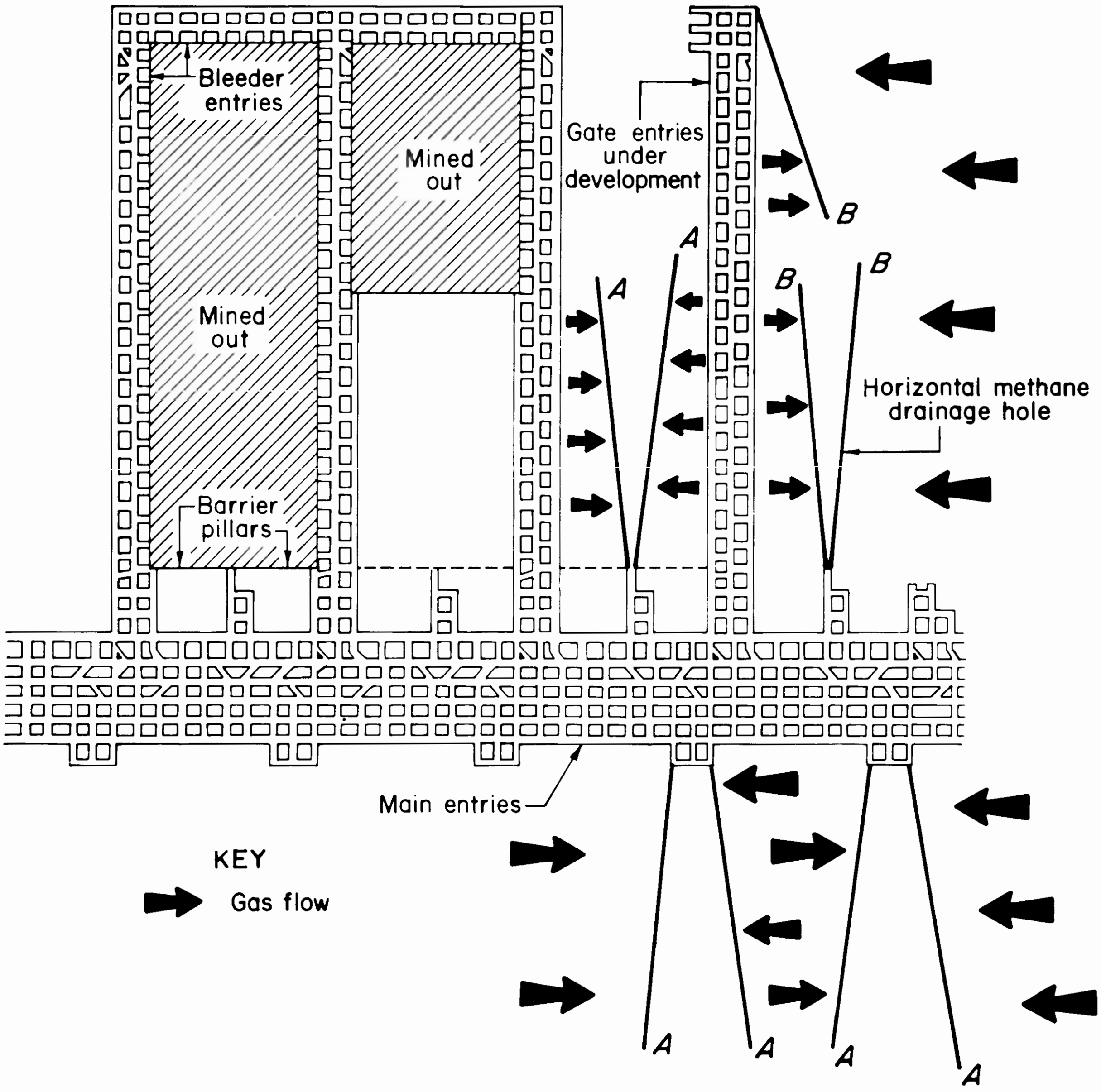


Figure 13.—Schematic plan view of long horizontal boreholes for methane drainage in longwall mining in advance of mining (*A*) and for shielding (*B*).

with the improvements in mining technology. At the lower longwall mining rates, sufficient time was available for the outline panel to effectively drain gas naturally, especially the middle and completion end of the panels, which have the longest time to drain gas. Initially, face emissions were effectively controlled by ventilation, and gob gas was drained using vertical ventholes. However, as productivity increased, these systems gradually reached their limit of effectiveness, and it became necessary to drain gas from the longwall panel prior to mining to help reduce emissions at the face.

In the initial attempts to drain gas from the panel, short, 7.6-cm (3-in) diameter, horizontal boreholes were drilled from the advancing entries on the headgate side, beginning at the completion end of the panel as illustrated in figure 14 (holes *A*). The holes were drilled perpendicular to the rib on 61-m (200-ft) centers to within about 46 m (150 ft) of the opposite side of the panel. Aul and

Ray (2) reported that this drilling program removed a substantial amount of gas from the middle and the completion end of the longwall panel, since the area drilled first was the last to be mined. However, gas-related mining delays were encountered at the startup end of the panel because the horizontal methane drainage boreholes were only on production for a short time prior to mining of the panel.

Three strategies can be employed to overcome this problem. Development sections can be advanced earlier to allow additional time for the headgate holes to drain gas. The horizontal boreholes at the startup end of the panel can be placed closer together to drain more gas in a shorter time. Alternatively, the holes can be drilled from the tailgate side into the developing panel (fig. 14, holes *B*) and/or from advancing entries into the virgin coal beyond the developing panel (fig. 14, holes *C*). Drilling from the tailgate side is the strategy generally adopted by most mine operators (*2, 71*).

The importance of drainage time for reducing the inplace gas content of coal in a developed longwall panel was found by Aul and Ray (*2*) to be significant in the Pocahontas No. 3 Coalbed. Only 30 pct of the gas could be removed from the coal if drainage time was less than 2 months. Horizontal boreholes that produced for 10 months were able to drain 80 pct of the gas from the coal. It was concluded that at least 6 months is required

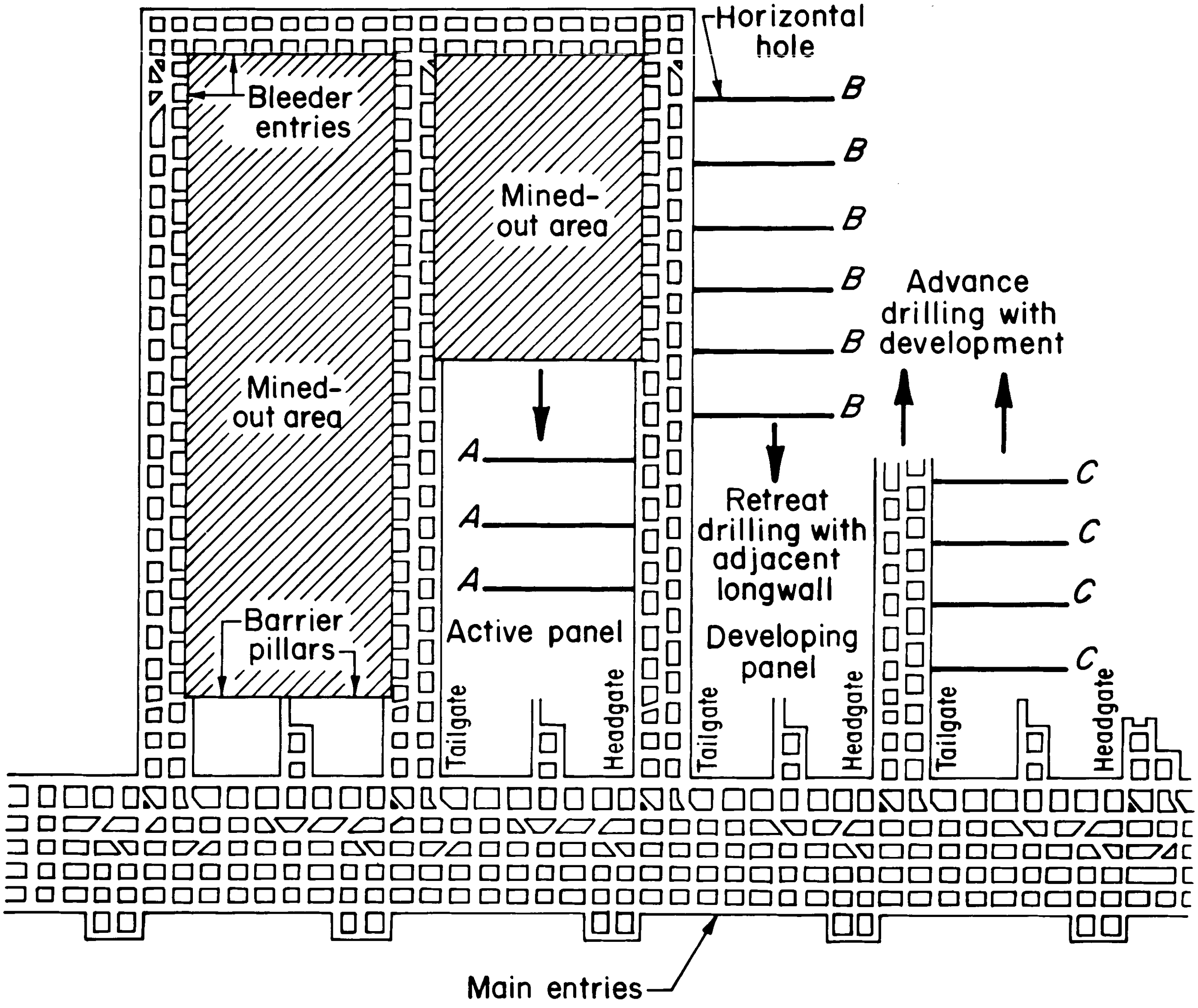


Figure 14.—Schematic plan view of short horizontal boreholes for methane drainage from longwall panels on active panel in advance of face (*A*), on developing panel adjacent to active panel (*B*), and from advancing development entries (*C*).

to drain a sufficient volume of gas from the Pocahontas No. 3 Coalbed with the holes drilled on 61-m (200-ft) centers. Horizontal boreholes that were drilled from the tailgate side increased the time available for drainage to 12 months and resulted in significantly higher gas production rates because the holes were drilled into the virgin coal away from mining (fig. 14, holes *C*).

Mining conditions in the Pocahontas No. 3 Coalbed were significantly improved as the result of the horizontal methane drainage program (*2*). Ventilation air volume at the longwall face was reduced from a high of 57 m^3/s (120,000 cfm) to only 12 m^3/s (25,000 cfm). The tailgate methane drainage boreholes also benefit the subsequent development entries for the next panel by reducing in-place gas volume in that area.

Similar conclusions were reached by Mills and Stevenson (*71*) from their experience with mining operations in the Blue Creek Coalbed, Alabama. Short horizontal methane drainage boreholes drilled from the tailgate entries (fig. 14, holes *B* and *C*) were preferred because drainage time from the panel was maximized and the holes provided relief during drivage of the development entries. In one panel, 43 pct of the in-place gas was removed by the short horizontal boreholes in advance of mining. In a comparison of two longwall panels cited by Mills and Stevenson (*71*), downtime was reduced from 146 h on one panel without horizontal methane drainage boreholes to no downtime on the adjacent panel that utilized the holes.

Aul and Ray (*2*) reported that in 1990, 28.3 × 10^6 m^3 (1 Bcf) of methane was removed from the Pocahontas No. 3 Coalbed, Virginia, using underground horizontal methane drainage boreholes. Mills and Stevenson (*71*) reported that approximately 12 pct of the 0.99 to 1.1 × 10^6 m^3/d (35 to 40 MMcfd) of commercial gas production at their mining operation in the Mary Lee-Blue Creek Coalbed, Alabama, is produced from horizontal methane drainage boreholes, while about 80 pct is from vertical gob gas ventholes and 8 pct from stimulated vertical wells. These high volumes of methane that have been captured and removed from the mine workings before entering the mine atmosphere are very significant since they will never have to be confronted underground. This has resulted in significant benefits, in both increased mining safety and productivity.

The optimization of the horizontal methane drainage system in the Pocahontas No. 3 Coalbed (as well as most other mines) includes the use of an underground gas pipeline (*2*). The pipeline gathers the gas from the individual holes and transports it to the surface through a vertical borehole. To aid the flow of gas through the pipeline, it is necessary to use exhausters on the surface to create a negative pressure on the system.

Underground pipeline safety is critical, especially protection from a rupture that could dump large volumes of methane into the mine atmosphere. A fail-safe system developed by the U.S. Bureau of Mines (*45, 84*) to shut in the individual holes and the pipeline has been utilized by most mine operators in the United States. The system uses a thin-walled, small-diameter (1.9-cm [0.75-in]) polyvinyl chloride (PVC) pipe that is either strapped to the top of the pipeline or suspended directly above it, along its entire length (fig. 15). The PVC pipe is connected to

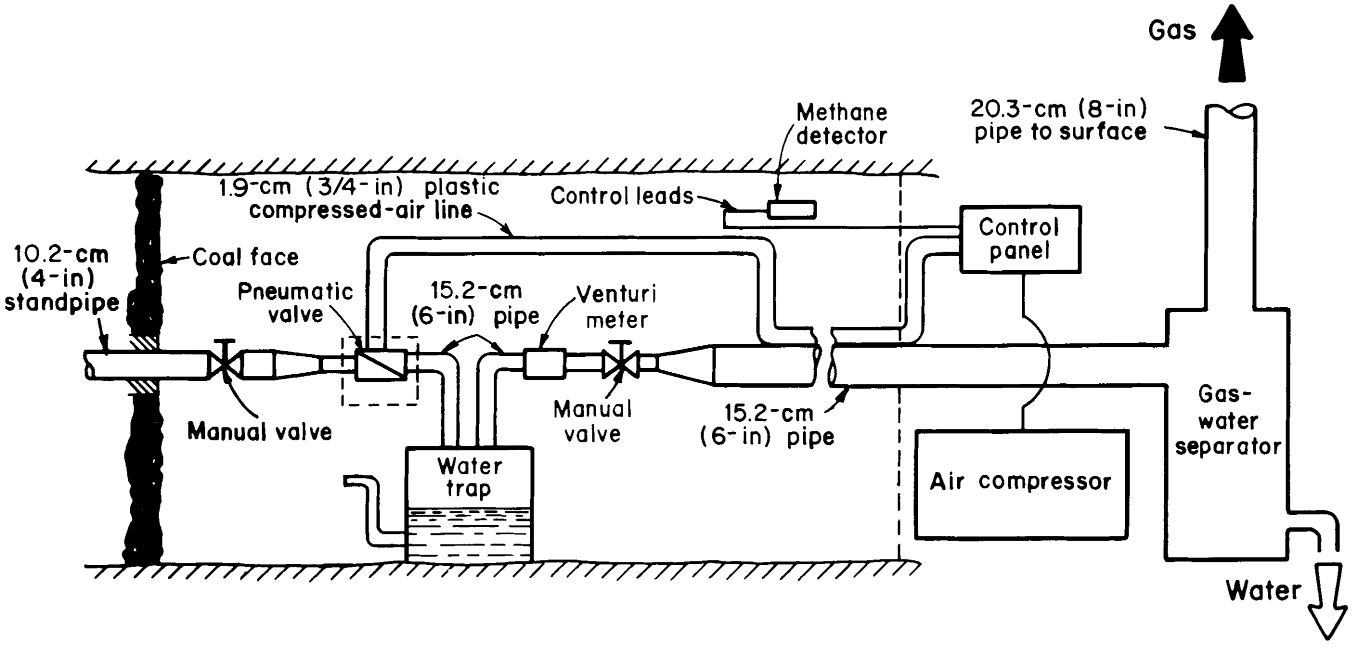


Figure 15.—Schematic section view of typical horizontal methane drainage borehole gas collection system with fail-safe pneumatic shut off valve (*84*).

pneumatic valves which are installed on each hole at completion. The valves are spring-loaded and held open by air pressure supplied by a small air compressor. If a roof fall hits the pipeline, it will break the small-diameter pipe on top, releasing the pressure holding the pneumatic valves open, which shuts in the holes.

The system also includes methane sensors spaced along the pipeline, typically every 152 to 305 m (500 to 1,000 ft), to provide additional protection. The sensors are wired into a control panel that can activate the pneumatic valves by venting the compressed air in the system. The system can be designed so that at any predetermined methane concentration (typically 1 pct), at any of the sensors, the holes will be shut in. The system is configured so that if any sensor stops functioning, or if the electrical line to the sensor is broken, the holes will also automatically be shut in.

Horizontal Boreholes - From Shaft Bottoms

One way to drain gas in advance of mining, perhaps even before development mining has started, is to drill long horizontal boreholes into the coalbed to be mined from the bottom of a shaft or slope. This application would, of course, require the construction of one or more shafts or a slope prior to their actual need in the mining operation. The expenditure of funds for such shaft sinking years in advance, at projected locations where the shafts may ultimately not be needed, is a financial risk that most coal companies will not accept. There is, however, the possibility that the cost of sinking a shaft will be less if the shaft is put in place sooner; also, the sale of the produced gas would to some extent offset the cost of sinking the shaft early.

Two experimental installations of this type were completed in the early and mid-1970's at a West Virginia mine operating in the Pittsburgh Coalbed. The first installation (fig. 16) was a large borehole (1.2-m [4-ft] diameter casing), with a 4.3-m (14-ft) diameter room in the coalbed (*30-31*). From the bottom of this simulated shaft, seven horizontal boreholes ranging in length from 152 to 259 m (500 to 850 ft) were drilled into the coalbed (fig. 17). In the 8 years this installation was on production, 33.4 × 10^6 m^3 (1,178 MMcf) of gas was drained from the coalbed, 15.2 × 10^6 m^3 (538 MMcf) of which was sold to a gas pipeline.

