Chapter 11

Methane Control for Underground Coal Mines

William P. Diamond
U. S. Bureau of Mines
Pittsburgh Research Center
Pittsburgh, Pennsylvania, USA

INTRODUCTION

It is estimated that coalbeds in the United States contain as much as 11.3 trillion m^3 (400 trillion ft^3) of in-place gas (Kuuskraa and Brandenburg, 1989). This volume of gas represents a source of clean-burning fuel; however, methane emissions into underground coal mines present a serious hazard to coal miners. Since the first documented major U.S. coal mine explosion in Virginia in 1839, several thousand fatalities have been recorded as a result of explosions where methane was a contributing factor (Skow et al., 1980). 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 methane emissions from coal mine ventilation systems from 1971 to 1988. The volume of methane and the number of operating mines remained stable through the early to middle 1970s (Irani et al., 1972, 1974), but as of the 1980 and 1985 surveys (Grau and LaScola, 1984; Grau, 1987), methane emissions increased substantially, while the number of operating mines declined.

The decline of methane emissions in 1988 is at least partially attributed to the increased use of methane drainage

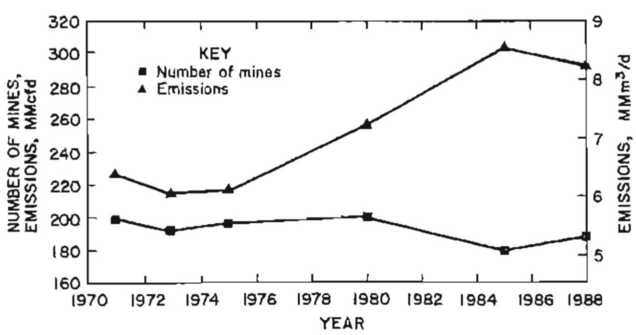

Figure 1. Daily U.S. gas emissions and number of contributing mines, 1971–1988 (Trevits et al., 1991).

technology, especially in the Black Warrior basin of Alabama. Methane emissions from Alabama coal mines decreased 17%, from 2.3×10^6 m^3/d (82.4 MMcfd) to 1.9×10^6 m^3/d (68.4 MMcfd) between 1985 and 1988 (Trevits et al., 1991). During this same time, the annual production and capture of coalbed methane for commercial sale increased 130% from 245×10^6 to 563×10^6 m^3/d (8,648 MMcf to 19,865 MMcf) (McBane, 1989). Approximately 90% of this commercial production was from methane drainage installations located on mine properties.

This paper describes the various methane control technologies available to the coal mining 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 (1955) 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 as early as 1733 at the Haig Pit, Whitehaven, England. As a result of an explosion at another colliery in 1844, 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 in the future, 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 impracticable.

In-mine cross-measure holes were used in North Wales in the late 1800s to drain gas from overlying virgin coalbeds. The first successful, large-scale use of cross-measure holes took place in the early 1940s at the Mansfield Colliery, in the Ruhr, Germany. The first recorded successful use of a vertical borehole to drain gas from virgin coal occurred at this same mine in 1943 (Venter and Stassen, 1953; Perry, 1959).

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 1900s (Darton, 1915). Lawall and Morris (1934) 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 an 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 (1941) 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 1219 to 1524 m (4000–5000 ft), control the elevation of the hole at any depth, and follow the contours of the coalbed. Unfortunately, Ranney (1941) 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 became widely used throughout the coal fields of Europe in the 1940s (Bromilow and Jones, 1955). 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 (Reeves, 1978).

In the early 1930s in the United States, a 26 m (85 ft) deep, 7.6 cm (3 in.) diameter core hole was used to successfully drain gas from "broken sandstone" above a mined-out section in the Pocahontas No. 5 Coalbed, Virginia. The coalbed was 52 m (170 ft) deep (Coal Age, 1938). 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%. The holes were similar in concept to the gob gas vent holes used today to drain gas from longwall mining operations.

Tilton (1976) noted the production of gas from vertical wells completed in 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 Pittsburgh Coalbed, with 36×10^6 m^3 (1217 MMcf) of gas produced through 1984 (Trevits and Finfinger, 1985).

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 (Spindler and Poundstone, 1960). The first well was a dual completion in the Sewickley Coalbed at a depth of 113 m (370 ft), and the Pittsburgh Coalbed at 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 due to the completion design that precluded removing water from that zone.

A second well at the same mine site was equipped with a down-hole water pump and a vacuum pump on the surface to draw gas from the coal. Maximum gas production reached 0.5×10^3 m^3/d (16 Mcfd). After 10 months of low production, an attempt was made to increase production by "shooting" the well with nitroglycerine. 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 (Spindler and Poundstone, 1960). 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 stimulation treatment consisted of 38 m^3 (10,000 gallons) 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 4137 kPa (600 psig) was reached. The pressure of 4137 kPa (600 psig) remained constant throughout the treatment, which 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 by Lawall and Morris (1934) and Burke and Parry (1936). Lawall and Morris (1934) noted 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; and that, based on a price of \$0.10/28.3 m^3 (Mcf), its value was \$1300.00/day. Ranney (1941) estimated 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 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." Price and Headlee (1943) 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 methane drainage program requires substantial capital expenditure and certainly should not be undertaken if it is not necessary. 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 et al. (1987). A mine operating in the Pocahontas No. 3 Coalbed, Virginia, lost 333 hours of production time due 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 et al. (1987) 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 (Diamond, 1979, 1982; Puglio, 1981). This course of action offers a distinct advantage to the common practice of waiting until a methane emission problem has become acute before methane drainage is considered. If a pre-mining course of action is taken, the necessary geologic, engineering, and reservoir data can be obtained early, so that the various methane drainage options can be evaluated for their effectiveness relative to the site-specific conditions (Mavor and Schwoebel, 1991). 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 become acute. Retrofitting a methane drainage system into an existing mine will 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 theoretical approach. If there are active mines in the general area with similar geologic conditions and coal characteristics, a review of the level 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 (Diamond et al., 1986). The "direct method" procedures require that the coal sample to be tested be sealed in a desorption canister as soon as it is retrieved from the core hole to minimize the amount of gas lost before gas content testing begins. Gas is periodically bled from the container, measured, and the results corrected to standard temperature and pressure conditions. 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 procedure provides an increased level of accuracy, but at a higher level of instrumentation sophistication, procedural complexity, and cost (Ulery and Hyman, 1991). 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 modified direct method 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. For additional information concerning gas desorption, see Yee et al. (this volume).

Gas content values can be compared to 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 to the test results from the new area of interest. A listing of direct method test

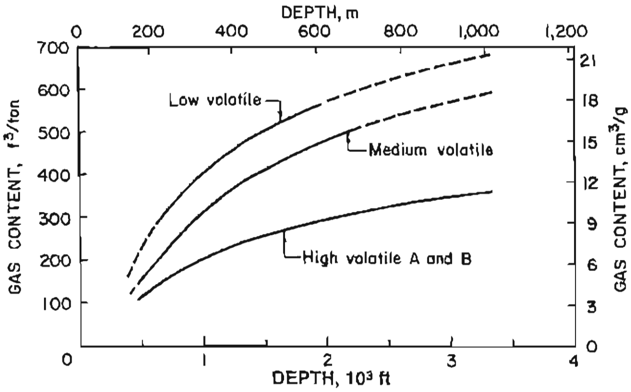

Figure 2. Gas content vs. depth and coal rank, Black Warrior basin, Alabama (McFall et al., 1986a).

results for approximately 1500 coal samples taken from more than 250 coalbeds in 17 states is included in Diamond et al. (1986).

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 (Diamond et al., 1976b, 1987; Steidl, 1977; Iannacchione and Puglio, 1979; Diamond, 1982; Iannacchione et al., 1983; McFall et al., 1986a, b; Kelafant et al., 1988). These curves can be used to estimate gas content values only if the rank and/or depth are known (Figure 2). The curves are best used for estimating in-place gas volumes in regional studies. They should be used with caution for a relatively small, mine-sized 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. There are numerous geologic and mining factors in addition to the in-place gas content that influence the 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 381 to 792 m (1250 to 2600 ft) where gas contents approach 18.8 cm^3/g (600 ft^3/st) (Kline et al., 1987), and in the high-volatile A, Pittsburgh Coalbed at depths up to 305 m (1000 ft) (Mazza, 1979; Thakur and Poundstone, 1980; Puglio, 1981) where gas contents are commonly only about 4.7 to 6.3 cm^3/g (150–200 ft^3/st) (Diamond et al., 1986).

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 (King and Ertekin, 1989). However, several models have been adapted to include horizontal holes drilled from underground workings, as well as the influence of adjacent mine workings (Schwerer et al., 1984; Hyman and Stahl, 1985; Sung et al., 1987; Saghafi, 1989; Mavor and Schwoebel, 1991). A more thorough treatment of the use and data requirements for the various coalbed gas reservoir models is given in the chapter in this volume on reservoir engineering by McElhiney et al.

A comprehensive mine simulator, combining the variables of mining operations and coalbed gas reservoir/production simulators, that could predict mine-wide ventilation/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 due to the difficulty in predicting the need for methane drainage.

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/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 (Von Schonfeldt et al., 1982; Dunn, 1984). To illustrate the commercial potential, coalbed gas wells in the Black Warrior basin of Alabama marketed 1.35×10^9 m^3 (47.6 billion cubic feet [BCF]) in the first three quarters of 1991 (McBane, 1992). Cumulative production from coalbed gas wells in the basin was nearly 5.04×10^9 m^3 (178 BCF) through September 1991, with about 75% of the production originating from wells located on mine property.

ESTABLISHING A GEOLOGIC FRAMEWORK

Once the need for methane drainage has been established, a geologic framework must be established for the site. A site-specific (mine-wide) 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 also be taken into account when finalizing drilling locations.

General Mapping Requirements

Two basic types of maps are required for methane drainage planning; isopachs 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 for the design 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 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, then 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 nevertheless disrupts the continuity of the strata. The void will likely result in drilling problems and may cause abandonment of the well before the target coalbed is reached.

Coalbed discontinuities also adversely affect both the drilling and production of gas from horizontal boreholes.

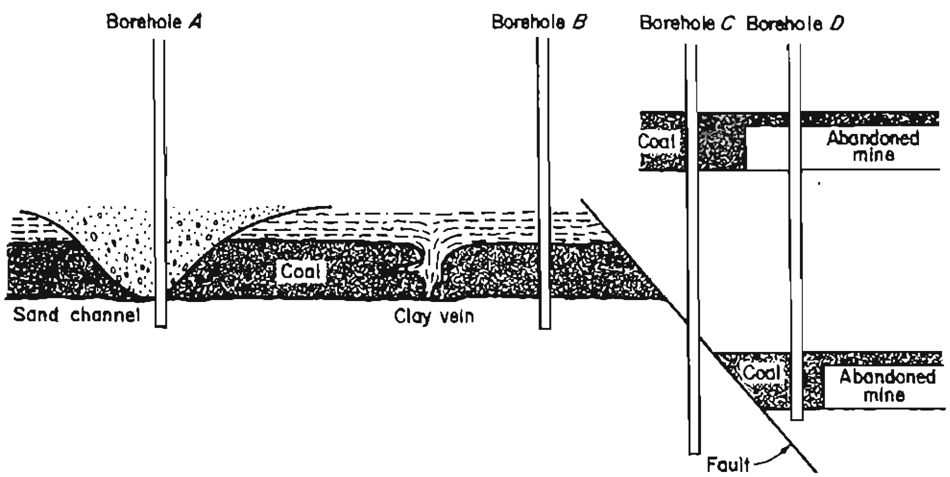

Figure 3. Schematic section view of effect of coalbed discontinuities on vertical methane drainage wells (Diamond, 1982).

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 due to the reduction in hole length caused by encountering splits and the eventual pinch-out of the coalbed 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.

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 can 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 (Houseknecht, 1982).

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 they 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 (Figure 5). Diamond et al. (1991) found that coalbeds as much as 66 m (200 ft) above the extracted 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 includes multiple zone completions in vertical wells drilled in advance of mining as well as post-mining 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 (Figure 6). In water-saturated coalbeds, the Darcy flow of gas through the cleat system is controlled by the degree of pressure reduction from dewatering. Dewatering is controlled by the permeability of the cleat and the conductivity of horizontal holes drilled into the coalbed or induced 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 (McCulloch et al., 1974). The face cleat is the dominant fracture, generally extending for several feet laterally and cutting through bedding. The butt cleats are usually less well developed and have a short lateral extent. Butt cleats commonly terminate against a face cleat and do 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 the coalbed was deposited. Gas flow should be enhanced in the face cleat direction due to the differences in physical character and associated permeability between the face and butt cleat. The influence of directional permeability on methane drainage is discussed in greater detail in later sections of this paper as well as in Close (this volume).

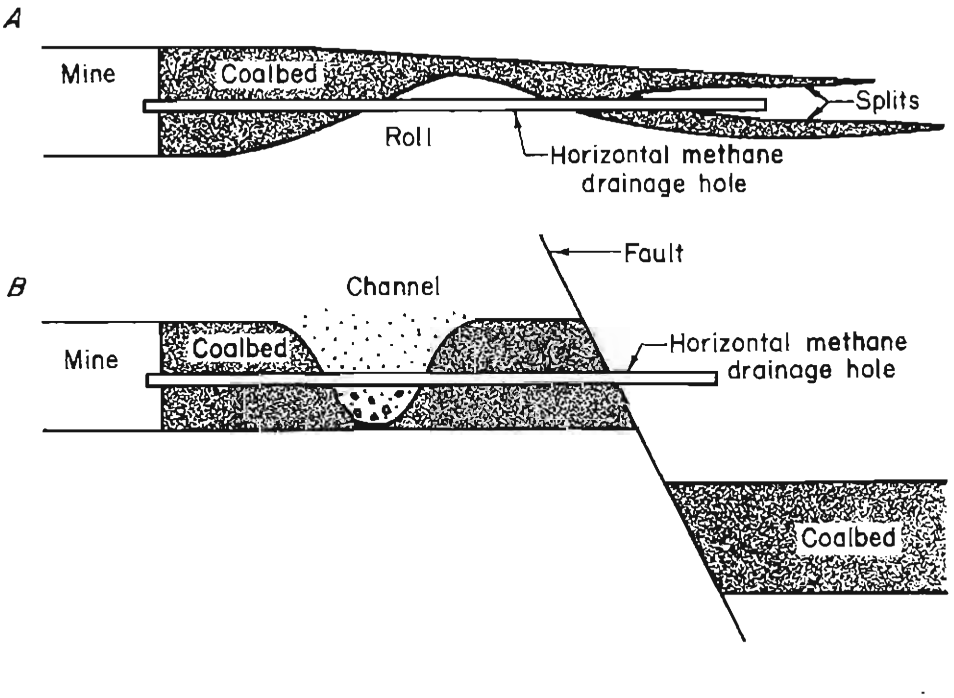

Figure 4. Schematic section view of effect of coalbed discontinuities on horizontal methane drainage holes.

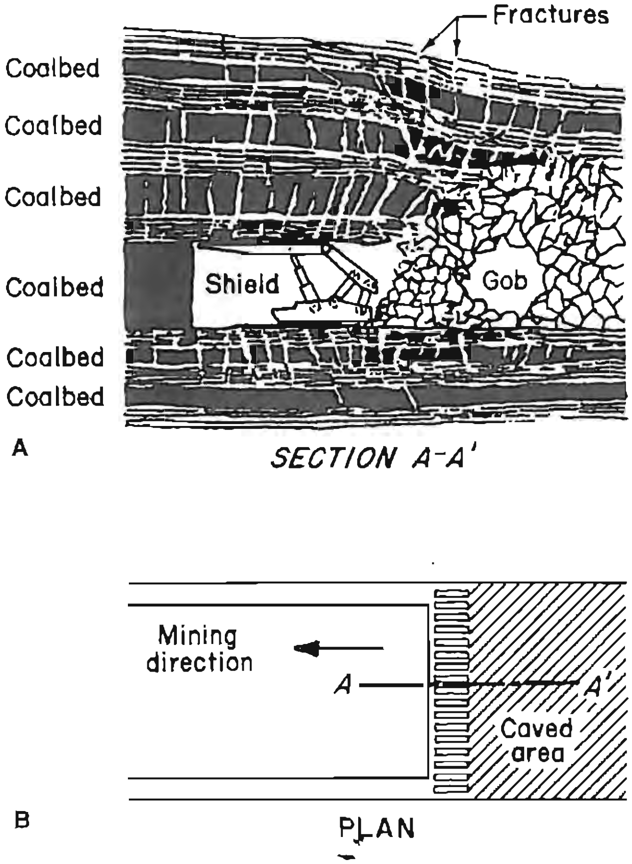

Figure 5. Schematic (A) section view of longwall mining with gob gas conduits, and (B) plan view of longwall panel (Cervik, 1979).

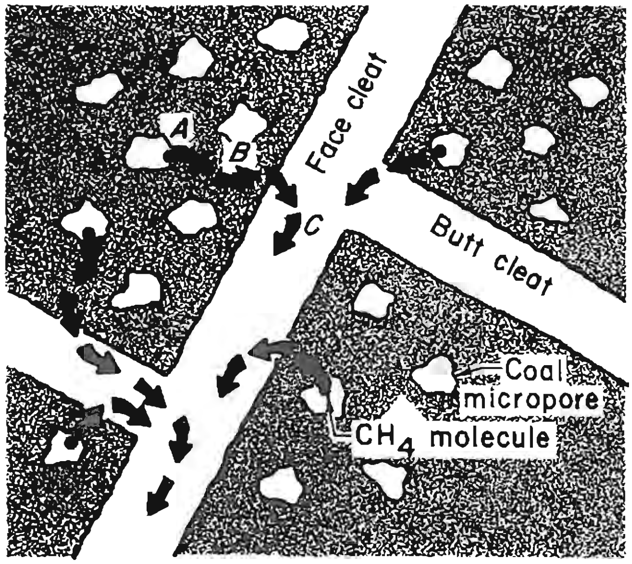

Figure 6. Schematic plan view of (A) desorption of methane from coal micropore, (B) diffusion through coal matrix, and (C) darcy flow through cleat.

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 (McCulloch et al., 1976; Diamond et al., 1976a). Where no other data are available, an oriented core sample can be used to determine cleat direction (Boyer et al., 1986).

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 et al. (1988) 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% greater gas production and 50% greater water production than wells in unfractured areas. Additionally, Briscoe et al. (1988) showed that the position of wells relative to the regional dip of the coalbed influenced production. Up-dip wells in a 38 well field dewatered and produced gas before the down-dip 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 (Patchen et al., 1991).