In a second experimental installation at this same mine, a 5.5-m (18-ft) diameter shaft was used to drill five long horizontal boreholes to depths of 204 to 648 m (670 to 2,126 ft) into the Pittsburgh Coalbed (*29*). This installation was on production for 3.7 years prior to interception by mining; and during that time 25.2 × 10^6 m^3 (889 MMcf) of gas was drained from the coalbed, 3.4 × 10^6 m^3 (121 MMcf) of which was sold. Periodic underground ventilation surveys revealed that methane emissions at the face decreased 70 pct as the installation was approached by mining (fig. 18) (*14*).

A final consideration relative to horizontal methane drainage boreholes is their safe interception by mining. Since the holes are a conduit for gas flow, mining through a hole that is still producing gas could be a hazard. Depending on site-specific circumstances and regulatory requirements, the holes may have to be plugged prior to interception (*1, 74*).

Horizontal Boreholes - Water Infusion

Horizontal boreholes can be used for methane control in other ways in addition to the drainage of gas. They can be used to block and/or divert the flow of gas by pumping water into the coalbed to form a barrier to gas flow. This process, generally referred to as water infusion, was developed in South Wales in the early 1940's (*48*). Water infusion using short horizontal boreholes was actually first used to control dust generation during coal cutting by wetting the coal ahead of the face just prior to mining. It was also observed that the process of infusing the water at the face reduced the rate of gas emissions (*37, 47*).

In water-saturated coalbeds, the flow of methane is controlled by a reduction in pressure in the cleat system that results from dewatering. Dewatering and associated pressure reduction are natural consequences of mining into a coalbed. Water infusion takes advantage of the reservoir properties of coal in a way directly opposed to that of the various methane drainage techniques. Water infusion puts water back into the coalbed to saturate the cleat, thereby hindering the flow of gas in the infused area.

A typical configuration for a water infusion hole is shown in figure 19. To form an effective water block at the face of a set of advancing entries, it is necessary to drill several horizontal boreholes, so that the water fronts from each infusion hole overlap. The distance between holes is dependent upon site-specific conditions, including cleat orientation (*10*). If the coalbed has a dominant permeability direction due to a well-developed face cleat and less developed butt cleat, the infusion water front will be an ellipse. When the advancing entries are perpendicular to the face cleat, as shown in figure 20, the horizontal infusion holes can be spaced farther apart. If the entries are advancing parallel to the face cleat, the holes must be spaced closer together to form a complete block. If a complete block is not formed, gas can still enter the face area (fig. 21).

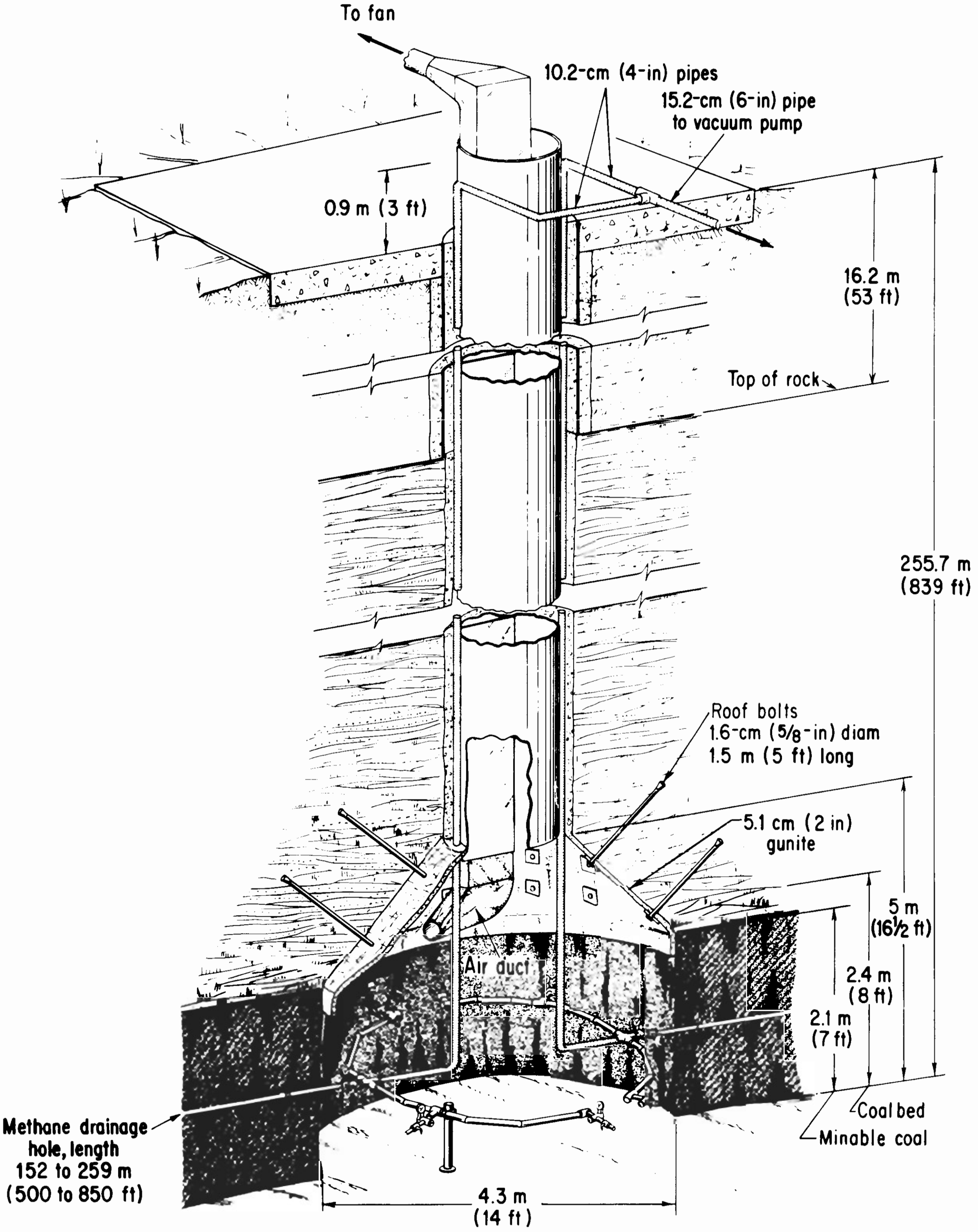


Figure 16.—Schematic section view of large-diameter vertical borehole for drilling horizontal methane drainage boreholes, Pittsburgh Coalbed, West Virginia (30).

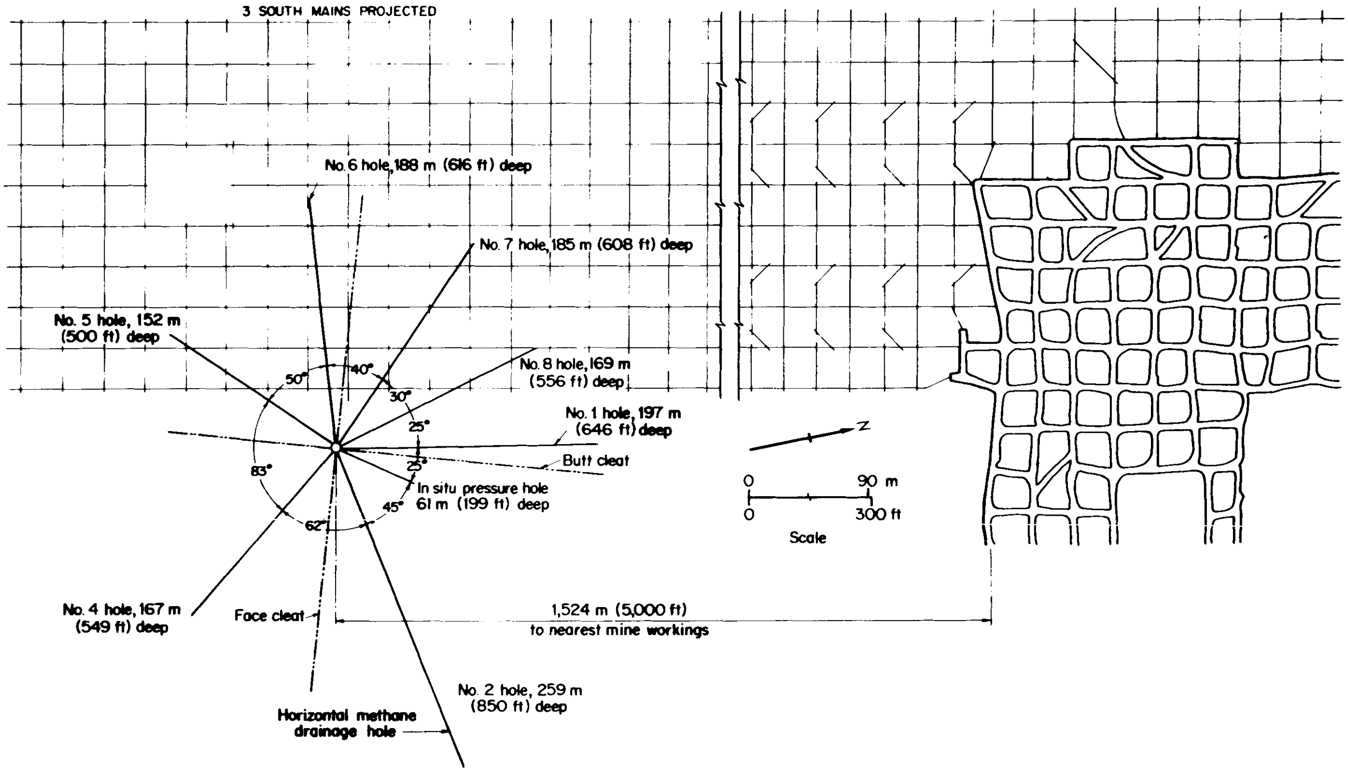


Figure 17.—Plan view of horizontal methane drainage boreholes drilled from large-diameter vertical borehole, Pittsburgh Coalbed, West Virginia (*30*). (There is no hole 3.)

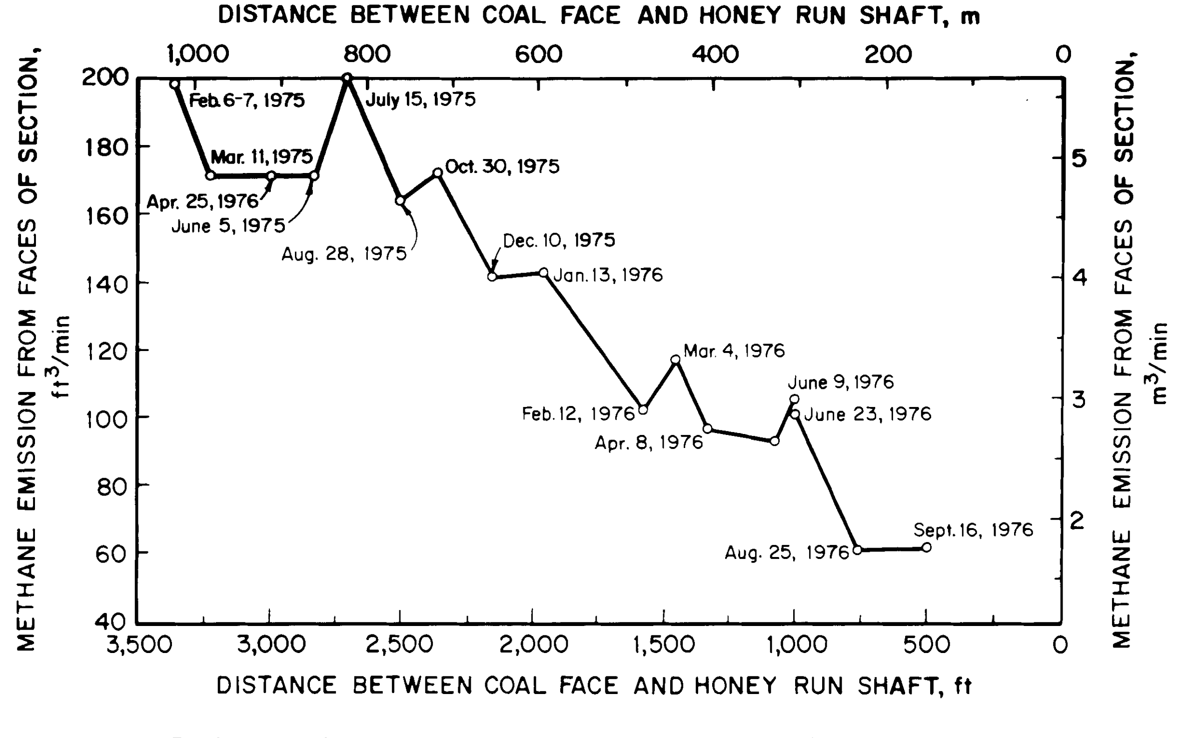


Figure 18.—Decline in methane emissions at the face as mining approached horizontal methane drainage boreholes drilled from a shaft bottom, Pittsburgh Coalbed, West Virginia (*91*).

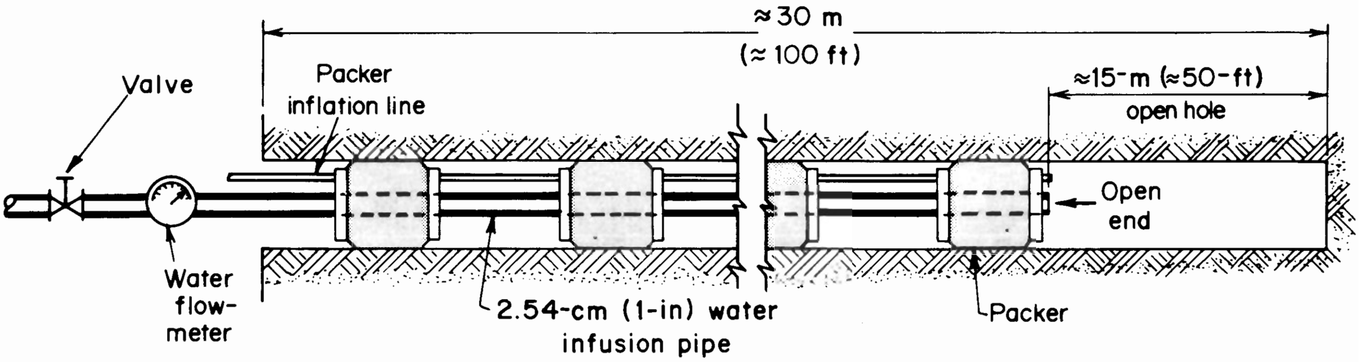


Figure 19.—Schematic section view of typical water infusion horizontal borehole completion (*11*).

Centinbas (*11*) evaluated the effectiveness of water infusion holes for methane control. Four 7.6-cm (3-in) diameter horizontal boreholes were drilled from a six-entry section into the Pittsburgh Coalbed to depths of 16.8 to 38.7 m (55 to 127 ft). The infusion ends of the holes were approximately 61 m (200 ft) apart. Water infusion rates were generally 3.2×10^{-4} to 6.3×10^{-4} m^3/s (5 to 10 gpm). Infusion was continued until water appeared at the face and ribs. The time for water to reach the workings ranged from 7.5 h for the 16.8-m (55-ft) hole to 42 h for a 38.7-m (127-ft) hole. Water infusion reduced the flow of methane at the face by 79 pct and increased the flow of methane from the ribs by 24 pct. This confirmed that the flow of gas was blocked and diverted from the active face.

Vertical Boreholes Into the Mine Roof

It is common to have methane bleeders into the workings of the mined coalbed from the overlying or underlying strata. A unique method of methane drainage designed to address this problem was successfully tested in the Pocahontas No. 3 Coalbed, Virginia (*32*). On initial development of a new mine, high methane emissions were causing methane levels to approach 1 pct. In this area of the mine, the Pocahontas No. 3 Coalbed was separated from the overlying, gassy Pocahontas No. 4 Coalbed by 2.7 to 4 m (9 to 13 ft) of sandstone.

Shortly after an entry was advanced, the sandstone roof would fracture, releasing methane into the entry, apparently from the overlying Pocahontas No. 4 Coalbed. To alleviate the problem, a series of small-diameter (4.1-cm [1.6-in]) methane drainage boreholes were drilled up through the overlying coalbed from the mine (fig. 22). After a series of test holes were drilled and evaluated, it was determined that holes should be spaced a maximum 15 m (50 ft) apart for optimum drainage. The holes were drilled along the center entries to drain gas from the strata

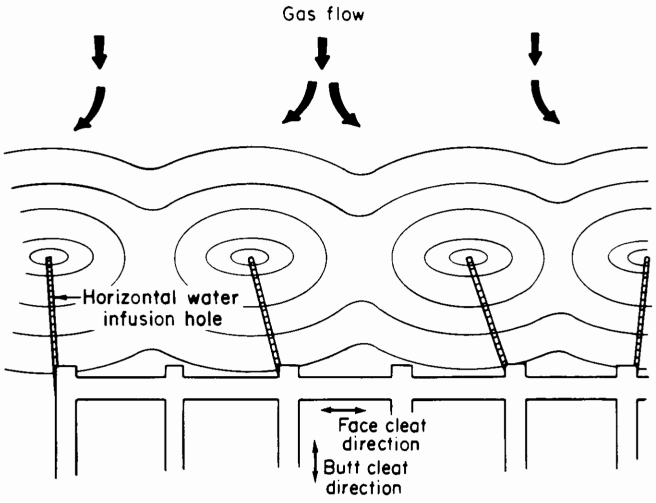


Figure 20.—Schematic plan view of elliptical water fronts developed from water infusion of coalbed with face cleat perpendicular to section advance (*10*).