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 practiced 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 differ from those in the United States. European coal measures 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 due 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 has 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. For this paper, they will generally be grouped as either underground or surface technologies.

Underground Methane Drainage

Horizontal Holes—In Mine

Most underground methane drainage technologies entail the drilling of horizontal holes into the coalbed being mined. In the United States, horizontal holes 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 holes 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 be drilled 305 m (1000 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 hole can be drilled perpendicular to the face cleat to maximize the drainage of gas by intercepting the greatest number of these primary conduits of gas flow.

A major disadvantage of horizontal holes is that they must be drilled in the very restrictive underground 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 holes underground also requires close coordination between the mining plan and the methane drainage plan. Neither operation must hinder the other, both in terms of logistics and in completing their respective activities so as not to impede the other's progress.

Underground horizontal holes 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. The drainage of gas can be either in advance of mining or during mining as part of the mining cycle. Shielding can be accomplished by either intercepting the gas before it enters the mine atmosphere or by diverting the migrating gas from the active face area. Proper placement of the holes can also provide a combination of control functions.

Horizontal holes drilled from existing underground mine workings can be used for long-term methane drainage in advance of mining. In the mid-1970s, two horizontal holes were drilled in the Upper Sunnyside Coalbed, Utah, from a set of entries abandoned for more than a year due to high methane emissions (Figure 7). The two holes were drilled 131 and 137 m (430 and 450 ft) into the coalbed. Averaged combined production from the two holes was over 4.0×10^3 m^3/d (140 Mcfd), or about 15 $m^3/d/m$ (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%. This enabled mining to resume in the area (Perry et al., 1978).

In the late 1970s, in a Pennsylvania mine, four long horizontal holes were drilled into the Pittsburgh Coalbed from a section that had been abandoned for 2.5 years due to high gas emissions. The length of the holes ranged from 299 to

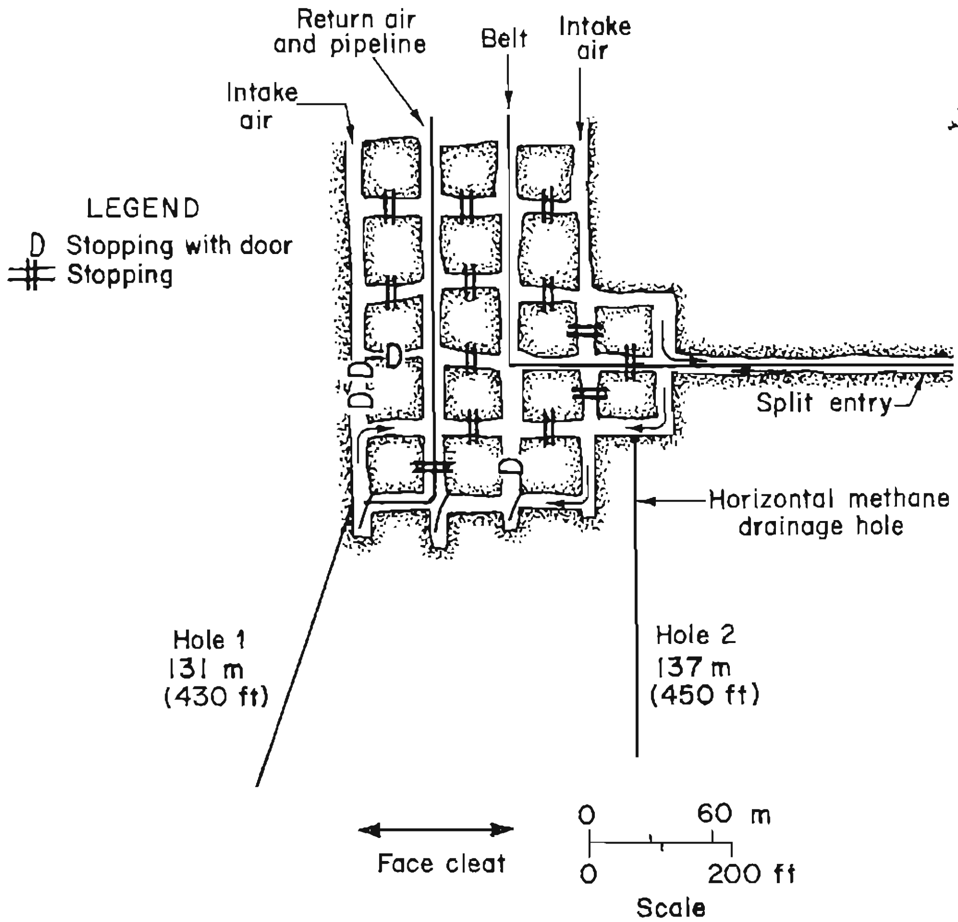

Figure 7. Plan view of horizontal methane drainage holes, Sunnyside Coalbed, Utah (Perry et al., 1978).

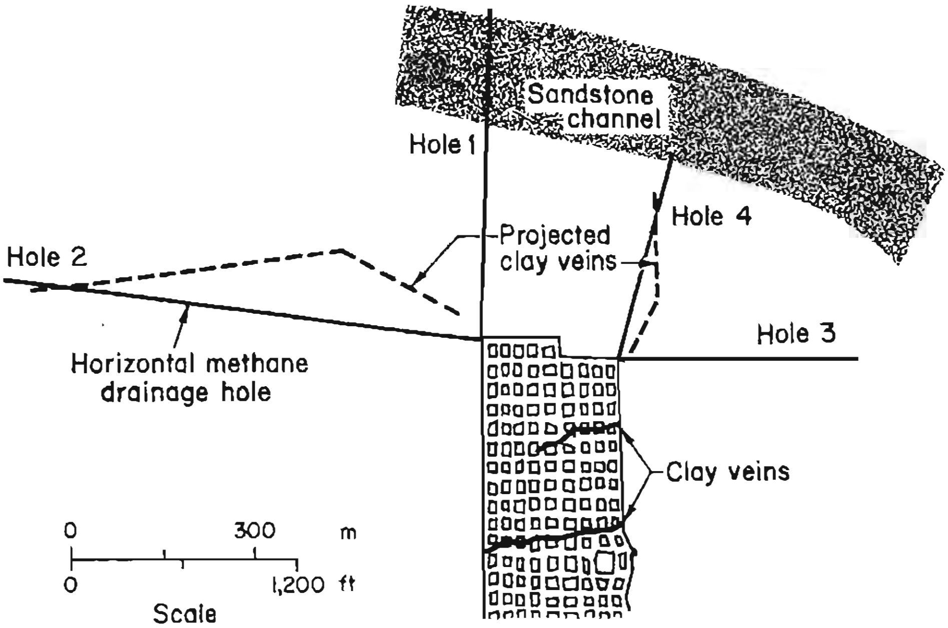

Figure 8. Plan view of horizontal methane drainage holes, Pittsburgh Coalbed, Pennsylvania (Prosser et al., 1981).

764 m (982 to 2505 ft) (Figure 8). The combined initial flow rates of the four holes 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 (Prosser et al., 1981). 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 due to the presence of a sandstone channel and clay veins that effectively isolated this area from the rest of the 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 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 holes 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 15.4 cm (6 in.) diameter steel underground pipeline was included in the methane drainage system to transport 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 a portion of the gas production to produce electricity from a turbine generator to power a ventilation fan (Prosser et al., 1981).

In the late 1970s, a 308 m (1010 ft) horizontal hole was drilled to drain gas from the Mary Lee Coalbed, Alabama (Perry et al., 1982). The hole was drilled from a set of old workings into an adjacent area that was to be mined in the following year (Figure 9). The hole produced gas at a rate of 5.7×10^3 m^3/d (200 Mcfd) or 18.4 $m^3/d/m$ (200 cfd/ft) of hole initially 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 $\times 10^6$ m^3 (40 MMcf). Methane emissions at the face were reduced by as much as 60% after the initiation of methane drainage (Figure 9).

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 et al. (1985) 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

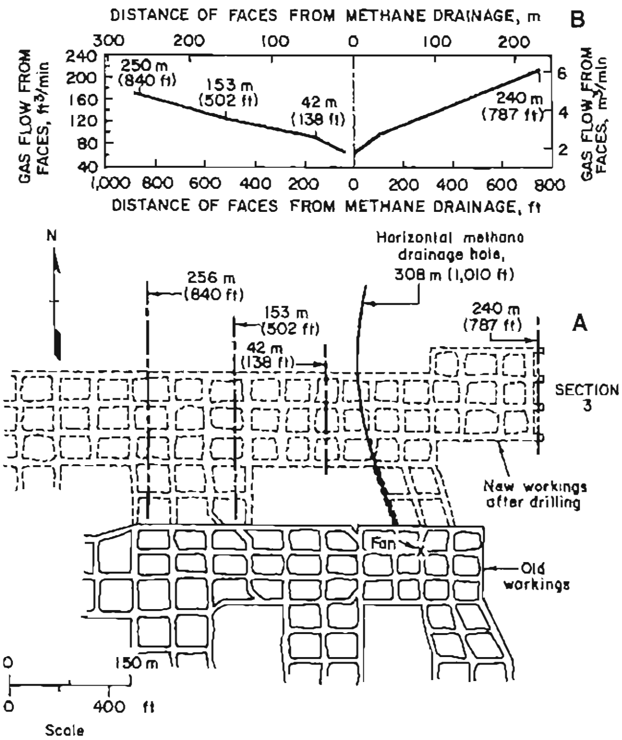

Figure 9. (A) Plan view of horizontal methane drainage hole, and (B) gas flow in relation to mine advance, Mary Lee Coalbed, Alabama (Perry et al., 1982).

development of down-hole surveying systems to replace the time-consuming single-shot survey tools that must be pumped down the hole and retrieved for each survey (Thakur and Poundstone, 1980; Thakur et al., 1988; Kravits and Millhiser, 1990).

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 require the use of several types of methane drainage systems, including several applications of horizontal holes.

Long (>305 m [>1000 ft]) horizontal holes 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 10 illustrates an application of long horizontal holes (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 (1991) observed that between 1983 and 1990, longwall productivity increased by 200 to 400%, accompanied by a 200 to 300% 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 (1200 to 2400 ft), with gas contents as high as 18.8 cm^3/g (600 ft^3/st). Methane emission rates at the mines averaged between 0.48 and 0.68×10^6 m^3/d (17 and 24 MMcfd) in 1990.

Due to the increase in methane emissions, methane control systems at this mine had to evolve to keep pace with the improvements in mining technology. At the lower longwall mining rates, sufficient time was available for the outlined panel to effectively drain gas naturally, especially the middle and completion end of the panel, which have the longest time to drain gas. Face emissions were effectively controlled by ventilation, and gob gas was drained using vertical vent holes. However, as productivity increased,

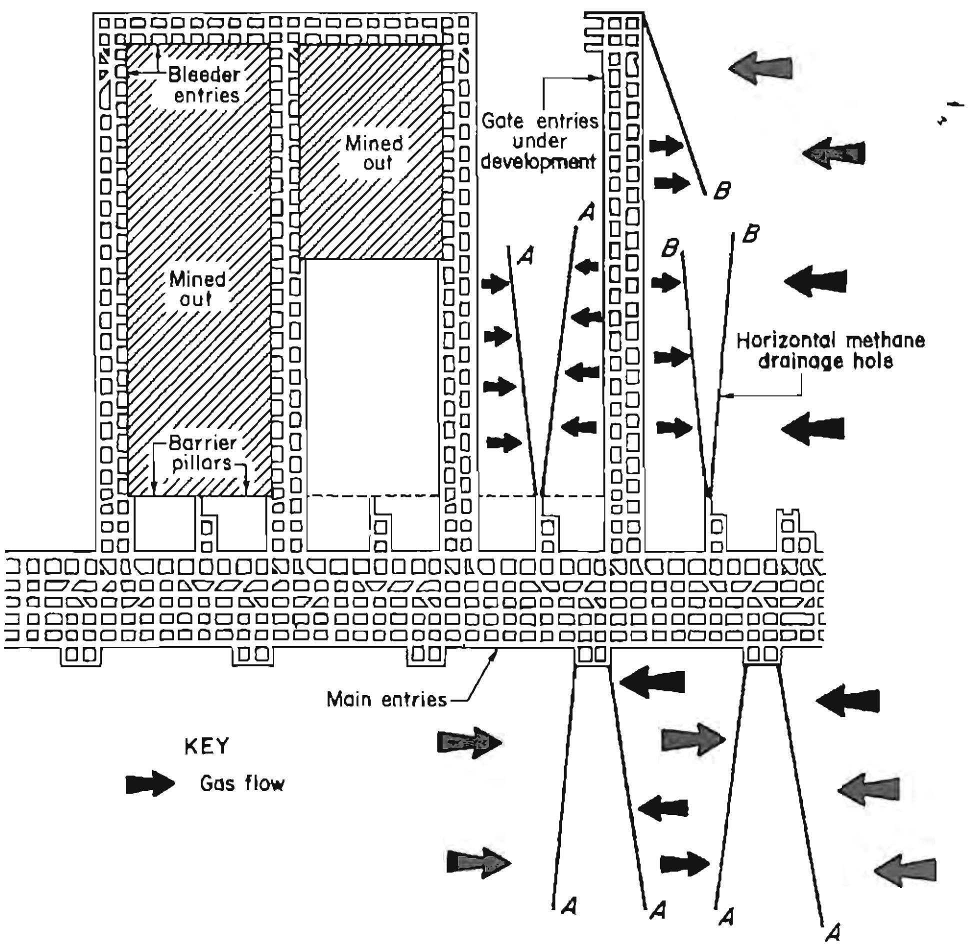

Figure 10. Schematic plan view of horizontal holes for methane drainage in longwall mining, (A) in advance of mining, and (B) for shielding.

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 11 (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 (1991) report that the 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, mining delays were encountered at the start-up end of the panel, because the horizontal methane drainage holes were only on production for a short time.

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 holes at the start-up end of the panel can be placed closer together to drain more gas in a shorter time. Or the drainage holes can be drilled from the tailgate side into the developing panel (Figure 11, Holes B) and/or from advancing entries into the virgin coal beyond the developing panel (Figure 11, Holes C). Drilling from the tailgate side is the strategy generally adopted by most mine operators (Mills and Stevenson, 1989; Aul and Ray, 1991).

The importance of drainage time on reducing the in-place gas content of coal in a developed longwall panel was found by Aul and Ray (1991) to be significant in the Pocahontas No. 3 Coalbed. Only 30% of the gas can be removed from the coal if drainage time is less than 2 months. Holes that produce for 10 months were able to drain 80% of the gas from the coal. It was concluded that at least 6 months are required to drain a sufficient volume of gas from the Pocahontas No. 3 Coalbed with the holes drilled on 61 m (200 ft) centers. Holes 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 virgin coal away from mining (Figure 11, Holes C).

Mining conditions in the Pocahontas No. 3 Coalbed were significantly improved as the result of the horizontal methane drainage program (Aul and Ray, 1991). 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). Reduced air volumes benefited the mine in several peripheral ways beyond reduced ventilation costs. Lower air volumes at the longwall face also reduced the amount of dust in the air, and generally increased worker comfort. The tailgate methane drainage holes also benefit the subsequent development entries for the next panel by reducing the in-place gas volume in that area.

Similar conclusions were reached by Mills and Stevenson (1989) from their experience with mining operations in the Blue Creek Coalbed, Alabama. Short horizontal methane drainage holes drilled from the tailgate entries (Figure 11, Holes B and C) were preferred, because drainage time from the panel was maximized (as much as 2 years) and the holes provided relief during drivage of the development entries. In one panel, 43% of the in-place gas was removed by the short horizontal holes in advance of mining. In a comparison of two longwall panels cited by Mills and Stevenson (1989), down time was reduced from 146 hours on a panel without horizontal drainage holes to no down time on the adjacent panel that utilized the holes.

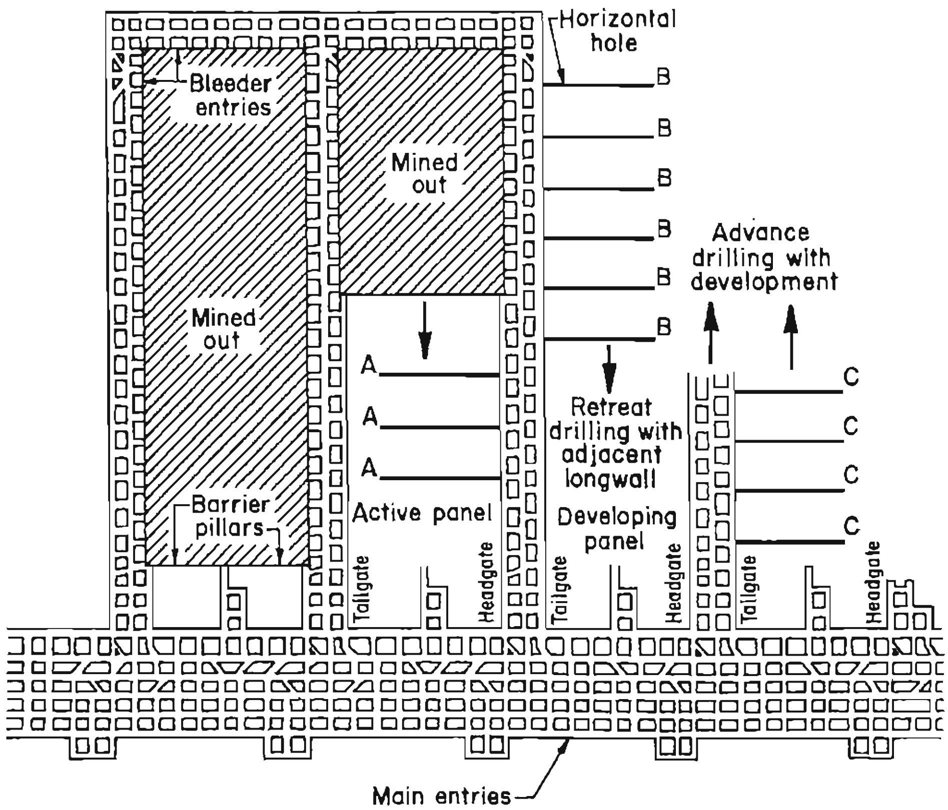

Figure 11. Schematic plan view of short horizontal holes used for draining gas from longwall panels, (A) on active panel in advance of face, (B) on developing panel adjacent to active panel, and (C) from advancing entries.