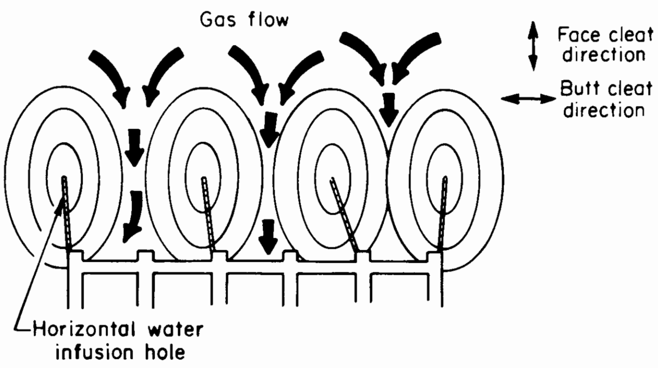


Figure 21.—Schematic plan view of elliptical water fronts developed from incomplete water infusion of coalbed with face cleat parallel to section advance (*10*).

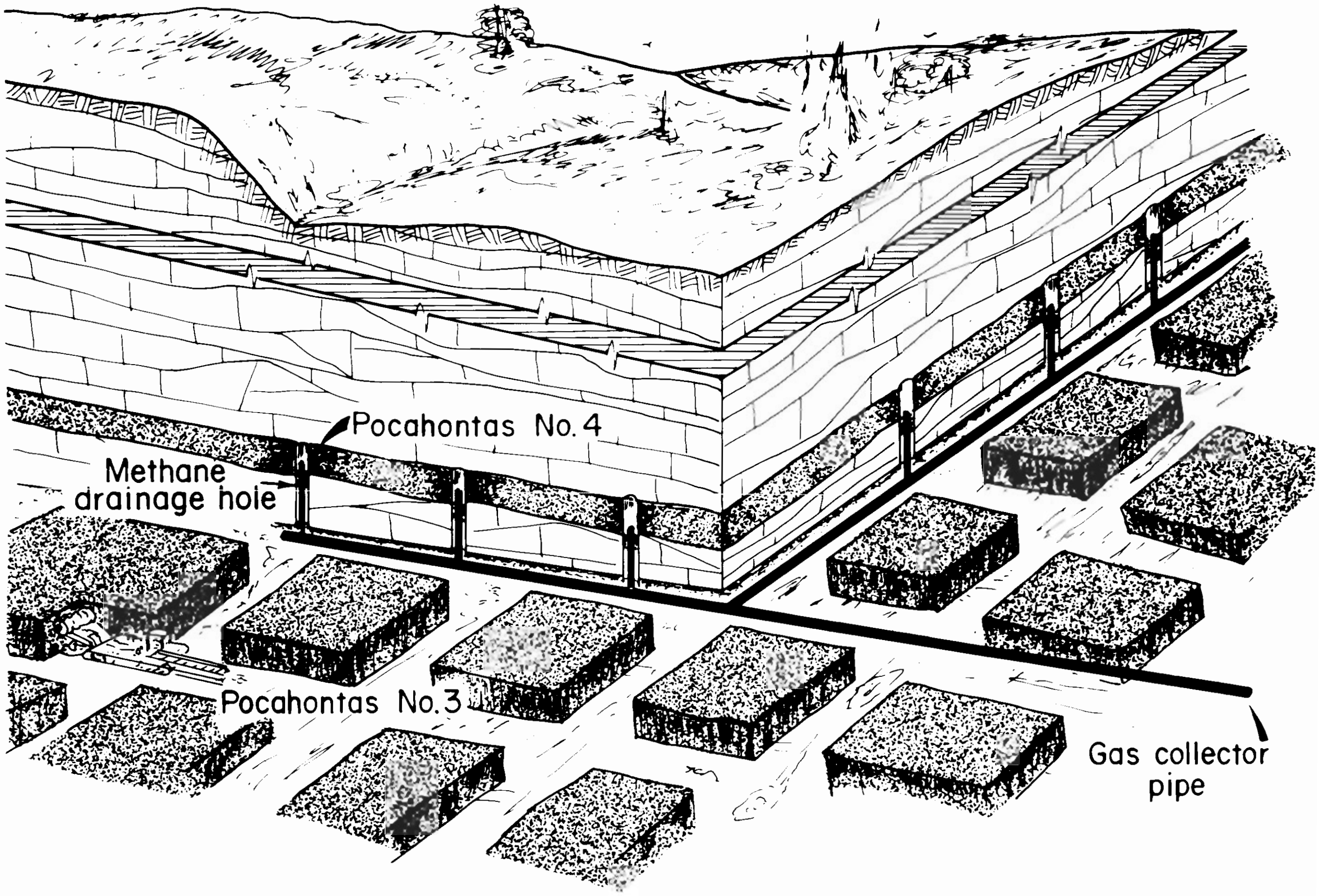


Figure 22.—Perspective view of vertical in-mine boreholes for methane drainage of overlying Pocahontas No. 4 Coalbed from mined Pocahontas No. 3 Coalbed, Virginia (*32*).

directly overlying the new development. Additional holes were drilled along the outside entries to intercept gas flowing from the surrounding virgin area. Because of the high methane levels in the returns, the drainage boreholes were connected to a pipeline to the surface.

In the first month of operation, the flow rate from these holes averaged 4.2×10^3 m^3/d (150 Mcfd), and methane emissions into the mine were reduced by 47 pct. Over the 96-day life of the 37 holes, 0.34×10^6 m^3 (12 MMcf) of methane was drained from the overlying Pocahontas No. 4 Coalbed. As mining progressed away from this area, methane emissions from the overlying strata decreased, and additional drainage boreholes were not required. This was probably due to both an increase in the interval between the Pocahontas Nos. 3 and 4 Coalbeds and a thinning of the Pocahontas No. 4 Coalbed.

Cross-Measure Boreholes

Longwall mining has been the most common coal mining technique outside the United States for many years. It has increasingly become the method of choice in the United States because of the high coal production rates longwalls can achieve (*3*). Since the total extraction of a large block of coal leaves no support to hold up the roof, the overlying strata cave into the mine void (fig. 5), in many cases releasing large volumes of gas into the mine atmosphere. Additional gas may also enter the mine from fractures that develop in the floor strata.

A common practice in Europe is to drill methane drainage holes underground into the strata that will cave and fracture above the extracted longwall panel. Cross-measure boreholes are preferred owing to the greater depth of the mines, which makes the drilling of gob gas ventholes from the surface more expensive. Also, owing to the long history of mining and habitation on the surface, a substantial portion of the surface is inaccessible for drilling sites.

European cross-measure boreholes are drilled at an angle over the longwall panel and oriented away from the advancing face so that they drain gas from the entire length of the relaxed zone on the return air side of the panel (fig. 23). Cervik (*9*) reported that in Poland holes are drilled over protective pillars at the ends of the panel, in addition to traditional cross-measure boreholes, to drain gas from the gob. It is general practice for the gas to be piped to the surface for utilization by the mines or other industries.

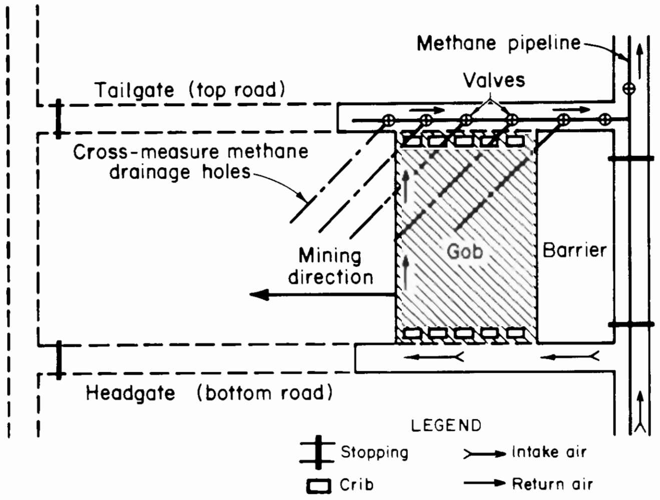


Figure 23.—Plan view of cross-measure boreholes on advancing European longwall (*9*).

The first experimental use of cross-measure boreholes on a retreating longwall panel was successfully demonstrated in the United States in the Lower Kittanning Coalbed, Pennsylvania (*89*). Some modifications to the European technology were required owing to the predominance of multiple-entry retreat longwall mining in the United States. Since development entries are driven first to outline the block of coal for the longwall, sufficient time and space are generally available to drill the cross-measure boreholes prior to the start of the longwall. With the multiple-entry system, it is also possible to drill the holes and place the pipeline in an entry away from the panel margin (fig. 24). This is an advantage because the holes and pipeline are protected from the caved area along the margin of the panel. One disadvantage is that the holes must be drilled a greater length to reach the gob.

In the original experimental programs (*8*, *89*), the 4.8-cm (1.9-in) diameter cross-measure boreholes were oriented toward the longwall face in an attempt to capture gas as early as possible from the gob near the face (fig. 24, panel A, holes 1-12). The experimental work, however, showed that most holes did not produce gas until the face passed 23 to 30 m (75 to 100 ft) beyond the end of the hole, but before the face reached the drilling location. It was also found that an exhauster had to be used on the vertical borehole to the surface to aid the flow of gas from the cross-measure boreholes to which it was connected. Detailed engineering drawings of a typical cross-measure methane drainage system are shown in figures 25-26.

In subsequent work at the same mine, Garcia and Cervik (*33*) and Goodman and Cervik (*34*) confirmed that it was not necessary to drill the holes at an angle towards the face (fig. 24, panel B, holes 1-13). Their analysis indicated that most of the gas production came from near the pillar line, and the extra length of hole beyond contributed little gas. This may be due to an increase in fracture permeability near the pillar line, where the overburden strata are partly supported by the surrounding pillars, thus preventing the quick recompaction of the gob in that area (*18*). Also, the ends of the holes beyond the pillar line may be sheared off as the longwall progressively mines under the holes. For this last reason, the Europeans commonly drill the cross-measure holes after the longwall face has passed a particular location.

Methane flow rates from the refined cross-measure boreholes generally averaged from 0.14 to 0.24 m^3/s (300 to 500 cfm) through the central part of the panels; they were slightly less at the beginning and greater at the completion end. Approximately 70 pct of the methane liberated during the mining of the panels was captured by the cross-measure boreholes and was transported out of the mine by a pipeline. Final recommendations for cross-measure borehole spacing at this mine in the Lower Kittanning Coalbed, Pennsylvania, were 61 m (200 ft), except on the first 183 m (600 ft) of the panel, where the spacing was 30 m (100 ft). The holes are spaced closer at the beginning of the panel to capture the large quantities of methane that are released when the initial large roof fall occurs.

Horizontal Boreholes Drilled to Other Horizons

In many of the longwall coal mines in Japan, coalbeds are steeply dipping and are at depths of about 700 m (2,300 ft). As mining depth has increased, methane emissions have also increased. It has become common practice

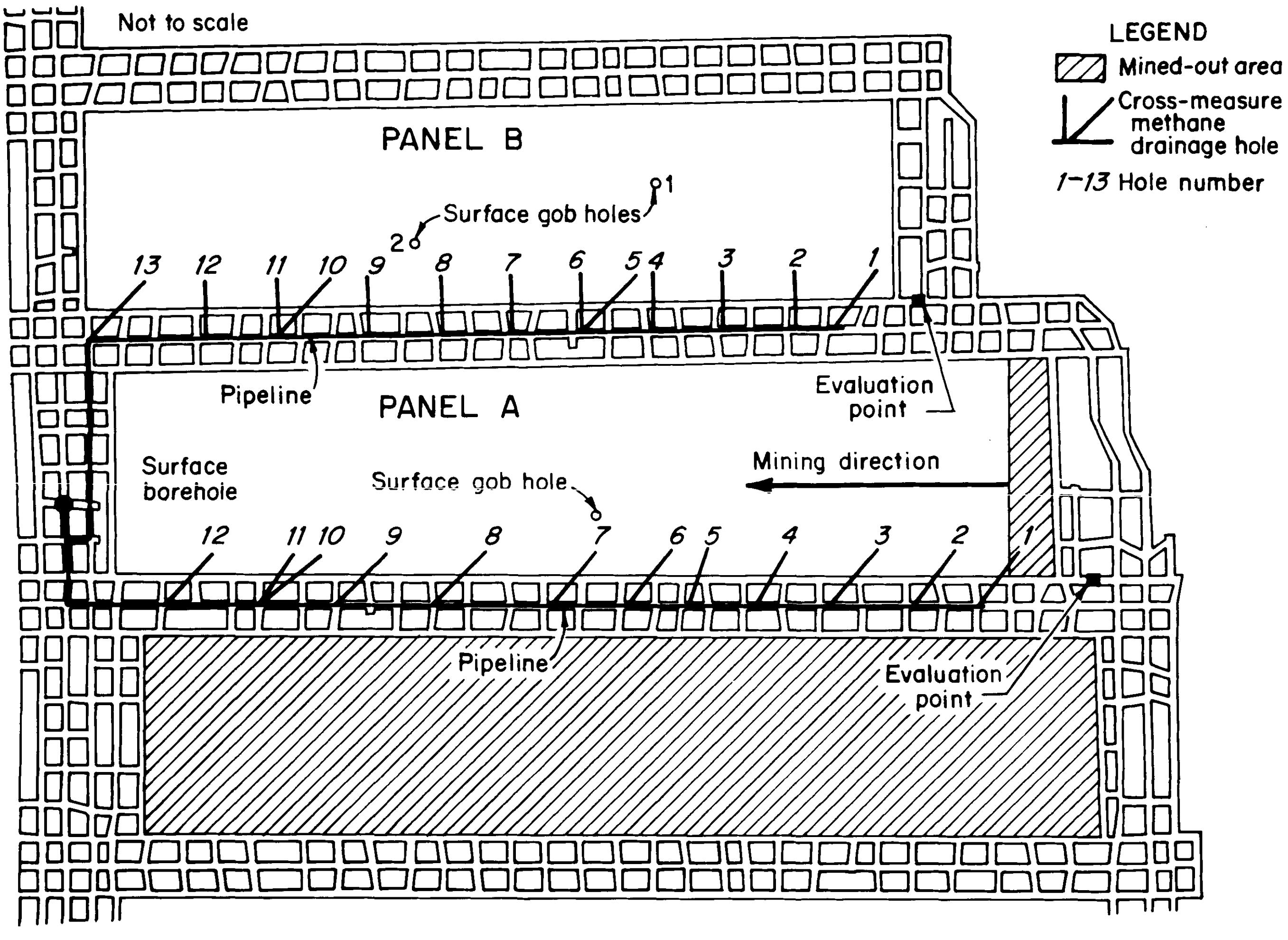


Figure 24.—Plan view of cross-measure boreholes on retreating U.S. longwall (34).

to predrain gas from both the coalbed to be mined and the surrounding strata, including other coalbeds, using a variation of the cross-measure technique. To reach the steeply dipping coalbeds, "roadways" are first driven along strike in the rock below the coalbed to be mined. The roadways are driven in rock instead of the coalbed itself for enhanced stability of the main haulage. The initial premining methane drainage is conducted in a manner similar to the cross-measure borehole technique described previously, by drilling holes at an angle up into the virgin coalbed (fig. 27). Methane drainage boreholes are drilled about 10 to 15 m (33 to 49 ft) apart in the coalbed and are allowed to drain gas for 6 to 12 months prior to the drivage of crosscuts to the coalbed.

Crosscuts are driven perpendicular to the main roadway to intercept the coalbed for the development of the longwall panels. Additional cross-measure-type predrainage boreholes are drilled into the coalbed from "boring stations" along the crosscuts (fig. 28). Once the coalbed is intercepted by the crosscuts, gate roads are driven along strike to connect adjacent crosscuts. A third series of horizontal boreholes drilled into the coalbed to be mined may be necessary to further reduce methane emissions in advance of the drivage and in the longwall block in general (fig. 29). Finally, the crosscuts or adjacent gate roads may be used to drill the more traditional cross-measure boreholes into the gob for postmining methane drainage.

A unique combination of the cross-measure borehole technique combined with long horizontal boreholes is reported by Ohga and Higuchi (*73*). At one mine in Japan, the coalbeds are relatively flatlying, but the overlying coalbed was reported to be of low permeability, which

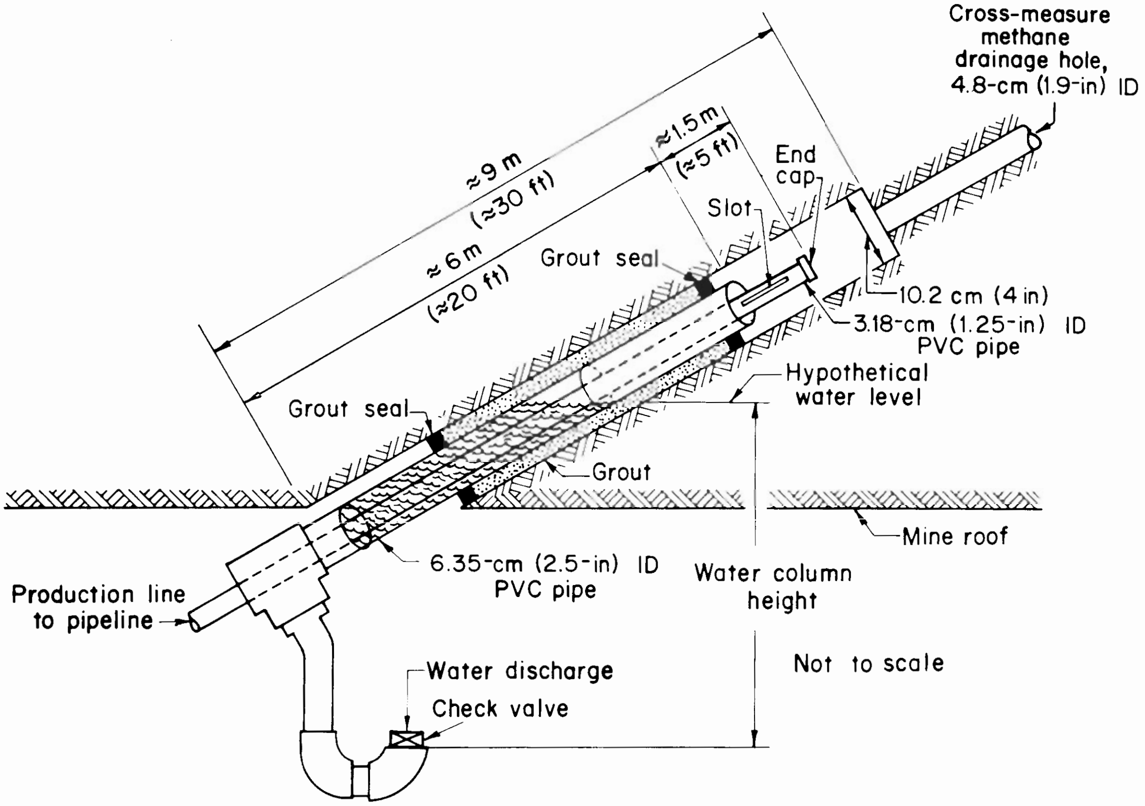


Figure 25.—Schematic section view of a typical cross-measure borehole completion with gas-water separator (*33*).

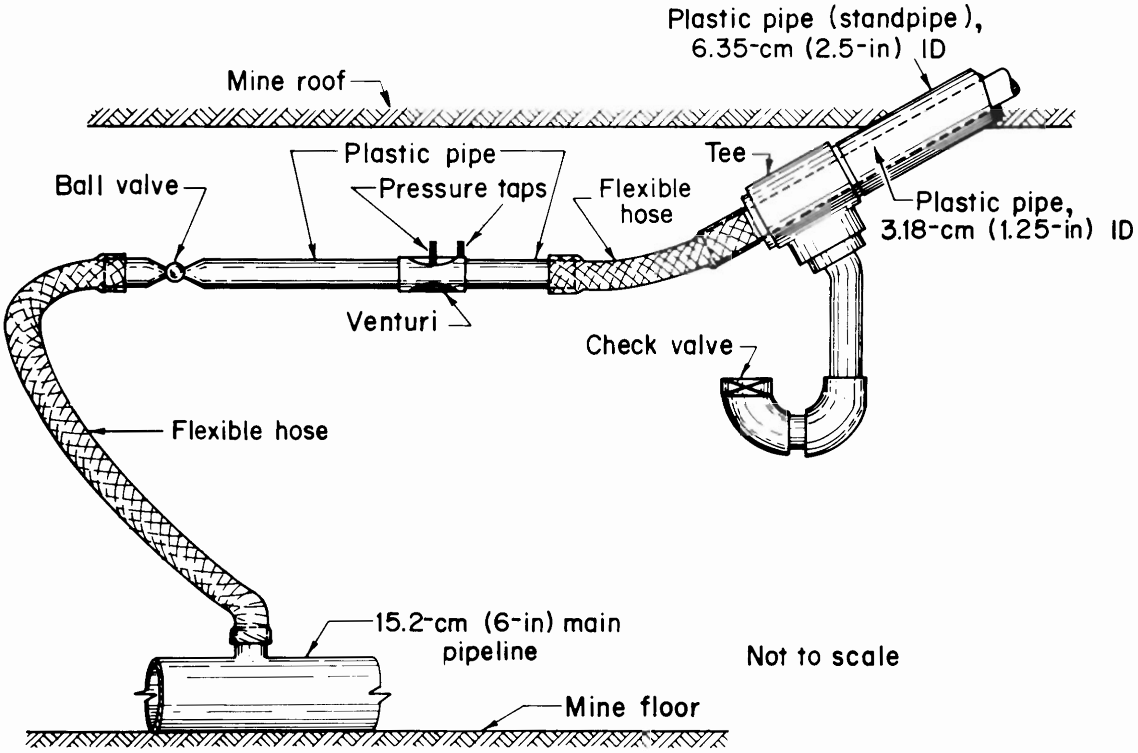


Figure 26.—Schematic section view of a typical gas-gathering system for cross-measure boreholes (*33*).

restricted the flow of gas for the typical premining drainage. In this case, holes were drilled at an angle into the strata below the overlying gassy coalbed toward the face area from the completion end of the panel (fig. 30). The holes were then drilled parallel to the strata for 500 to 700 m (1,640 to 2,300 ft) toward the approaching face location. As the strata relaxed above the caved zone, sufficient fracturing apparently developed to allow the long horizontal boreholes to drain significant volumes of gas. More gas was drained by this technique than by the previously attempted premining drainage using multiple, short, cross-measure-type boreholes. In addition to the increased gas production, a 45-pct reduction in manpower and 60-pct reduction in drilling cost for the long horizontal boreholes were realized.

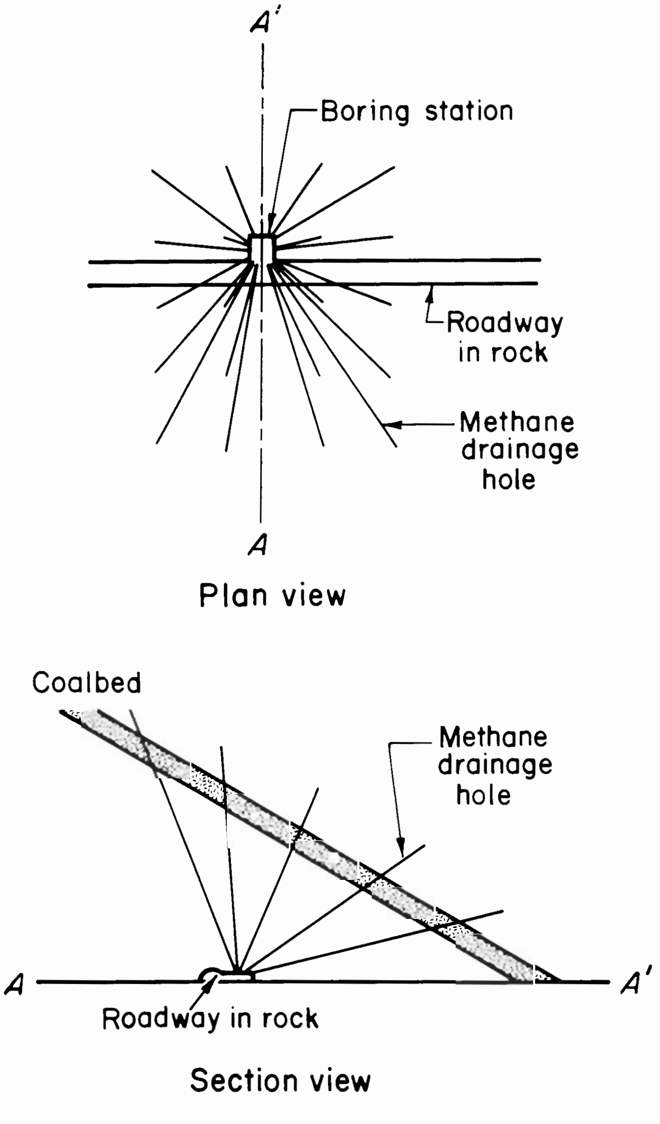


Figure 27.—Schematic plan and section views of methane drainage boreholes drilled from roadway driven along strike in rock below mined coalbed, Japan (modified from Ohga and Higuchi (73)).

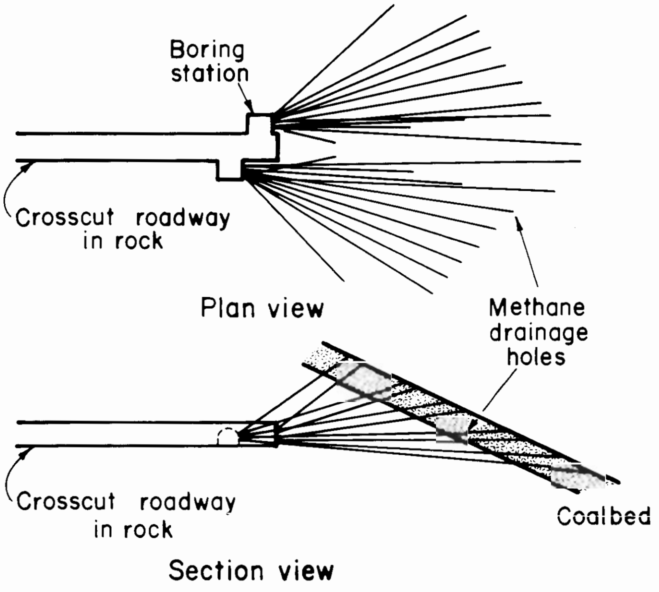


Figure 28.—Schematic plan and section views of methane drainage boreholes drilled from crosscut driven perpendicular to strike to intercept coalbed, Japan (modified from Ohga and Higuchi (73)).

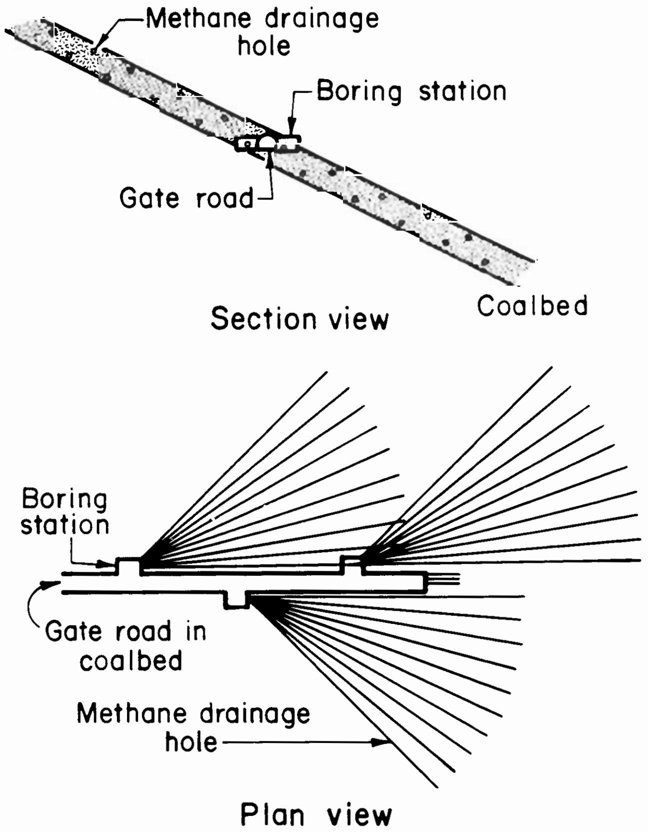


Figure 29.—Schematic plan and section views of methane drainage boreholes drilled from gate roads driven along strike in coalbed to outline longwall panels, Japan (modified from Ohga and Higuchi (73)).

An experimental application of this concept in the United States included the directional drilling of nine horizontal boreholes to strata above the Lower Kittanning Coalbed at a Pennsylvania mine. A total of 4,877 m (16,000 ft) of hole was drilled over two longwall panels, with the longest hole extending 771 m (2,530 ft). Preliminary evaluation of this application was encouraging, with the horizontal in-mine gob ventilation boreholes effectively shielding the mine ventilation system from the inflow of gob gas (*54*).

In addition to gas entering a longwall mining operation from overlying strata, underlying strata can contribute significant volumes of gas to the mine atmosphere. As a longwall face advances, relaxation of thc floor strata can open joints or create new fractures to connect underlying gas-bearing strata to the mine. In Australia, the cross-measure concept combined with horizontal drilling has been used to drain gas from strata underlying a longwall panel. A hole was drilled at a trajectory of -11° from the workings in the Bulli Coalbed (fig. 31) to the 1-m (3.3 ft) thick Balogownie Coalbed, lying 14 m (46 ft) below. The hole was then drilled 829 m (2,720 ft) in the coalbed. A second "branch" hole was drilled 723 m (2,372 ft) into the coalbed. At the time of the report by Hungerford (*40*), production data were not yet available.

A common methane control and gas drainage practice in longwall mines outside the United States is the sealing of the gob with walls across the entries. By sealing the gob, the flow of gas from the old workings to the active mining area can be minimized. However, since the buildup of gas pressure behind the seals can eventually force gas into the active workings, the gas must be drained using pipes installed through the seals (fig. 32) (*9*). This gas is then removed from the mine by pipeline.

SURFACE METHANE DRAINAGE

Methane drainage techniques undertaken from the surface have the distinct advantage of not being conducted in the restrictive underground environment. They can be utilized far in advance of mining for maximum gas reduction (and commercial production) before mining, or they can be used during and after mining to drain gas from longwall gobs. However, methane drainage wells drilled from the surface are not without limitations. A primary requirement for these technologies is a surface site from which the drilling operations can be conducted. Topography, lakes, rivers, wetlands, cultural development, adverse ownership, archeological sites, and environmental and oil and gas regulations are factors that can hinder the development of surface sites. Gas production from most in-mine systems begins quickly because the mine provides an efficient pressure sink to initiate the desorption of gas. Wells drilled from the surface into virgin, water-saturated

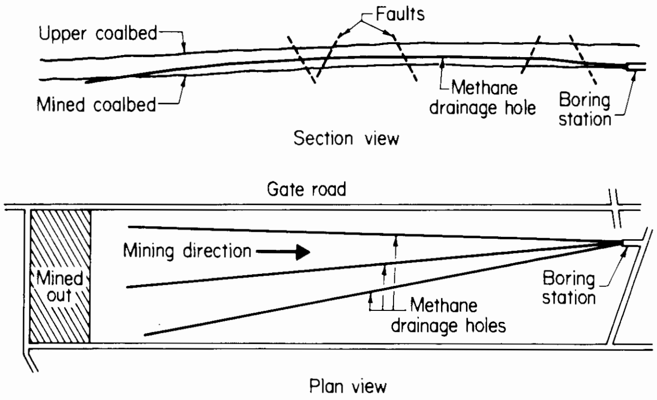


Figure 30.—Plan and section views of long horizontal methane drainage borehole drilled in strata above longwall panel, Japan (modified from Ohga and Higuchi (*73*)).

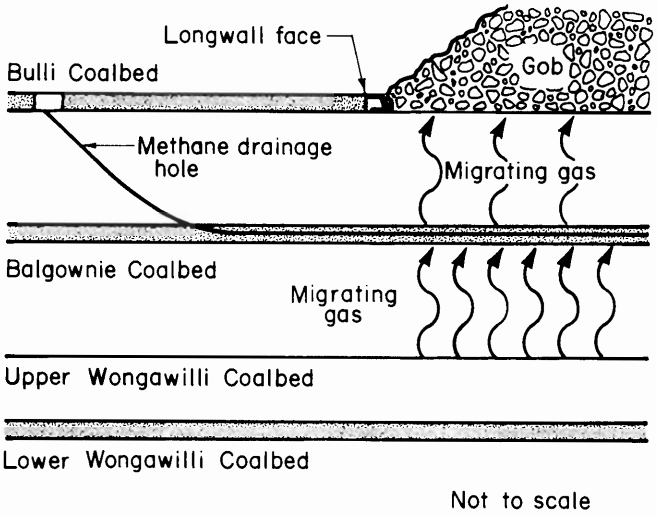


Figure 31.—Section view of methane drainage borehole drilled into an underlying coalbed, Australia (modified from Hungerford (*40*)).

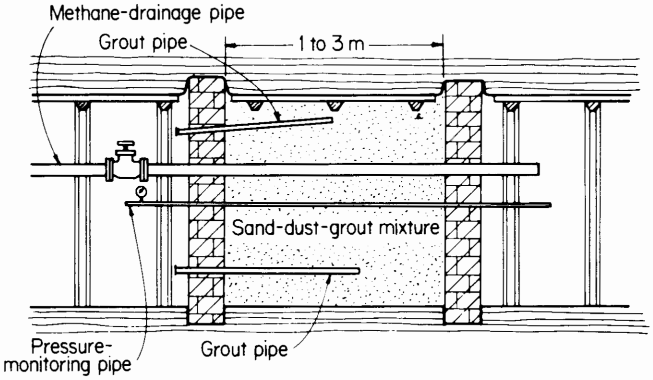


Figure 32.—Schematic section view of gas drainage from sealed entries and/or gob (*9*).

coalbeds must be dewatered to lower the reservoir pressure and initiate gas desorption and flow. This can result in a considerable time lag before gas is actually produced and in additional expense to dispose of the water according to State and Federal regulations.

Despite the drawbacks, vertical wells drilled into virgin coalbeds are a viable alternative to in-mine methane drainage systems. Vertical gob gas ventholes are the method of choice in the United States, after ventilation, to control gas emissions from longwalls. The majority of gas produced commercially from coalbeds in the United States has been from methane drainage systems drilled from the surface. This is in contrast to other countries, where holes drilled from the surface are less common, but where utilization of the gas produced from the underground systems has long been a standard practice.

Stimulated Vertical Wells in Virgin Coalbeds

The use and effectiveness of stimulated vertical wells to drain gas from virgin coalbeds, specifically related to mining operations, has been well documented (*17, 27, 55, 93, 96*). Vertical coalbed methane drainage wells are currently being used extensively in only two coal basins in the United States: the San Juan Basin in southern Colorado and northern New Mexico, and the Black Warrior Basin of Alabama. Only the wells in Alabama, at depths of 305 to 610 m (1,000 to 2,000 ft), are generally associated with mining operations. The wells in the San Juan Basin, at depths generally greater than 610 m (2,000 ft), have been developed solely for commercial purposes and are not associated with mining. Programs to use vertical wells associated with mining operations have also been implemented in the Central Appalachian Basin of Virginia and West Virginia, and activity in this area has been increasing (*63*).