Aul and Ray (1991) reported that in 1990, 28.3×10^6 m^3 (1 BCF) of methane was removed from the Pocahontas No. 3 Coalbed using underground horizontal methane drainage boreholes. Mills and Stevenson (1989) reported that approximately 12% 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 is produced from horizontal holes, while about 80% is from vertical gob gas vent holes and 8% 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, both in 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 (Aul and Ray, 1991). The pipeline gathers the gas from the individual holes and transports it to the surface through a vertical borehole. In order 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 (Irani et al., 1980; Prosser et al., 1981) to shut in the individual holes and the pipeline has been utilized by most companies 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 (Figure 12). The PVC pipe is connected to pneumatic valves that 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.

Methane sensors spaced along the pipeline, typically every 152 to 305 m (500 to 1000 ft), 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%), 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, even perhaps before development mining has started, is to drill horizontal holes 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 they 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 expensive if put in place sooner, and that 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-1970s at a West Virginia mine operating in the Pittsburgh Coalbed. The first installation (Figure 13) was a large borehole (1.2 m [4 ft] diameter casing), with a 4.3 m (14 ft) diameter room in the coalbed (Fields et al., 1973, 1975). From the bottom of this hole, seven horizontal holes ranging in length from 152 to 259 m (500 ft to 850 ft) were drilled into the coalbed. In the 8 years this installation was on production, 33.4×10^6 m^3 (1178 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 hor-

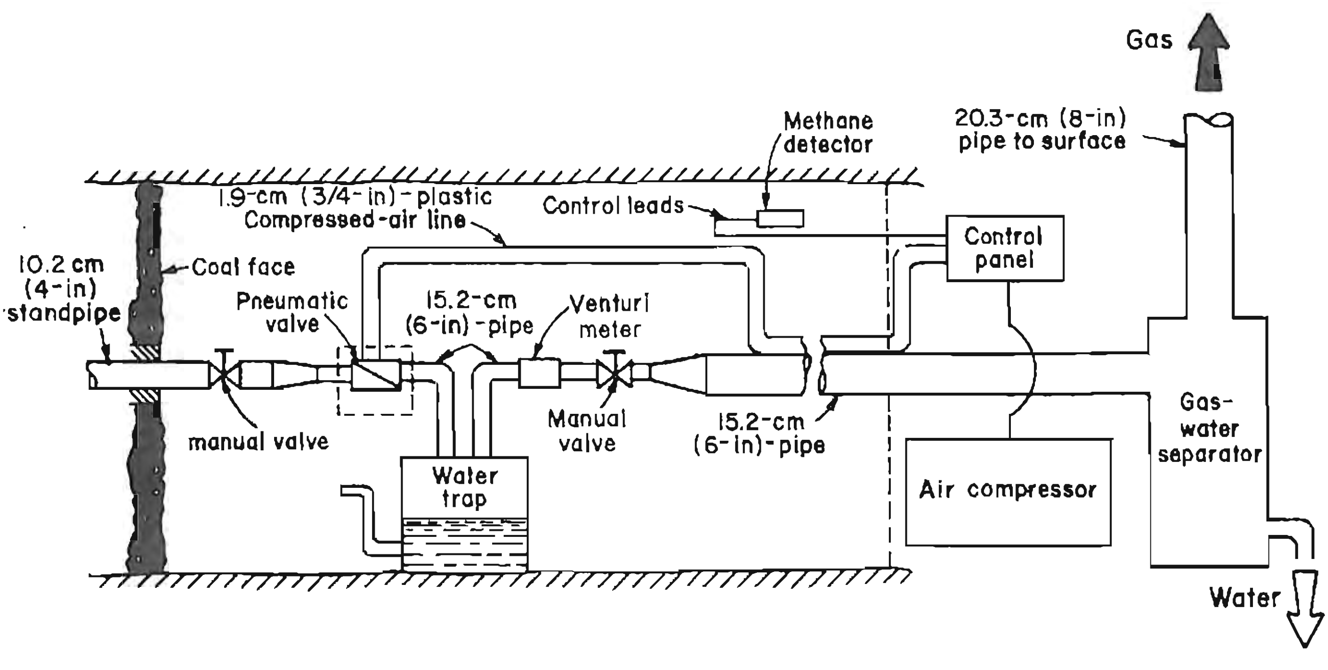

Figure 12. Schematic section view of typical horizontal methane drainage hole gas collection system with fail-safe pneumatic shut-off valve (Prosser et al., 1981).

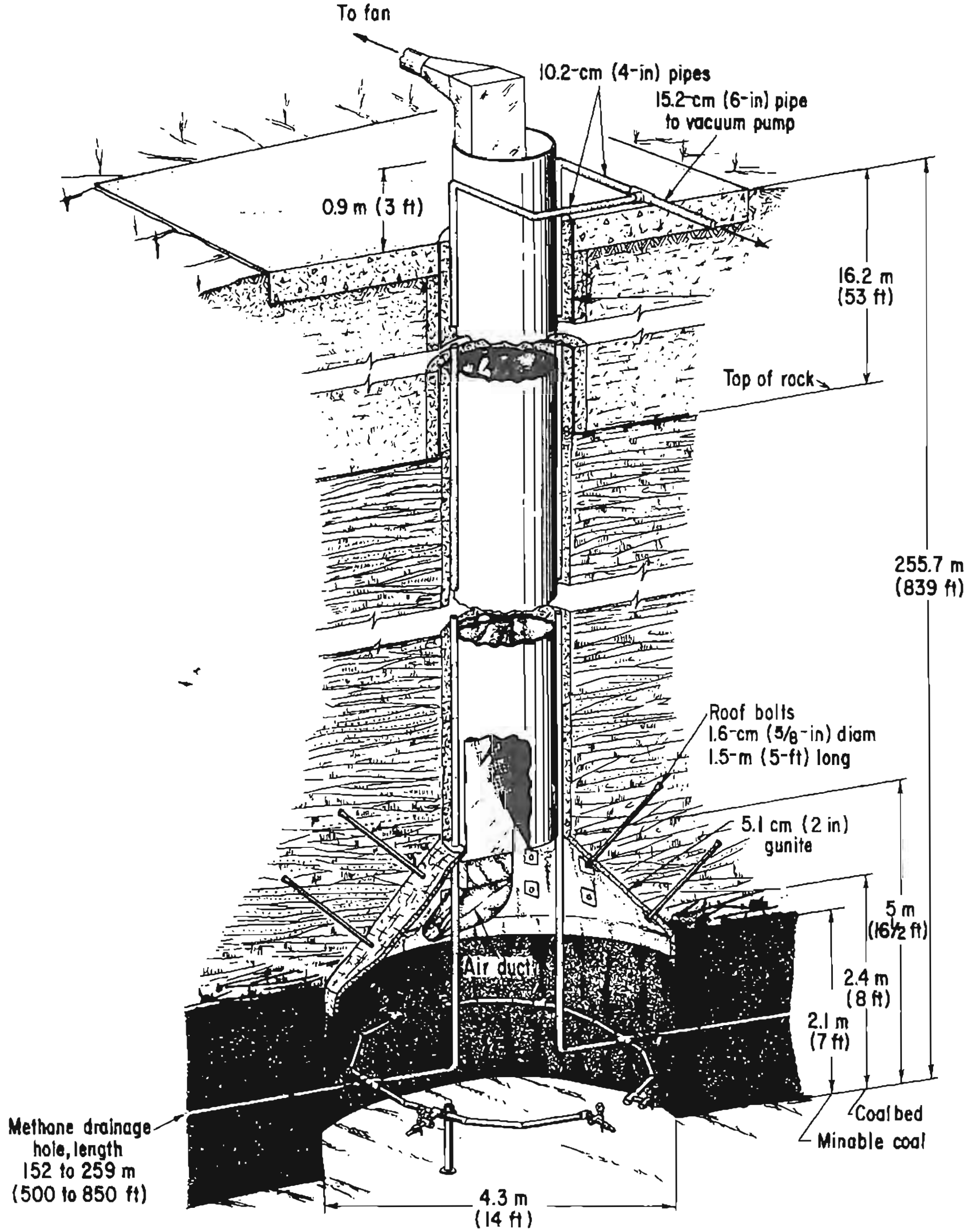

Figure 13. Schematic section view of large diameter vertical borehole for drilling horizontal methane drainage holes, Pittsburgh Coalbed, West Virginia (Fields et al., 1973).

izontal holes to depths of 204 to 648 m (670 to 2126 ft) into the Pittsburgh Coalbed (Fields et al., 1976). 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% as the installation was approached by mining (Deul et al., 1977).

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

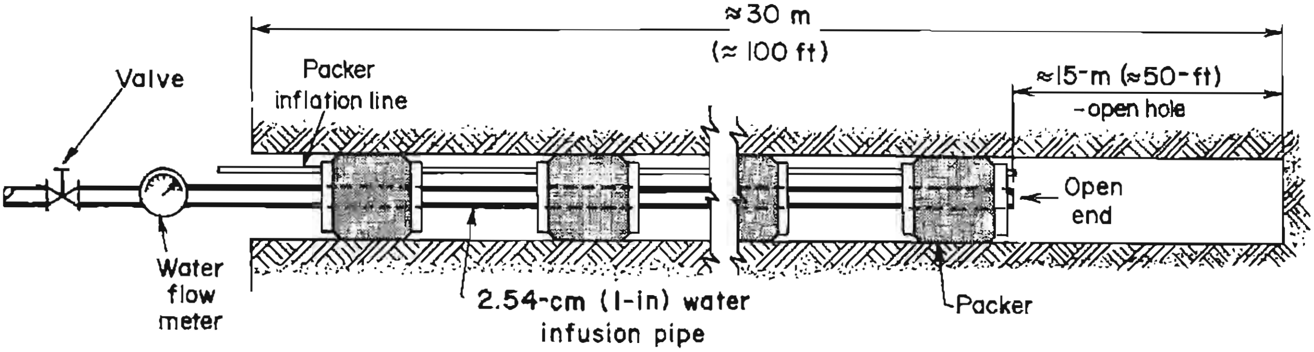

Figure 14. Schematic section view of typical water infusion horizontal hole completion (Cetinbas et al., 1972).