Even though stimulated vertical wells have been shown to be an effective means of draining gas from virgin coalbeds, the technology has not been universally accepted in the mining industry. The reasons are varied, but lack of acceptance is related to questions of coalbed gas ownership, as well as a concern that the stimulation treatments required to enhance the generally low permeability of the coalbed may adversely affect the integrity of the mine roof, resulting in future mining problems.

Coal mine operators in the United States are obligated under Federal and State law to control the concentration of methane underground. The primary means to comply with methane concentration regulations is ventilation. However, methane drainage is also an allowable option. It is generally recognized that as long as the gas is produced as part of the mining operations and is not captured for commercial purposes, the coal leaseholder may dispose of it by venting to the atmosphere (*69*). However, when the gas is captured for commercial sale, legal issues as to its ownership may arise if the coal and gas rights are not owned by the same party (*57*).

Coalbed gas ownership has generally been an issue primarily in the Northern Appalachian Basin of the United States, where a potential commercial methane drainage site may involve multiple oil and gas leases and separate and multiple coal leaseholders and surface owners. Because many of the leases and deeds were conveyed prior to the recognition of the potential value of coalbed methane, this resource was not addressed in deed descriptions of mineral rights ownership. Consequently, when commercial production is planned, multiple claims to the produced gas may ensue, resulting in protracted legal proceedings. Concern over the potential for adverse ownership issues and/or unwillingness to make the effort to negotiate agreements with all parties that may have some claim to the gas has slowed commercial development.

Another concern expressed by mining companies, particularly in the Northern Appalachian Basin, is the potential for mine roof damage resulting from the hydraulic stimulation of coalbeds. There is direct evidence and experience that addresses this issue. Coalbeds as gas reservoirs are unique production horizons in that access to the reservoir is made possible by mining. This allows for the direct observation of the results and consequences of the drilling, completion, and stimulation of the reservoir.

The results of the underground observation and mapping of 22 stimulation treatments in U.S. coalbeds were presented by Diamond and Oyler (*24*). Their compilation covers the early history of stimulations from 1974 to 1982 and includes data from several different coal basins. These treatments were generally of low fluid volume (189 m^3 [50,000 gal] maximum) and low injection rates (1.1 to 2.5 m^3/min [7 to 16 bbl/min]). Sand proppant weights were generally under 9,080 kg (20,000 lb). The fluids were predominantly foam (16 of 22), with the rest being gelled water and water alone.

The work by Steidl (*95*) covers 15 recent stimulations (1982 to 1986) exclusively in the Mary Lee-Blue Creek Coalbeds of the Black Warrior Basin of Alabama. This compilation updates the previous study because the treatment volumes were significantly larger and the injection rates were higher. All but one of these treatments used water as the stimulation fluid. Nine of the treatments used 378 m^3 (100,000 gal) or more of fluid, with a maximum of 711 m^3 (108,000 gal). Sand proppant weights were also higher, with most treatments using 18,160 kg (40,000 lb) or more, with a maximum of 45,400 kg (100,000 lb). Injection rates were generally over 3.2 m^3/min (20 bbl/min), with several at 6.4 m^3/min (40 bbl/min).

The penetration of either the sand proppant or stimulation fluids into the strata directly overlying the stimulated coalbed was observed in nearly half (10 of 22) of the early treatments. However, most of these penetrations were minor, and most importantly, no adverse mining conditions were reported as a consequence of any of the stimulation treatments. It was concluded that few, if any, new fractures were actually created by the stimulation treatments. The stimulation fluids and sand proppant appeared to have invaded preexisting planes of weakness in the coalbeds and roof strata. These included the coal cleat and roof joints and the horizontal interfaces along partings, the roof, and rider coals (fig. 33).

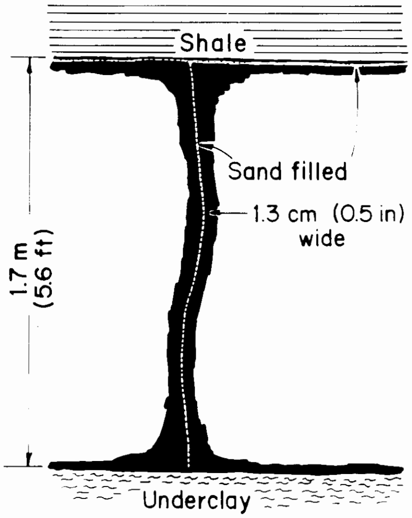
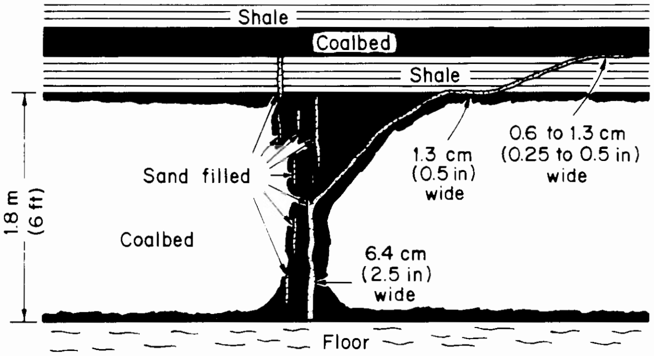


Figure 33.—Schematic section view of sand proppant from hydraulic stimulation placed in face cleat and along horizontal interface of coalbed with roof shale, Lower Kittanning Coalbed, West Virginia (*24*).



Not to scale

Figure 34.—Schematic section view of sand proppant from hydraulic stimulation placed in face cleat, along inclined fracture in coal and shale parting, and along horizontal surfaces above and below shale parting, Pittsburgh Coalbed, Pennsylvania (*24*).

Most of the roof penetrations (6 of 10) observed in the smaller volume treatments (*24*) were associated with stimulations in the Mary Lee-Blue Creek coal interval in the Black Warrior Basin of Alabama. In addition to being more numerous, these roof penetrations were of greater extent than those observed elsewhere. In the more recent study by Steidl (*95*), similar observations were made for the generally larger treatments in the Blue Creek Coalbed with higher injection rates. These roof penetrations were characterized as thin, generally less than 0.25 cm (0.1 in) wide, with an orientation similar to that of naturally occurring roof joints in the same area of the mine. The typical roof penetrations outside Alabama generally extended less than 0.3 m (1 ft) vertically and 1 m (3.3 ft) laterally into the overlying strata (fig. 34).

It is of particular significance that the Black Warrior Coal Basin has the highest incidence of roof penetrations and is also the mining area with the greatest number of stimulated vertical wells being used for methane drainage in the United States. Many of the wells drilled in the Black Warrior Basin are on mine property and are intended for commercial gas production. In addition to revenue from gas sales, the mines will benefit from the mining of coal with lower gas content. With the continued drilling and stimulation of vertical wells on mine property, it is quite evident that these mining companies have concluded that the roof penetrations have not been a problem, and any potential for adverse mining conditions is an acceptable risk.

The reason for the more extensive roof penetrations in the Black Warrior Basin of Alabama is not conclusively known, but may be related to the complex structural history of the area. In situ state of stress (ISSOS) tests conducted in the vicinity of the underground observations indicate lower in situ stress values for the rocks surrounding the Mary Lee-Blue Creek Coalbeds than were measured in the coal (*82*). In the absence of a stress barrier or mechanical strength barrier, upward fracture breakout is more likely. Upward fracture breakout from this coal section was reported during the ISSOS testing. The presence of naturally occurring roof joints coupled with lower or similar in situ stresses above the coal probably influenced the extent of roof penetrations observed.

It would be advisable early in a methane drainage program to place one or more stimulated wells relatively close to mining, so that the effects of the stimulation treatment on the coalbed and surrounding strata can be determined. Roof penetrations that are observed can then be evaluated in conjunction with the prestimulation geologic mapping of the mine. If roof penetrations have occurred, and if they are preferentially oriented, such as along a minewide roof joint system parallel to the face cleat, it may be possible in room-and-pillar sections to place the vertical methane drainage wells so that the probable orientation of the roof penetrations cuts across the short dimension of an entry instead of the long dimension (fig. 35). Intercepting roof penetrations in this manner would expose the least length of such penetrations to the mine workings.

Modifications to the stimulation design may also be made to minimize the penetration of the roof strata. Steidl (*95*) concluded that water stimulations at high injection rates (3.2 m^3/min [20 bbl/min] or higher) had a greater propensity for creating thin fractures that more readily penetrated the strata overlying the coalbed stimulated. Foam and gel stimulation treatments with lower injection rates tended to result in shorter and wider fractures that stayed in the coalbed (*24*).

Steidl (*95*) also pointed out that the general practice of using open-hole completions in coalbed gas wells that would eventually be mined through may also contribute to the increased occurrence of stimulations outside the coalbed. Steel pipe in the minable coal interval is generally unacceptable to the mining industry; therefore, the well casing is generally placed 0.3 m (1 ft) or more above the coalbed (fig. 36, coalbed A) to ensure that it does not extend into the coal. However, the exposure of a portion of the roof strata to the open-hole interval being stimulated may aid the fluids in penetrating these strata. When the stimulation interval is behind casing, communication to the desired gas-bearing zone can be controlled by the use of perforations or slots (fig. 36, coalbed B). This type of completion introduces the stimulation fluid into the desired zone at the wellbore but may not influence the ultimate placement of the stimulation treatment. Steidl (*95*) reports that fiberglass casing has been successfully used in mining-related applications and was an acceptable completion alternative for eventual mine-through.

A recent development in enhancing the flow of gas from vertical wells without hydraulic stimulations has been the use of cavity completions. With this technique, a cavity is created in the coalbed by one of several methods, as described by Mavor (*59*). The creation of the cavity is thought to increase permeability by a process of stress relaxation and subsequent cleat aperture increase. This factor plus the minimizing of formation damage and the increase in wellbore diameter that more effectively links the well to the cleat system has in some cases resulted in higher gas production than that from comparison wells that were hydraulically stimulated. This completion technique may be a viable alternative for mining-related methane drainage in some cases where hydraulic stimulations are not acceptable.

As with all methane drainage systems, it is essential that the drilling and placement of stimulated vertical wells be coordinated with both current mining operations and future development. It is even more important with the

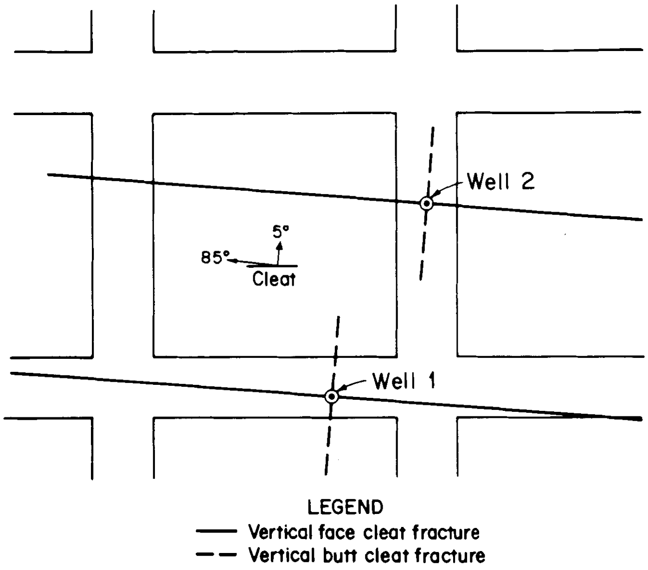


Figure 35.—Schematic plan view of relationship of mine entry orientation and interception of vertical fracture from hydraulic stimulation preferentially oriented in face cleat direction (*24*).

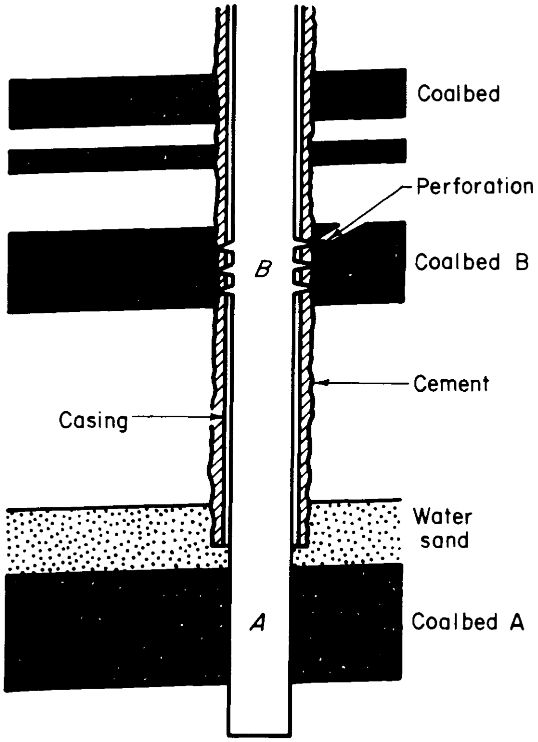


Figure 36.—Schematic view of open hole (*A*) and cased hole (*B*) completions for vertical methane drainage well.

vertical wells to be able to predict where the mining operations will be in the future, since gas drainage from virgin coal reserves usually requires several years to positively impact mining. Once a multiyear mine development plan is available and the degasification area is defined, the drilling pattern must be selected. Multiple wells are required to drain gas from virgin coalbeds because the gas will not desorb from the coal until the pressure is reduced. The pressure reduction is accomplished by removing the water from the hole using a pump installed in the wellbore (fig. 37). Multiple wells more efficiently reduce the pressure by forming overlapping drainage radiuses.

Optimum well spacing is a particularly difficult, but important, variable to determine, since many interrelated factors must be considered. Two primary factors to be considered are the length of time before a particular area will be mined and the budget. If the lead time before mining is short, the wells must be closer together to sufficiently lower the gas in place prior to mining. However, closer well spacing requires more wells, increasing the cost. The ideal situation would be to have at least 4 or 5 years of methane drainage before mining, allowing the placement of wells on a wider spacing, which would be less costly.

Computer-based reservoir simulators and production models are available to aid in evaluating the optimum vertical well spacing to drain gas from an area in a specified timeframe (*50*). The reliability of the models is dependent on the theory that describes the processes being modeled and the ability to determine site-specific values for the variables. Many of the reservoir variables can be determined during the exploration phase of mine development or through well testing in preliminary holes, such as the near-mine wells recommended for underground observation of stimulation treatments. With reasonably accurate reservoir values and underground observations of stimulation treatments, the models can provide an acceptable estimate of optimum well spacing for the site-specific conditions. Past experience with stimulated vertical wells in the same coalbed should also be considered when determining well spacing.

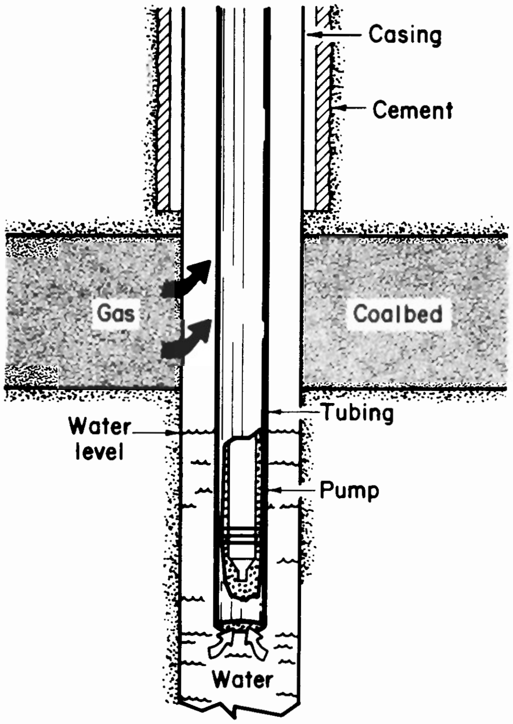


Figure 37.—Schematic section view of water pump installed in vertical methane drainage well.

A production pattern of stimulated vertical wells is generally initially laid out on a grid of predetermined spacing to provide the optimum balance of gas drainage and cost. The final drilling locations may have to be adjusted owing to various surface conditions, including the presence of buildings, roads, utility easements, bodies of water and wetlands, topography, and adverse surface ownership.

The cleat system in the coalbed can also affect the drainage pattern in the coalbed, and hence the basic configuration of the grid for the wells. Orientation of the cleat system, in particular, the relative dominance of the face cleat over the butt cleat, influences fluid movement and sand proppant placement from stimulation treatments, and the subsequent flow of water and gas to the wellbore. Mine-throughs of stimulation treatments underground in coal mines have consistently shown that the fluids and sand proppant preferentially penetrate and flow along the existing cleat, with the face cleat being the primary flow path (*24*). An example of the preference for the stimulation fluids to penetrate face cleat is shown in figure 38. The resulting drainage pattern for a stimulated well, such as that shown in figure 38, would be expected to be elliptical in shape, with the long axis of the ellipse parallel to the face cleat. This suggests that the wells should be drilled on a rectangular grid, with the wells spaced farther apart in the face cleat direction, and closer together in the butt cleat direction.

Gas content testing of coal cores obtained prior to the start of methane drainage and additional cores obtained at the same locations as methane drainage progresses can be correlated to methane emission levels to determine the extent to which the in-place gas content must be reduced to sufficiently reduce the mine emissions. Pressure monitoring holes can be used in place of, or in addition to, the gas content data to monitor the progress of methane drainage (*77*).