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 (Aul and Cervik, 1979; Oyler, 1984).

Horizontal Boreholes—Water Infusion

Horizontal holes 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 1940s (Jenkins, 1943). Water infusion using short horizontal holes 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 (Jackson and Merritts, 1951; Gregson, 1966).

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 is a natural consequence of mining into the 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 14. To form an effective water block at the face of a set of advancing entries, it is necessary to drill several horizontal holes, so that the water fronts from each infusion hole overlap. The distance between holes is dependent upon site-specific conditions, including cleat orientation (Cervik et al., 1977). 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 15, the horizontal infusion holes can be spaced further 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 (Figure 16).

Cetinbas et al. (1972) evaluated the effectiveness of water infusion holes for methane control. Four 7.6 cm (3 in.) diameter horizontal holes 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

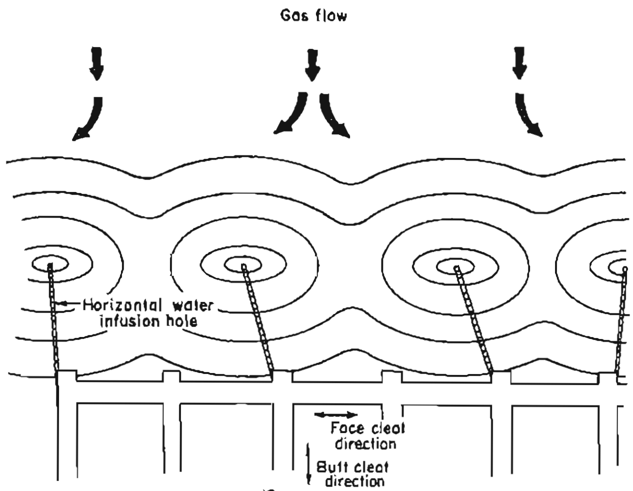

Figure 15. Schematic plan view of elliptical water fronts developed from water infusion of coalbed with face cleat perpendicular to section advance (Cervik et al., 1977).

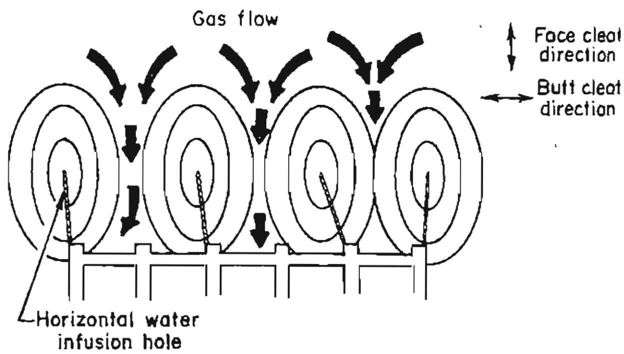

Figure 16. Schematic plan view of elliptical water fronts developed from incomplete water infusion of coalbed with face cleat parallel to section advance (Cervik et al., 1977).

3.2×10^{-4} to 6.3×10^{-4} m^3/s (5 to 10 gpm), which were continued until water appeared at the face and ribs. The time for water to reach the workings ranged from 7.5 hours for the 16.8 m (55 ft) hole to 42 hours for a 38.7 m (127 ft) hole. Water infusion reduced the flow of methane at the face by

79% and increased the flow of methane from the ribs by 24%. This confirmed that the flow of gas was blocked and diverted from the active face.

Vertical Holes into the Mine Roof

It is common for methane to enter underground workings from 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 (Finfinger and Cervik, 1979). On initial development of a new mine, high methane emissions were causing methane levels to approach 1%. 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]) holes were drilled up through the overlying coalbed from the mine. 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 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 holes were connected to a pipeline to the surface.

In the first month of operation, the flow rate from these holes averaged 4.3×10^3 m^3/d (150 Mcfd), and methane emissions into the mine were reduced by 47%. Over the 96 day life of the 37 production 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 holes 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 (Barczak, 1992). Since the total extraction of a large block of coal leaves no support to hold up the roof, the overlying strata caves into the mine void (Figure 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 outside the United States is to drill holes over the longwall panel to drain gas from the gob after the roof strata caves as the face advances. Cross-measure boreholes are preferred due to the greater depth of the mines, which makes the drilling of gob gas vent holes from the surface more expensive. Also, due to the long history of mining, and the accompanying time for cultural development on the surface, a substantial portion of the surface is inaccessible for drilling sites.

European cross-measure holes 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 (Figure 17). Cervik (1979) reported that in Poland, holes are drilled over protective pillars at the ends of the panel, in addition to cross-measure holes, 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.

The first experimental use of cross-measure boreholes on a retreating longwall panel was successfully demonstrated

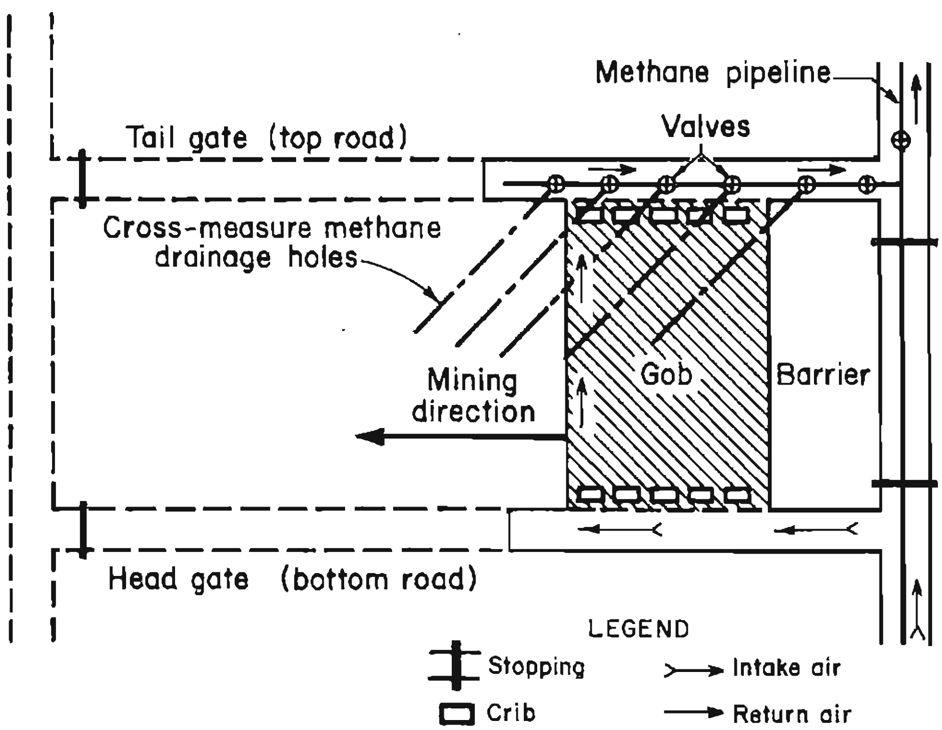

Figure 17. Plan view of cross-measure holes on advancing European longwall (Cervik, 1979).

in the United States in the Lower Kittanning Coalbed, Pennsylvania (Shatzel et al., 1982). Some modifications to the European technology were required due 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 cross-measure holes 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 (Figure 18). 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 (Shatzel et al., 1982; Campoli et al., 1983), the 4.8 cm (1.9 in) diameter cross-measure holes were oriented towards the longwall face in an attempt to capture gas as early as possible from the gob near the face (Figure 18, 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 borehole, 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 holes. Detailed engineering drawings of a typical cross-measure methane drainage system are shown in Figure 19.

In subsequent work at the same mine, Garcia and Cervik (1985) and Goodman and Cervik (1986) showed that it was not necessary to drill the holes at an angle towards the face (Figure 18, Panel B, Holes 1–13). Their analysis indicated that most of the gas production came from near the pillar line and that 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 is partially supported by the surrounding pillars, thus preventing the quick recompaction of the gob in that area (Diamond, 1991). Also, the ends of the holes beyond the pillar line may be sheared off as the longwall progressively mines under the holes.

Methane flow rates from the refined cross-measure holes generally averaged from 0.14 to 0.24 m^3/s (300 to 500 cfm) through the central part of the panels, were slightly less at the beginning, and more at the completion end. Approximately 70% 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 hole 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 as deep as 700 m (2300 ft). As mining depth increased, methane emissions have also increased. It has become common practice to pre-drain gas from both the coalbed to be mined as well as 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 pre-mining 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 (Figure 20). 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 cross-cuts to the coalbed.

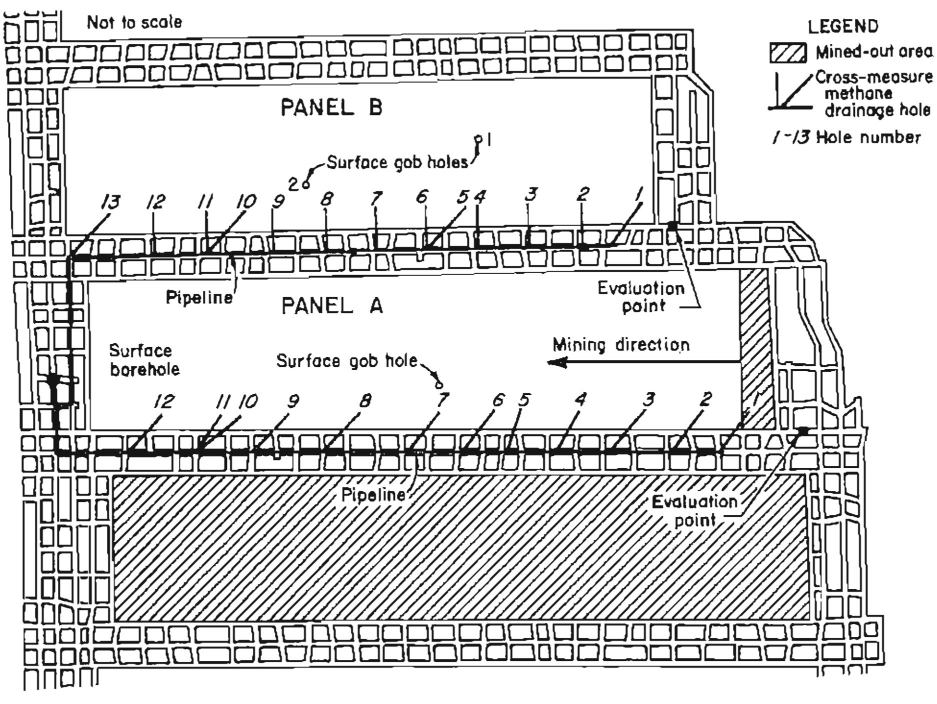

Figure 18. Plan view of cross-measure holes on retreating U.S. longwall (Goodman and Cervik, 1986).

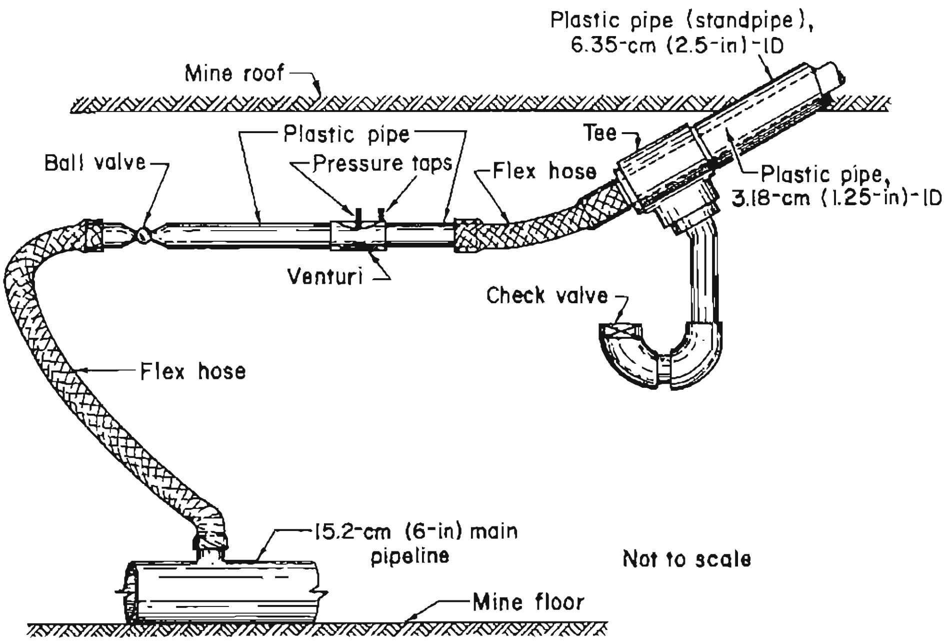

Figure 19. Schematic section view of a typical gas-gathering system for cross-measure holes (Garcia and Cervik, 1985).

Cross-cuts are driven perpendicular to the main roadway to intercept the coalbed for the development of the longwall panels. Additional cross-measure type predrainage holes are drilled into the coalbed from "boring stations" along the cross-cuts (Figure 21). Once the coalbed is intercepted, then the gateroads are driven along strike to connect adjacent cross-cuts. A third set of horizontal holes 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 (Figure 22). Finally, the cross-cuts or adjacent gateroads may be used to drill the more traditional cross-measure holes into the gob for post-mining drainage.

A unique combination of the cross-measure technique with long horizontal holes is reported by Ohga and Higuchi (1987). At one mine, the coalbeds are relatively flat-lying, but the overlying coalbed was reported to be of low permeability, which 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 coalbed towards the face from the completion end of the panel (Figure 23). The holes were then drilled parallel to the strata for 500 to 700 m (1640 to 2300 ft) towards the approaching face location. As the strata relaxed above the caved zone, sufficient fracturing apparently developed allowing the long horizontal holes to drain significant volumes of gas. More gas was drained by this technique than by the previously attempted pre-mining drainage using multiple, short cross-measure type holes. In addition to the increased gas production, a 45% reduction in manpower and 60% reduction in drilling cost for the long horizontal holes was realized.

In addition to gas entering a longwall operation from overlying strata, underlying strata can also contribute significant volumes of gas to the mine atmosphere. As a longwall face advances, relaxation of the 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 (Figure 24) to the 1 m (3.3 ft) thick Balogownie Coalbed, lying 14 m (46 ft) below. The hole was then drilled 829 m (2720 ft) in the coalbed. A second "branch" hole was drilled 723 m (2370 ft) into the coalbed. At the time of the report by Hungerford et al. (1988), production data was not yet available.

A common methane control 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 build-up 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 (Figure 25) (Cervik, 1979). 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 boreholes 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 and 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. Holes drilled from the surface into virgin, water-saturated coalbeds must be dewatered to lower the pressure and initiate gas flow. This can result in a considerable time lag before gas is actually produced and 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 drainage systems. Vertical gob gas vent holes are the method of choice

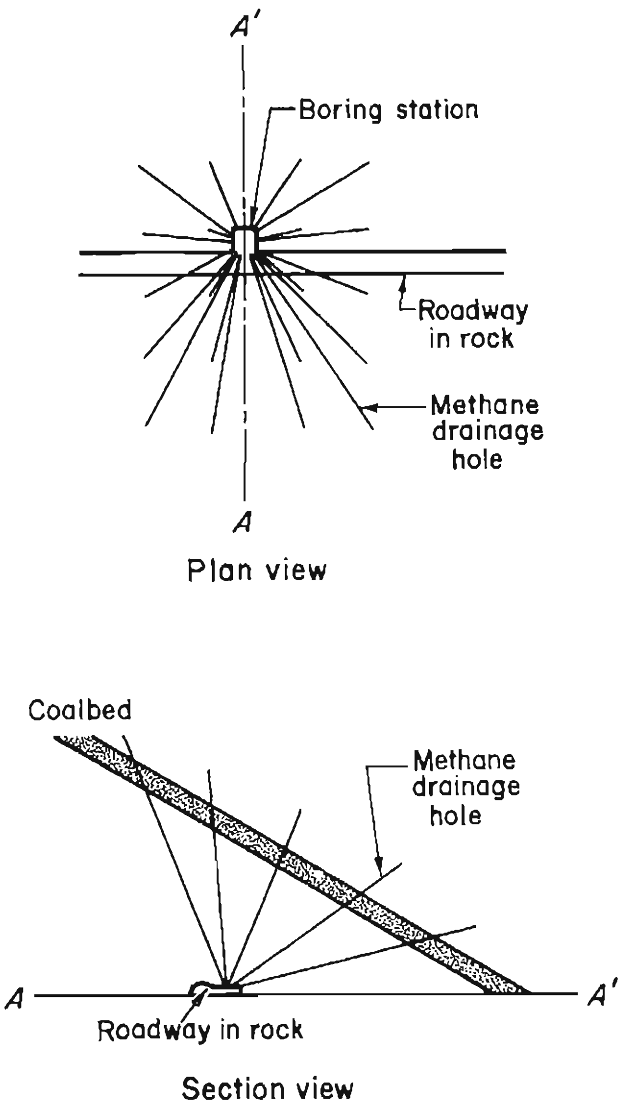

Figure 20. Schematic plan and section view of methane drainage holes drilled from roadway driven along strike in rock below mined coalbed, Japan (modified from Ohga and Higuchi, 1987).

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 drainage systems drilled from the surface. This is in contrast to other countries where holes drilled from the surface are less common and where utilization of the gas produced from the underground systems has long been a standard practice.

Stimulated Vertical Wells in Virgin Coalbeds

The drilling, completion, and production aspects of stimulated vertical wells used to drain gas from virgin coalbed gas reservoirs are discussed in detail in various other papers in this volume and therefore will not be repeated here. However, issues of particular relevance to the mining environment will be addressed.