It is not generally necessary, or even possible, to remove all the gas from a coalbed to have a significant impact on mine emissions. Several examples of declining

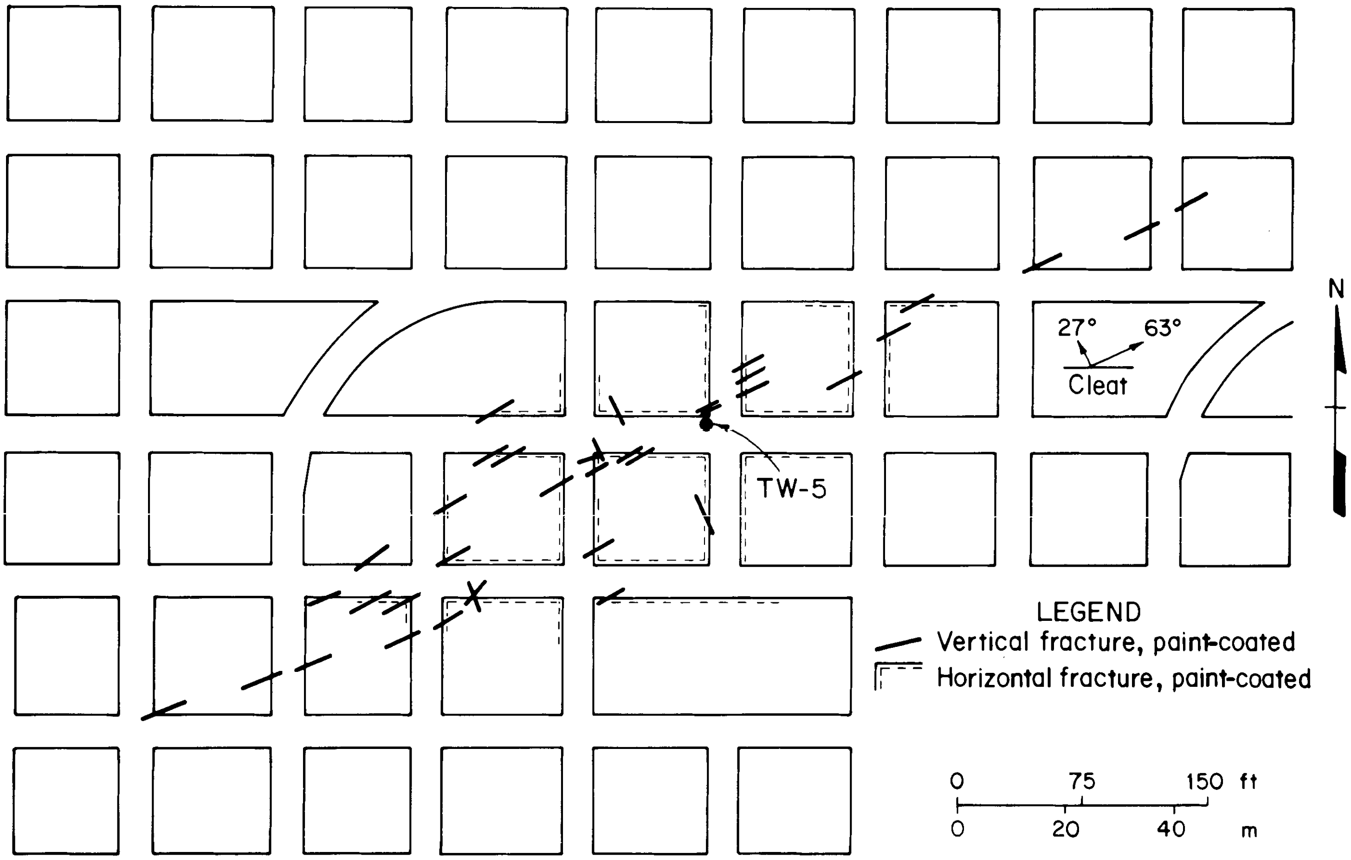


Figure 38.—Plan view of elliptical placement of fluids in the Blue Creek Coalbed, Alabama, from a stimulated vertical methane drainage well (*24*).

methane emissions cited in this paper are associated with short-term methane drainage projects, where a substantial percentage of the in-place gas could not have been drained. It appears that most coalbeds have a certain percentage of their total gas content that is relatively mobile. This gas flows quite readily to either mine workings or methane drainage holes as the pressure is reduced in the coalbed. This gas will be produced from progressively greater distances from the wellbore in preference to that portion of the in-place gas that is more difficult to release from the coal, even though it may be closer to the wellbore (*17, 22*). With the gas content and/or pressure monitoring results and production data from the wells, the computer-based reservoir and production simulations can be updated to continually refine the well spacing and lead time required to provide the optimum impact on mine emissions.

Another important factor to consider in the design of a vertical well methane drainage program is the need to shield the mine workings or property from gas migrating from the surrounding area. As methane drainage progresses, an expanding area of reduced pressure and gas desorption is created outside the perimeter of the pattern. A study in the Mary Lee-Blue Creek Coalbed, Alabama, showed that after 10 years of gas production from a 23-well pattern of vertical wells, the drainage radius extended as much as 1,524 m (5,000 ft) from the perimeter of the pattern (*17*). The gas desorbed from this reduced-pressure area migrates to the production wells in the pattern. While this may be desirable from a commercial gas production perspective, it can be a problem from a mining perspective.

If no shielding wells are drilled between the mine workings and the migrating gas (fig. 39), increased methane levels may be experienced in the mine, even though the gas content of the coal has been reduced by the vertical methane drainage wells. A line of wells could be drilled around the perimeter of a mine property to intercept migrating gas. However, it is more practical to position additional shielding wells just outside the actual mining area (fig. 39). It may also be possible to reinject water into wells near the mine workings to block the flow of gas, similar to underground water infusion. Reinjection of water may not be an option in some locations, depending on applicable oil and gas regulations.

The problem of migrating gas on mining operations was experienced at a longwall mine in the Lower Kittanning Coalbed, Pennsylvania (*25*). A series of new longwall panels was developed downdip from an area of extensive old workings, some of which had been mined more than 20 years previously. Unexpectedly high methane emissions were experienced when the first of a new series of panels was mined. Through evaluation of gas content tests and material balance calculations, it was concluded that over the 20-plus years that this area had been idle, the old workings had created a sufficient pressure sink to induce the desorption of gas from the downdip coal reserves. This gas was migrating updip to the old workings. When the new longwall was placed in the path of the migrating gas, it provided a closer pressure sink and outlet for the migrating gas.

The direct influence of methane drainage by stimulated vertical wells on mine emissions was demonstrated by Lambert (*55*). In an experiment at a mine operating in the Mary Lee-Blue Creek coal interval, two test holes were drilled in advance of a set of entries in one part of the mine, while a second set of entries was mined in the opposite direction without methane drainage (fig. 40). The two experimental wells were on production for a relatively short time (11 months). The wells produced 0.71 × 10^6 m^3 (25 MMcf) of gas, which had a significant influence on mine emissions. The "east" entries, driven without the benefit of methane drainage, required 70 days to advance a distance of 180 m (590 ft). During that time, 1.7 × 10^6 m^3 (61 MMcf) of gas was vented from the workings (fig. 41). The "west" entries, which were driven toward the two methane drainage wells, required only 63 days to mine 180 m (590 ft), and only 1.0 × 10^6 m^3 (37 MMcf) of gas was encountered. This represents a 40-pct reduction in the amount of gas liberated into the mine atmosphere.

The effectiveness of a large-scale pattern of stimulated vertical wells in reducing the gas content of coalbeds has been shown by Diamond (*17*). In 1976, a pattern of 23 methane drainage wells was drilled and stimulated in the Blue Creek Coalbed on mine property. The wells were drilled on a 305-m (1,000-ft) square grid (approximately 100 × 10^3-m^2 [25-acre] spacing). After 10 years, the wells had produced a total of 90.6 × 10^6 m^3 (3.2 Bcf) of methane that will never have to be controlled in the underground mine environment.

Coal samples obtained from coreholes in and around the 23-well pattern after 10 years of gas production were tested for gas content and compared with samples obtained from the same area prior to the start of methane drainage. Inside the pattern, 73 pct of the original gas in place had been drained from the Blue Creek Coalbed, the only coalbed that had been completed for production. Similar gas reduction results were measured in the Mary Lee and New Castle Coalbeds, situated 1.5 and 13.7 m (5 and 45 ft), respectively, above the Blue Creek Coalbed. The same naturally occurring joints observed underground in the roof strata above the Blue Creek Coalbed that were penetrated by the stimulation treatments likely provided the conduits for gas flow to the completions below.

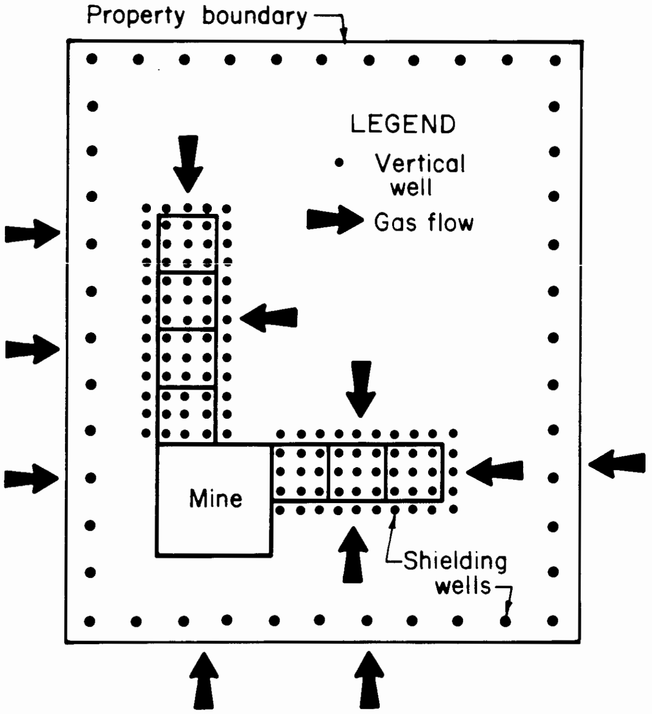


Figure 39.—Schematic plan view of vertical methane drainage wells placed to shield mine workings from migrating gas.

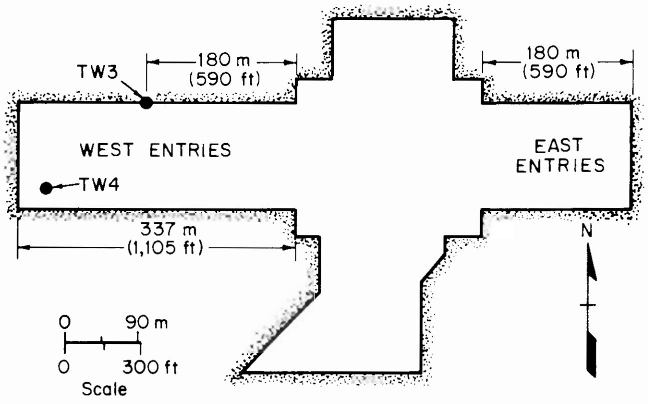


Figure 40.—Schematic plan view of location of two near-mine experimental stimulated vertical methane drainage wells, Blue Creek Coalbed, Alabama (*55*).

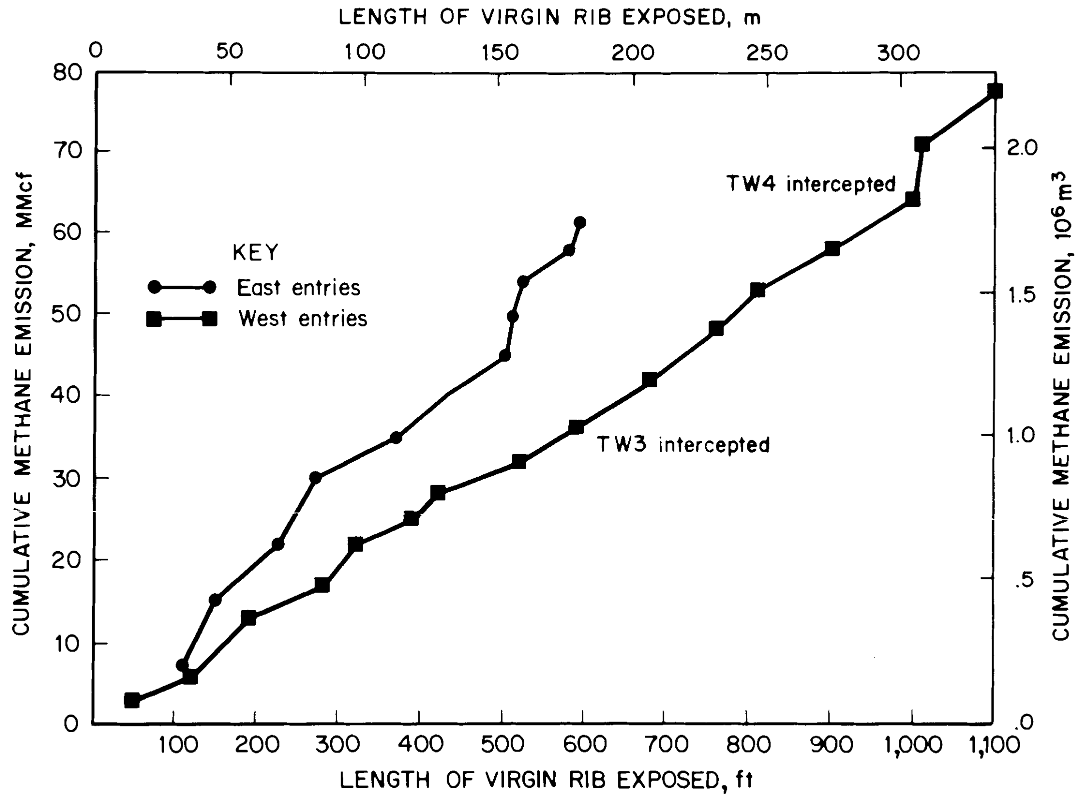


Figure 41.—Comparison of cumulative methane emissions in entries developed into areas with and without stimulated vertical methane drainage wells, Blue Creek Coalbed, Alabama (*55*).

The early success of the vertical methane drainage program at this mine led to the drilling of a large number of additional commercial wells on the property. Total production through 1992 was 1.75 × 10^9 m^3 (62 Bcf) of gas. At a nearby mine operating in the same coal interval, Mills and Stevenson (*70*) reported a decrease of about 50 pct in methane emissions in the mining of longwall development entries in an area where 31 stimulated vertical wells had drained gas for at least 5 years prior to mining.

Directionally Drilled Boreholes

Boreholes directionally drilled from the surface are a unique methane drainage technology that combines the best attributes of the underground horizontal boreholes and the stimulated vertical wells. These holes can be drilled from the less restrictive surface environment, but by deviating the well path from the vertical, the hole can be turned to intercept horizontally the coalbed to be degasified. Once the well path has intercepted the coalbed, the hole can be continued in the coalbed to drain gas in the same manner as the horizontal boreholes drilled underground. Directional boreholes can also be oriented to preferentially intercept perpendicularly the greater permeability of the face cleat. Drilling long horizontal boreholes into virgin coalbeds also eliminates the need for the stimulation treatments required in the vertical methane drainage wells.

The first experimental directional boreholes drilled for coalbed methane drainage were long radius, turning from vertical to horizontal at a rate of about 6° per 30 m (100 ft) (*76*). These well paths required about 305 m (1,000 ft) of depth to intercept the target coalbed horizontally (fig. 42). Downhole motors and various configurations of drilling assemblies were used to drill the directional boreholes and control the well path. A directional well methane drainage system into the Pittsburgh Coalbed, Pennsylvania, included three long horizontal boreholes (539 m, 912 m, and 977 m [1,767 ft, 2,993 ft, and 3,207 ft]) drilled from the bottom of the single well path to the coalbed (fig. 43) (*75*). Sloughing of the bottom portion of the uncased part of the hole in the roof shale above the Pittsburgh Coalbed and dewatering problems severely limited the gas production from this hole.

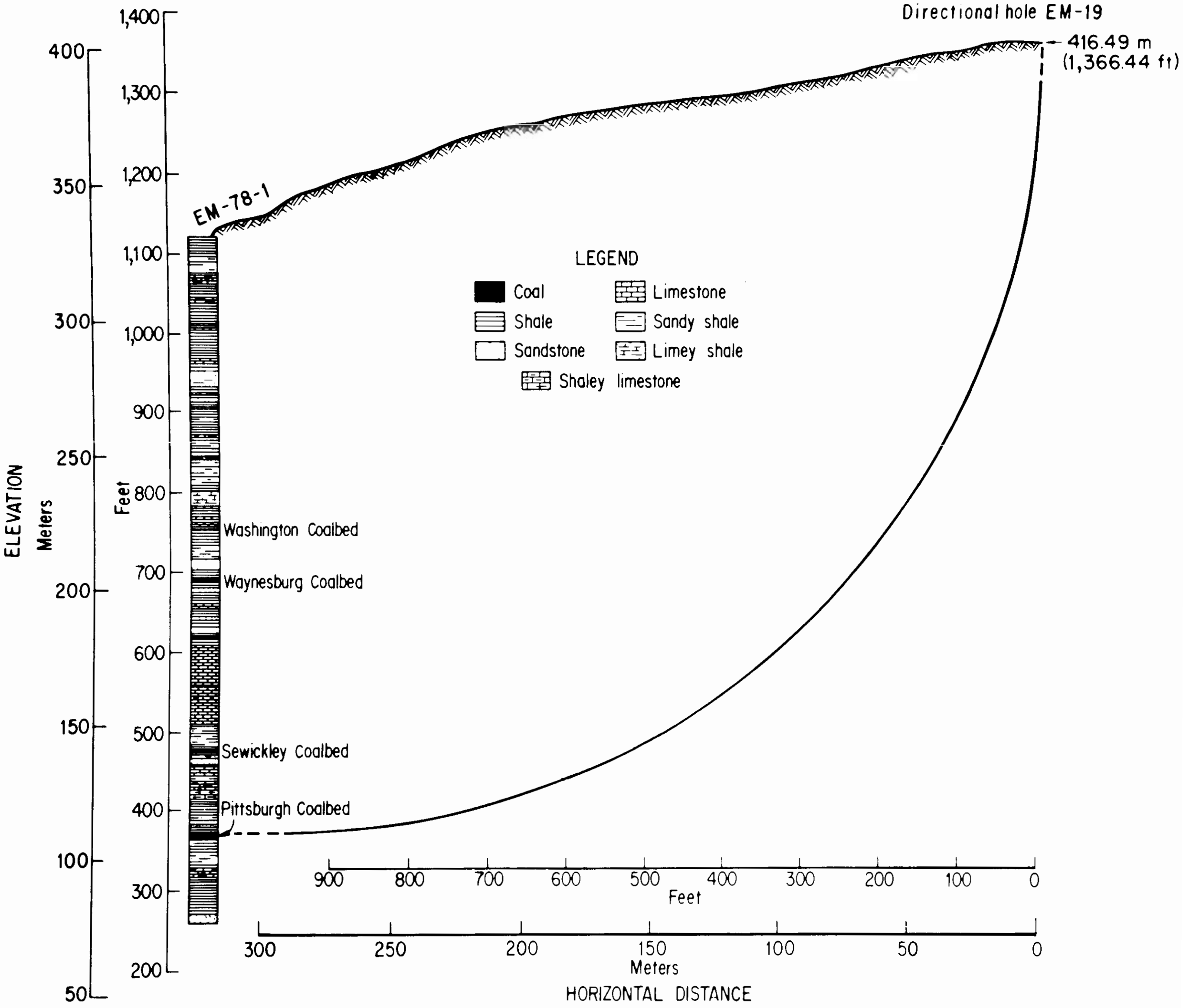


Figure 42.—Section view of long-radius directionally drilled well path to intercept the Pittsburgh Coalbed horizontally from the surface, Pennsylvania (*75*).

Alternative to the long-radius directional drilling system are the medium- and short-radius systems that have been developed in the oil industry over the past few years (*58*, *72*) (fig. 44). Medium-radius systems are turned at a rate of 8° to 20° per 30 m (100 ft), requiring 91 to 213 m (300 to 700 ft) of vertical section. Short-radius systems can be deviated at a rate of 1.5° to 3° per 0.3 m (1 ft), which requires only 6.1 to 12.2 m (20 to 40 ft) of vertical section to make the turn from vertical to horizontal. Nazzal (*72*) reports that holes can be drilled up to 305 m (1,000 ft) horizontally using the short-radius system.

This new technology in directional drilling, especially the short-radius boreholes, may have significant applications to coalbed methane drainage. Shorter radius drilling reduces the length of unproductive directional hole in the overlying rock, thus reducing drilling time and costs. Also, with the short-radius systems, a pump can be installed in the bottom of the vertical well section below the kickoff point of the directional hole (fig. 45). This pump configuration may provide for more effective dewatering than was possible in the long-radius wells. This proven directional drilling technology, which uses off-the-shelf

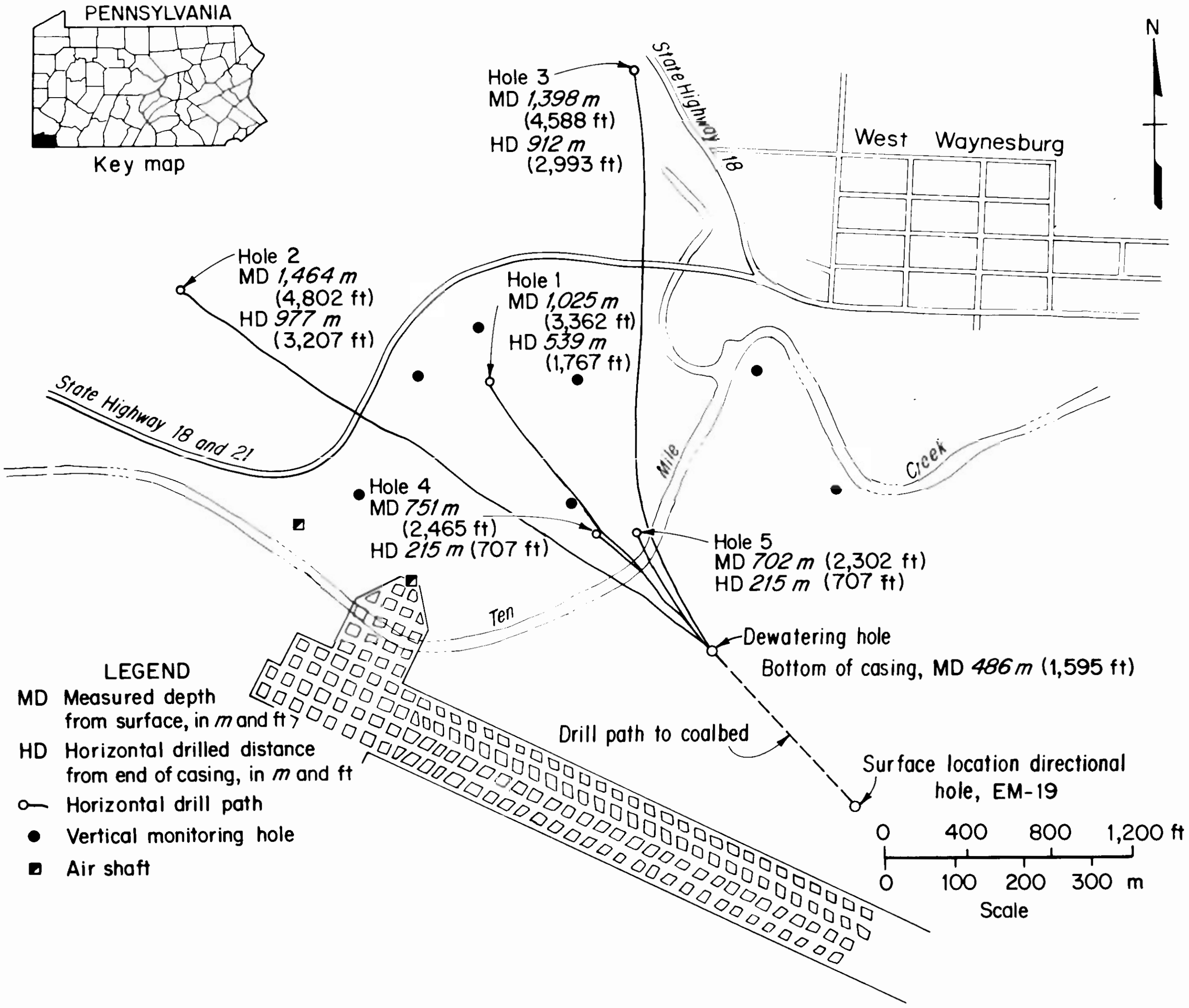
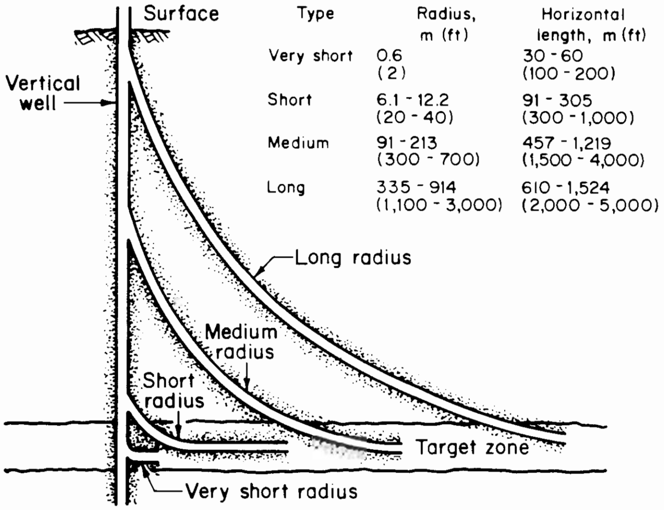


Figure 43.—Plan view of multiple horizontal methane drainage boreholes drilled from a directional surface borehole, Pittsburgh Coalbed, Pennsylvania (*75*).

components, has a greater potential for successful implementation in coalbed methane drainage than the experimental directional boreholes drilled in the 1970's, which required in-the-field development of prototype tools and drilling procedures.

Longwall Gob Gas Ventholes

Vertical gob gas ventholes are drilled over longwall panels to drain gas from the gob that results from the complete extraction of the large block of coal. As the coal is extracted, the roof strata are allowed to cave in behind the movable supports that protect the men and equipment on the face. Gas-bearing strata, particularly overlying gas-bearing coalbeds, either are directly exposed to the caved zone, or are connected by fractures that extend into the caved zone. This allows gas to enter the mine atmosphere from above (fig. 5). Gas-bearing strata below the mined bed may also contribute gas to the mine atmosphere. It is not uncommon for longwall sections to be shut down for a shift or more while excessive volumes of gas emitted after a large roof fall behind the longwall supports



Type	Radius, m (ft)	Horizontal length, m (ft)
Very short	0.6 (2)	30 - 60 (100 - 200)
Short	6.1 - 12.2 (20 - 40)	91 - 305 (300 - 1,000)
Medium	91 - 213 (300 - 700)	457 - 1,219 (1,500 - 4,000)
Long	335 - 914 (1,100 - 3,000)	610 - 1,524 (2,000 - 5,000)

Figure 44.—Schematic section view of available directional hole drilling radiuses (modified from Logan (*58*)).

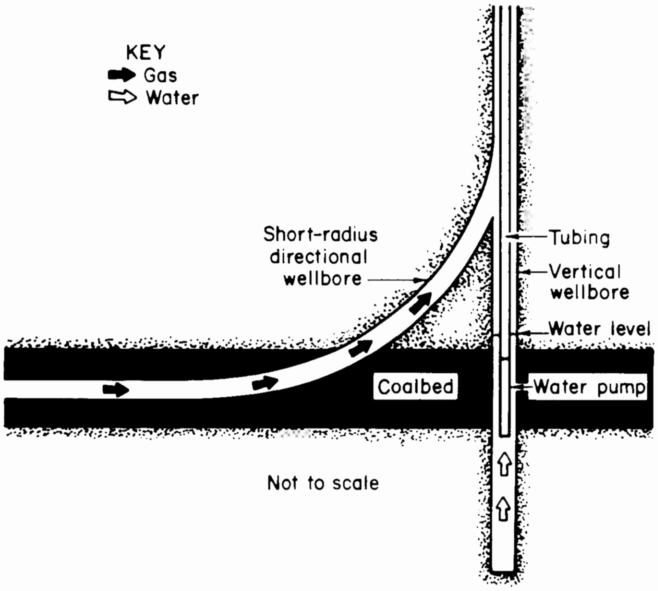


Figure 45.—Schematic section view of short-radius directional methane drainage borehole equipped with downhole pump for dewatering.

dissipate from the working area. Gas-related mining delays are becoming an increasingly common occurrence, even with the use of vertical gob gas ventholes. This is due to the coal industry's use of advanced mining technology and progressively larger panels to increase coal production.

The use of vertical gob gas ventholes is most common in the United States, probably owing to the greater ease of obtaining surface drill sites than in the more mature mining districts of Europe. The relatively shallow depth of the longwall mines in the United States also makes the use of gob gas ventholes more cost effective. The first experimental vertical gob gas venthole was drilled at a mine operating in the Lower Kittanning Coalbed, Pennsylvania, in the late 1960's (*28*). This hole produced 1.7 × 10^6 m^3 (61 MMcf) of methane in 9 months at a maximum rate of over 8.5 × 10^3 m^3/d (300 Mcfd). The success of this first experimental hole led to the continued use of the technique as longwall mining gained popularity in the United States.

Vertical gob gas ventholes are quite similar to the holes that are used to drain gas from coalbeds in advance of mining. The primary difference is that no stimulation treatment is required to enhance the permeability of the coalbed, and the gas is drained after mining. Since the first experimental hole was drilled in the late 1960's, gob gas ventholes have been drilled and completed in several different ways. Completion techniques are influenced by site-specific conditions as determined by trial-and-error (*70*). Once a successful drilling and completion design is found that keeps the methane concentrations within the regulatory limits, few if any changes in the design are initiated.

Most gob gas ventholes are drilled to within a short distance of the coalbed being mined and cased with steel pipe. Commonly the bottom section of pipe is slotted and placed adjacent to the gas production zone, where extensive fracturing occurs as the overburden caves into the unsupported mine void (fig. 46, hole 173). In some cases, the hole is only drilled and cased to within about 30 m (100 ft) or more of the coalbed, and then a smaller diameter open hole is drilled through the bottom of casing to the coalbed (fig. 46, hole 175-B). Numerous variations on these basic designs are possible, as illustrated in figure 46, which represents the trial-and-error process to find a more productive venthole completion technique on a single longwall panel in the Lower Kittanning Coalbed, Pennsylvania.

The distance between the gob gas ventholes, like the basic drilling and completion design, is determined by experience and site-specific mining conditions. When conditions are stable from panel to panel, the holes may be drilled several months in advance. However, when conditions are not stable, the sites for the holes are based on increasing mine emissions as the panel progresses. The holes are drilled only a few days in advance of interception by mining under these circumstances, occasionally resulting in mining delays due to high methane emissions. The time required to drill and complete a gob gas venthole to a typical depth of 229 m (750 ft) is only a few days. The gob gas ventholes will usually produce only a small volume of gas under natural flow conditions. The holes are typically equipped with exhausters on the surface to draw gas from the gob (fig. 47). The installation of the surface equipment requires about 1 day. In most cases, a gob gas

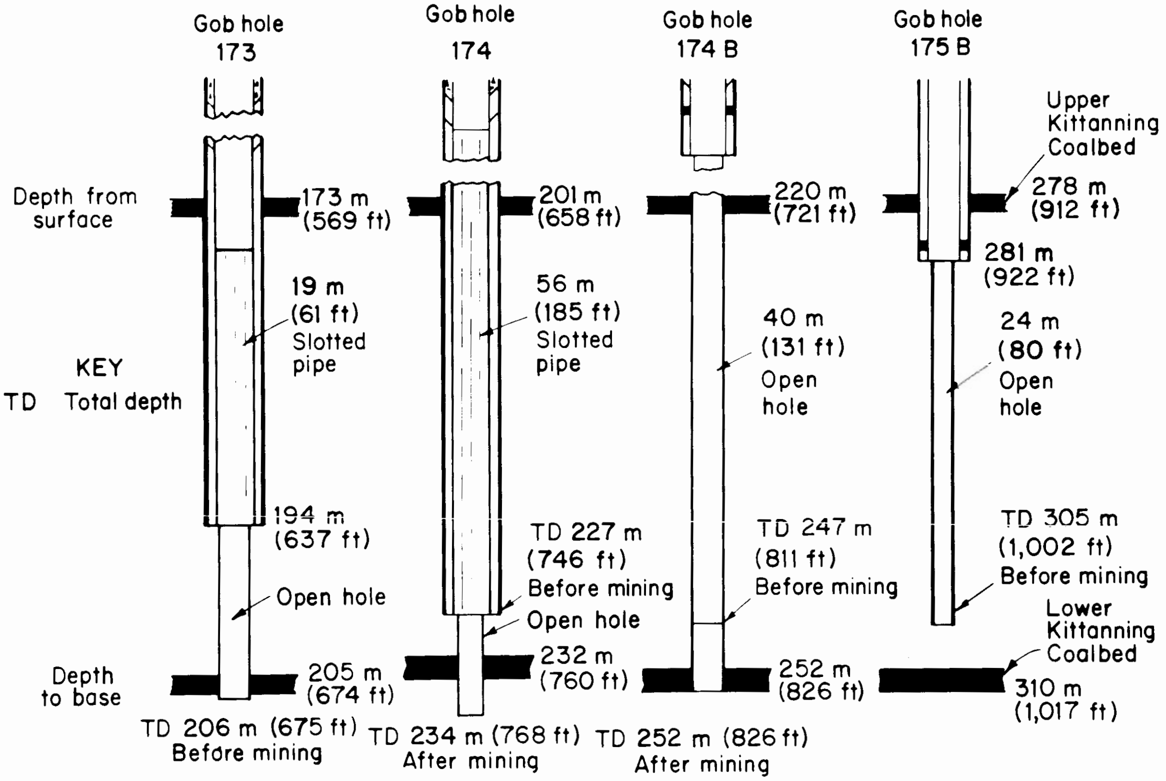


Figure 46.—Schematic section view of various longwall gob gas venthole completion designs.

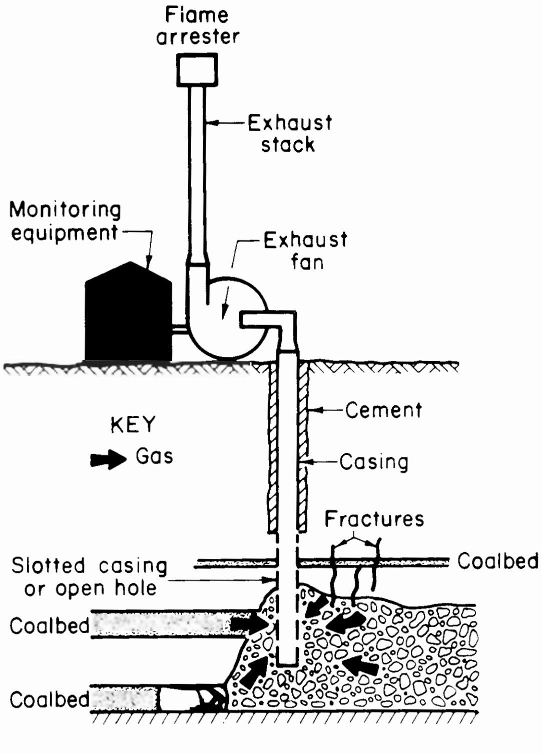


Figure 47.—Schematic section view of complete longwall gob gas venthole system.

venthole can be drilled and put in operation in less than 1 week.

An individual gob gas venthole over a longwall in the Lower Kittanning Coalbed, Pennsylvania, produced over 10.0 × 10^6 m^3 (357 MMcf) of methane (*18*). A hole in the Pocahontas No. 3 Coalbed, Virginia, produced nearly 17 × 10^6 m^3 (600 MMcf) of methane during mining of that coalbed (*64*). Maximum daily methane production generally occurs within the first several days after a hole is intercepted by the longwall. Relatively high production rates are usually sustained for only a few weeks (fig. 48), or in some cases for a few months (fig. 49). In most circumstances, no effort is made on the part of the mine operator to control the methane concentration in the produced gas. The initial methane concentration in the gas stream is generally high (>80 pct) and remains relatively high for several months after mine-through (fig. 50). The methane concentration usually declines gradually with time. Commonly, when the methane concentration reaches 25 pct, the exhausters are turned off as a safety precaution, because the explosive range of methane in air is 5 to 15 pct. The holes are generally allowed to free flow after the exhausters are turned off.

Gob gas ventholes are an effective technology to drain gas from longwall gobs. Mills and Stevenson (*70*) reported that approximately 30 to 40 pct of the total gas liberated from several mines operating in the Mary Lee-Blue Creek coal interval, Alabama, was produced by gob gas ventholes. Dixon (*26*) stated that the mines could not operate at economic levels without gob gas drainage. Dixon (*26*) also reported that the methane level in the mine bleeder entries can be reduced by as much as 80 pct using the gob gas ventholes.

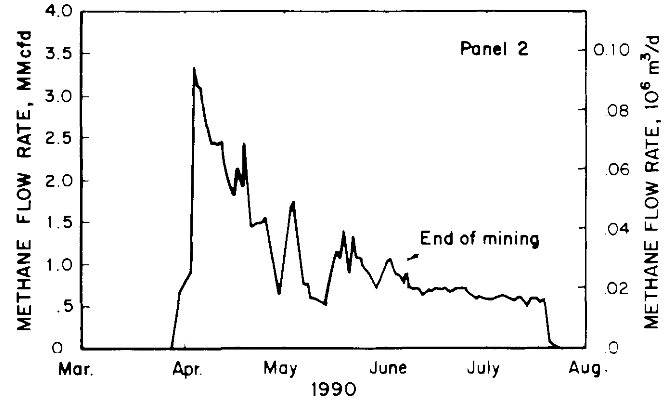


Figure 48.—Daily methane flow rate, gob gas venthole 178, Lower Kittanning Coalbed, Pennsylvania.

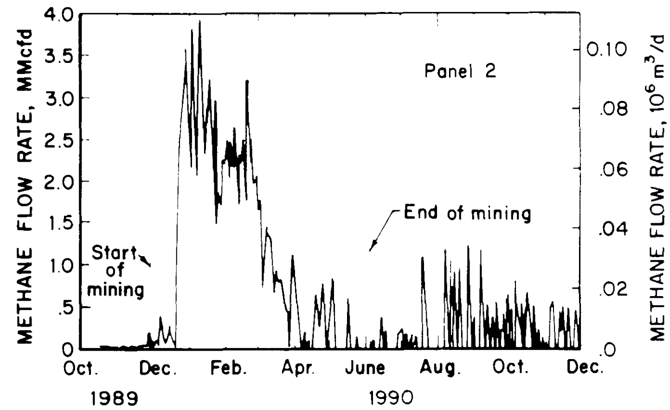


Figure 49.—Daily methane flow rate, gob gas venthole 176, Lower Kittanning Coalbed, Pennsylvania.

In some cases, the methane produced from the gob gas ventholes is sold to commercial gas pipelines. Under these circumstances, it is desirable to maintain pipeline-quality gas for maximum revenue. This is accomplished by closely monitoring the methane concentration at the holes and adjusting the amount of vacuum to minimize the volume of mine air drawn into the gob. Mills and Stevenson (*70*) reported that 0.48 to 0.65 × 10^6 m^3/d (17 to 23 MMcfd) of methane from gob gas ventholes at two mines in the Mary Lee-Blue Creek coal interval, Alabama, was sold to a commercial gas pipeline.

Figure 51 shows the total methane production for all gob gas ventholes on a panel in the Lower Kittanning Coalbed, Pennsylvania (including holes 176 and 178, figs. 48-49). The numerous peaks above the base level production of about 0.11 × 10^6 m^3/d (4 MMcfd) represent the successive interception of each of the 13 gob gas ventholes drilled on this panel. The holes produced 29.4 × 10^6 m^3 (1,039 MMcf) of methane through 12 months after the panel was completed.

Methane production rates of 0.11 × 10^6 m^3/d (4 MMcfd) for Lower Kittanning gob gas ventholes, Pennsylvania (*18*), 0.17 × 10^6 m^3/d (6 MMcfd) for the Mary Lee-Blue Creek coal interval, Alabama (*70*), and 0.26 × 10^6 m^3/d (9.1 MMcfd) for the Pocahontas No. 3 Coalbed, Virginia (*64*) have been reported. Note that these maximum values do not necessarily represent typical or average production rates. In fact, the production of gas from gob holes can be quite variable (fig. 52). Some of the variability (low gas production) can be due to completion problems, such as inadvertently cementing fractures during the setting of casing in holes drilled after mining

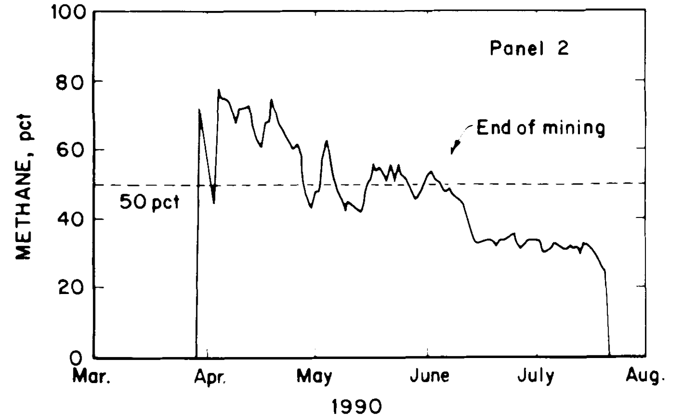


Figure 50.—Daily methane percent of produced gas, gob gas venthole 178, Lower Kittanning Coalbed, Pennsylvania.

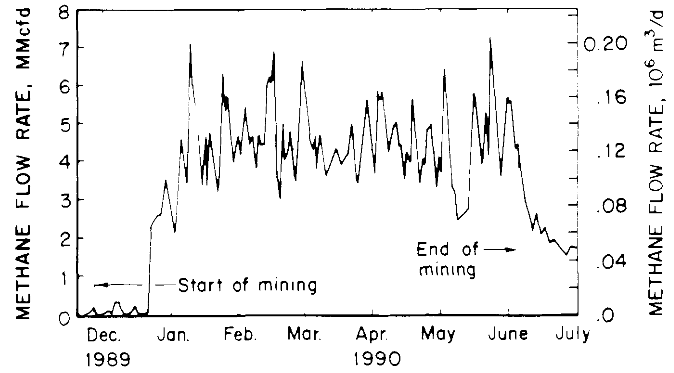


Figure 51.—Combined daily methane production from 13 gob gas ventholes on a longwall panel in the Lower Kittanning Coalbed, Pennsylvania.

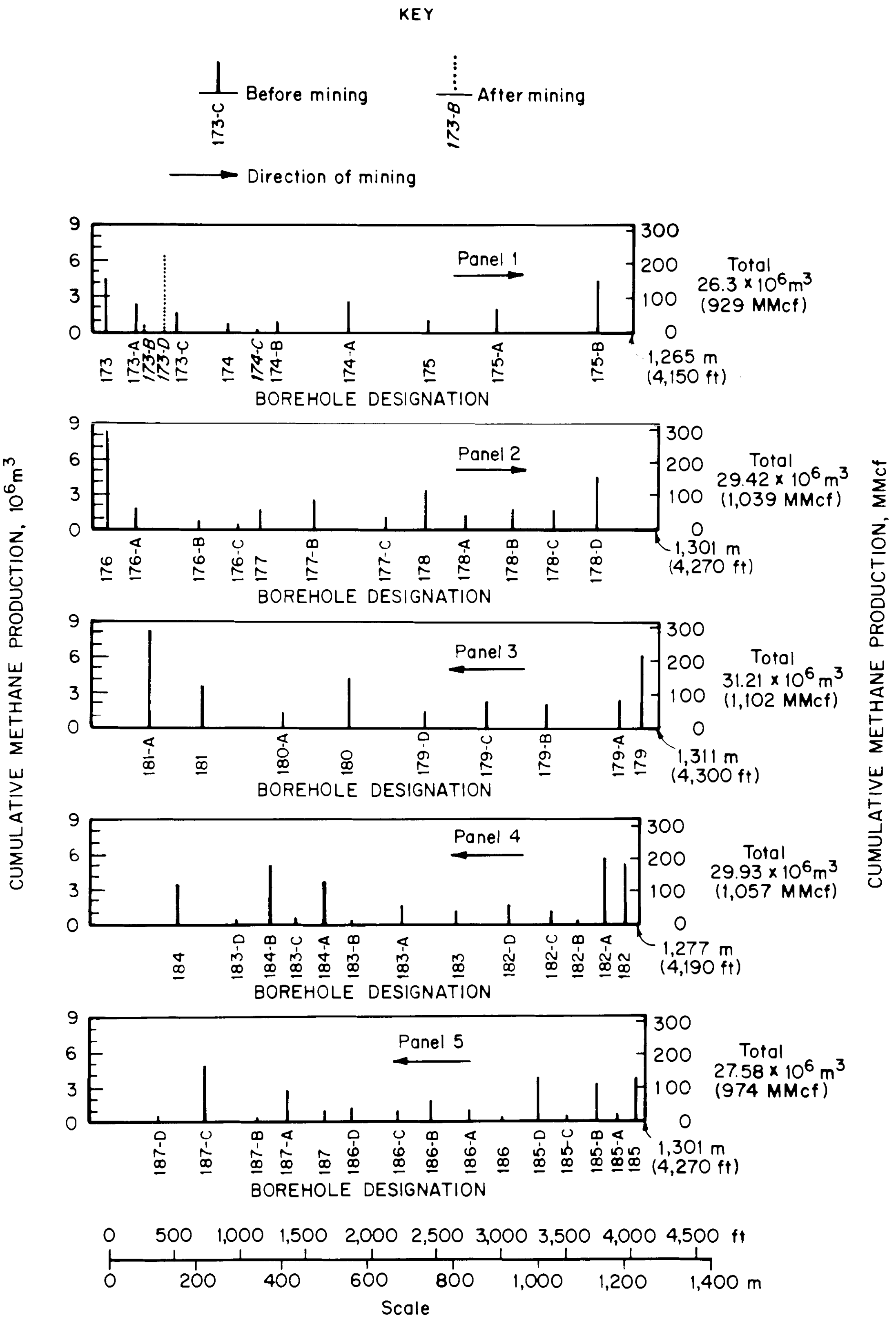


Figure 52.—Histograms of methane production from individual gob gas ventholes through 12 months (panels 1-4) and 9 months (panel 5) after panel completion, Lower Kittanning Coalbed, Pennsylvania (*18*).

(fig. 52, panel 1, hole 174-C). Another problem is setting casing above water-bearing zones that flow water into the open hole and restrict the flow of gas. If the casing is crushed or sheared off when the overburden collapses into the mine void, gas production will cease or be restricted. Geologic and/or rock strength anomalies can also influence the production rates from gob gas ventholes (*18*).

The position of the holes on the longwall panel may also influence gas production rates. In a study of five adjacent longwall panels in the Lower Kittanning Coalbed, Pennsylvania, gob gas ventholes drilled on either end of the panels tended to have the highest cumulative production (fig. 52) (*18*). The reason for this may be related to the subsidence mechanics of longwalls. At the ends of the panels, the overburden strata are partly supported on three sides by the surrounding pillars of the development entries (fig. 53). Strata in this area are draped into the subsidence trough and are under tension. This allows the mining-induced fractures at the ends of the panel to stay open longer than those in the center of the panel, where complete subsidence and recompaction occur relatively quickly. The longer the fracture permeability is maintained, the longer the gob gas ventholes remain on production, and hence, the higher the cumulative production. This, along with the gas released in the "first break" of the strata over the longwall, may also explain why higher gas emissions are commonly experienced at the beginning of panels (*70*).

Strata along the margin of the panels are also draped into the subsidence trough and should have enhanced fracture permeability (fig. 53). It is possible that placing gob gas ventholes along the centerline of the panels, as is the customary practice, may not be the optimum approach for gas production. Holes placed along the margin of the panels may produce more gas for a longer time. In an experimental application of this concept in a Pennsylvania mine operating in the Lower Kittanning Coalbed, near-margin holes vented approximately 80 pct more gas than the centerline holes on the same panel (*18*). The optimum distance from the panel margin for hole placement must be determined by evaluating the subsidence mechanics of longwall overburden, combined with site-specific experimental evaluations. The holes must be placed close enough to the panel margin to be in the zone of tension, but not so close that excessive amounts of mine ventilation air are drawn into the system. Close monitoring of the methane concentration of the produced gas and of the magnitude of vacuum applied to the system is necessary for the holes to operate at maximum efficiency.

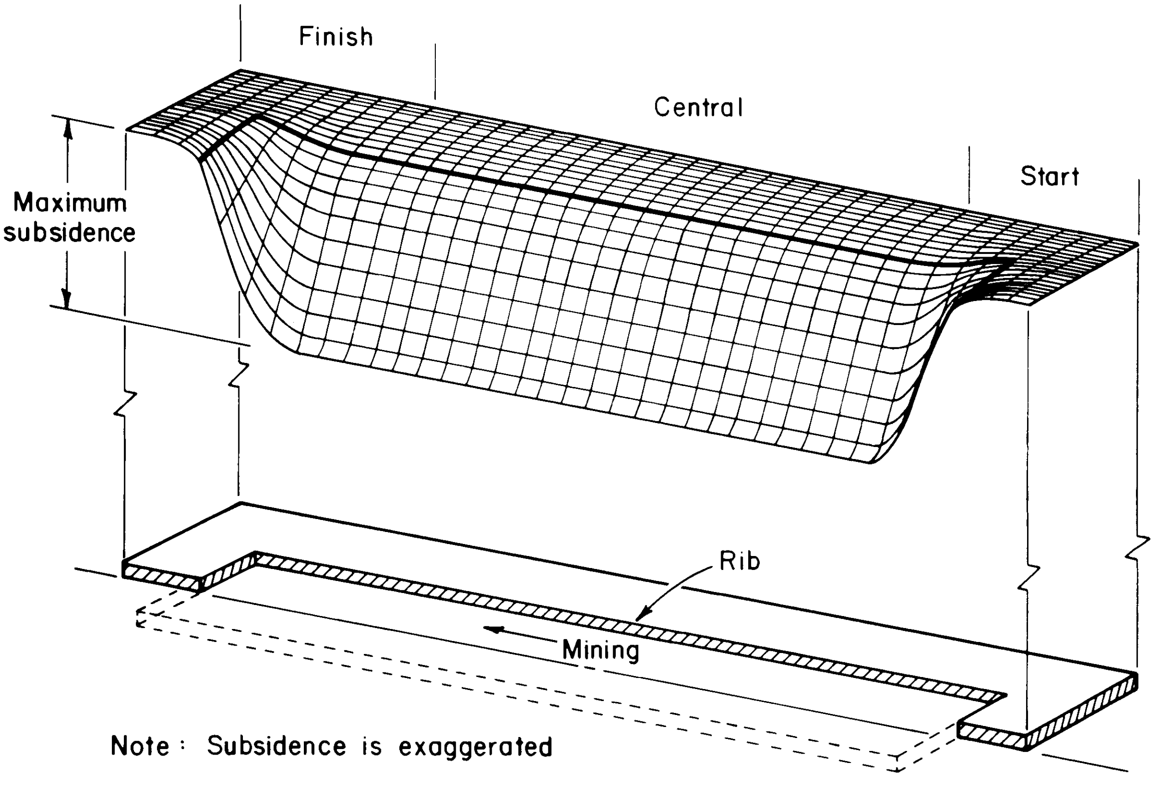


Figure 53.—Schematic perspective view of subsidence trough developed over an extracted longwall panel.

Since gob gas ventholes are not stimulated, there is generally only a small flow of gas, if any, from the holes before they are intercepted by mining. The holes could be drilled and stimulated far enough in advance of mining to produce gas from the coalbed being mined and/or from overlying coalbeds or other gas-bearing strata. By predraining gas for several months or longer before mining and converting the holes to gob gas ventholes, it may be possible to use fewer holes per panel, thereby offsetting the added cost of the stimulation treatments.

SUMMARY

Control technology exists that addresses many of the current mining-related methane emission problems in underground coal mines. A combination of general research results, experience, trial-and-error methodology, and computer-based simulations can usually provide the information necessary to select or modify appropriate methane control technology for site-specific situations. As more is learned about the occurrence, storage, and migration of coalbed methane, more effective control technologies or modifications to existing technologies will be developed.

The ability to more accurately measure coalbed reservoir properties, both in the laboratory and in the field, will improve the reliability of computer-based simulations. This will lessen the reliance on trial-and-error methods to design site-specific methane control systems and thus shorten the time required for implementation.

There has been a tremendous increase over the past 10 years in the use of stimulated vertical boreholes to produce gas from coalbeds for commercial purposes. The research and experience associated with these efforts are valuable assets that can be used to improve the applicability of the technology to the mining environment.

An area of particular concern for methane control in the United States is the increase in methane emissions as larger longwall panels are mined to increase productivity. As panel size increases, larger volumes of gas in the roof and floor strata are exposed to the mine atmosphere on a daily basis. Mining delays are already being experienced on some of these larger panels owing to higher-than-expected methane emissions. Methane emission consequences must be taken into account if the mining industry is to take advantage of the potential for increased productivity from advanced mining technology.

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