The use and effectiveness of stimulated vertical wells to drain gas from virgin coalbeds, specifically related to min-

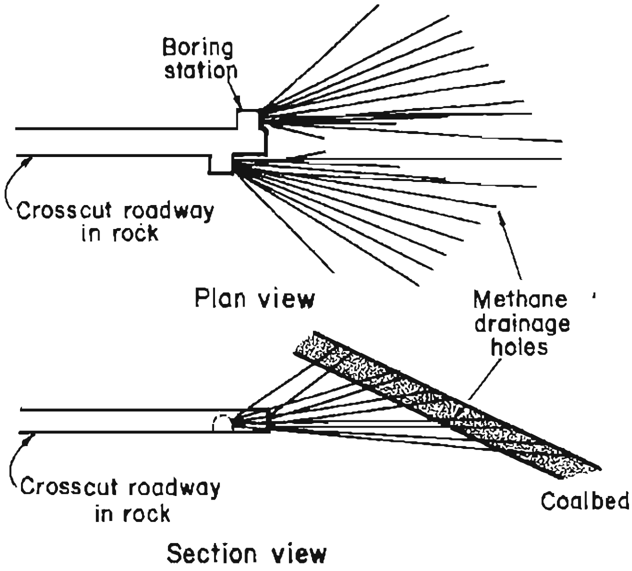

Figure 21. Schematic plan and section view of methane drainage holes drilled from cross-cut driven perpendicular to strike to intercept coalbed, Japan (modified from Ohga and Higuchi, 1987).

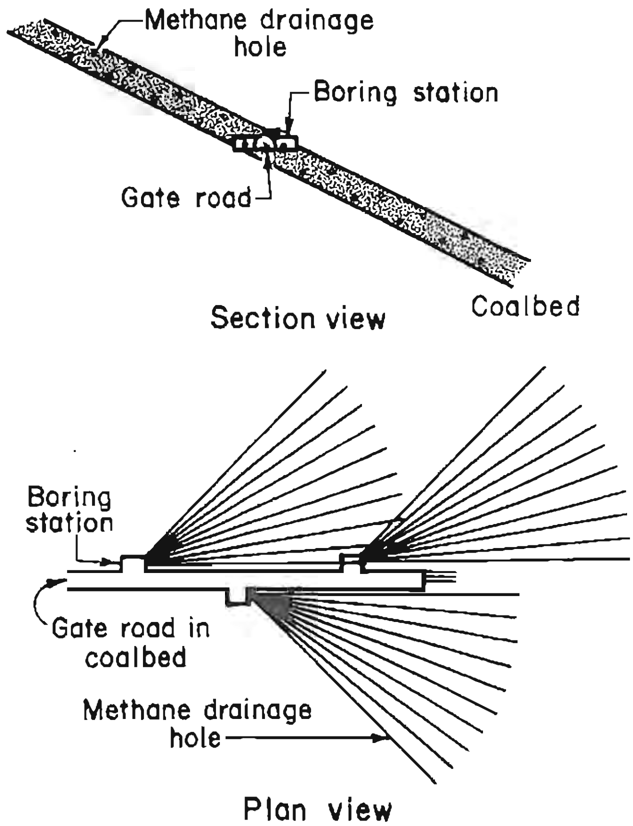

Figure 22. Schematic plan and section view of methane drainage holes drilled from gate roads driven along strike in coalbed to outline longwall panels, Japan (Modified from Ohga and Higuchi, 1987).

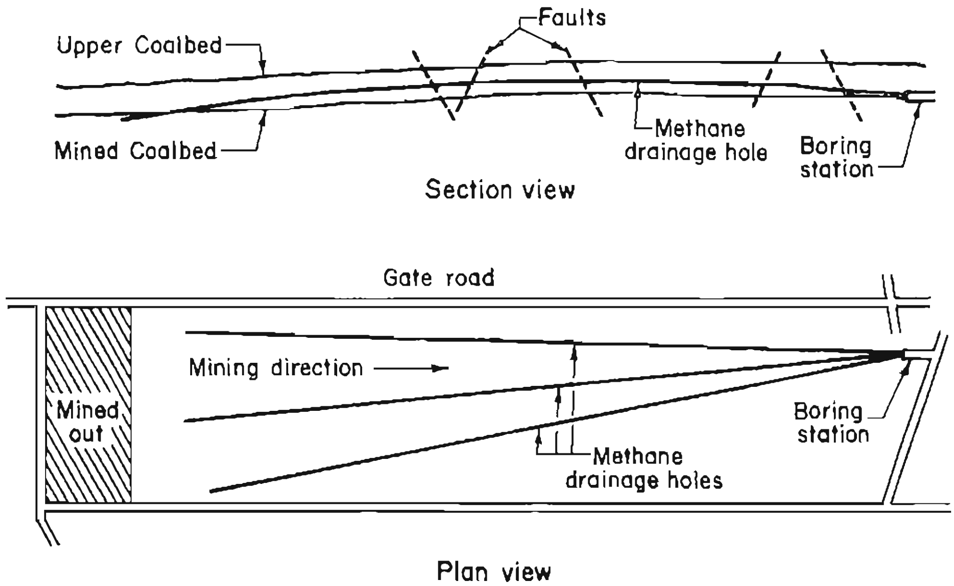

Figure 23. Plan and section view of long horizontal methane drainage hole drilled in strata above longwall panel, Japan (modified from Ohga and Higuchi, 1987).

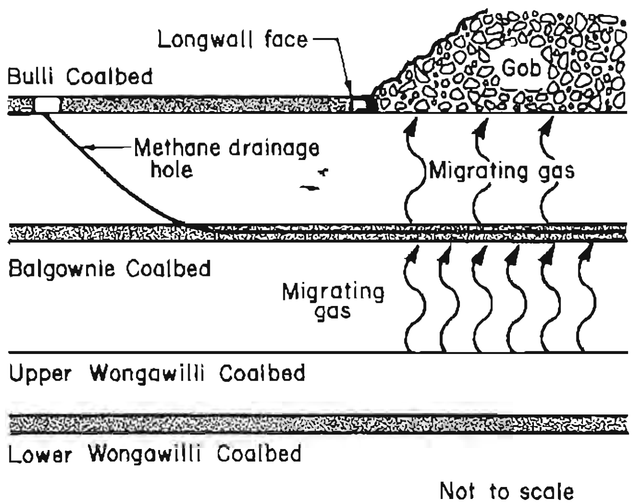

Figure 24. Section view of methane drainage hole drilled into an underlying coalbed, Australia (modified from Hungerford et al., 1988).

ing operations, has been well documented (Steidl, 1978; Stubbs et al., 1979; Lambert et al., 1980; Dunn, 1984; Diamond et al., 1989). Vertical coalbed methane drainage wells are currently 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 (1000–2000 ft), are generally associated with mining operations. The wells in the San Juan basin, at depths generally greater than 610 m (2000 ft), have been developed 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 (McBane, 1992).

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 typically low permeability of coalbeds may adversely affect the integrity of the mine roof, resulting in future mining problems.

Coal operators are obligated in the United States under federal and state law to control the concentration of methane underground. The primary method 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 lease holder may dispose of the gas by venting to the atmosphere (McGinley, 1978). However, when the gas is captured for commercial sale, legal issues as to the ownership of the gas may arise if the coal and gas rights are not owned by the same party (Lewin et al., 1992).

Coalbed gas ownership has been an issue primarily in the Northern Appalachian basin of the United States, where a potential commercial methane drainage site may encompass multiple oil and gas leases, and separate and multiple coal lease holders 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. The concern over the potential for adverse ownership issues, and/or the 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 possible by mining. This allows for the direct observation of

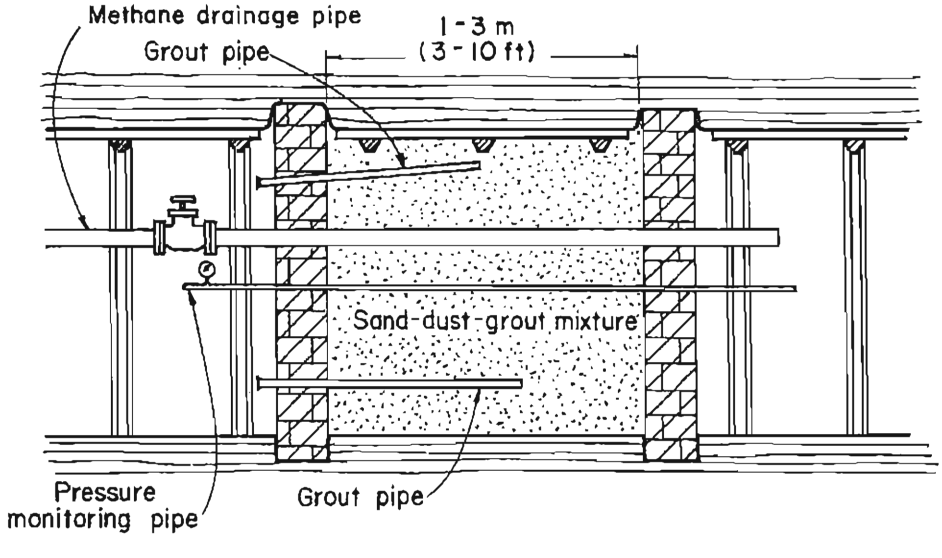

Figure 25. Schematic section view of gas drainage from sealed entries/gob (Cervik, 1979).

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 (1987). This compilation of data 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 rate (1.1 to 2.5 m^3/min [7 to 16 bbl/min]). Sand proppant weights were generally under 9080 kg (20,000 lbs). The fluids were predominantly foam (16 of 22), with the rest being gelled water and water alone.

The work by Steidl (1991) reviews 15 recent stimulations (1982 to 1986) in the Mary Lee/Blue Creek Coalbeds of the Black Warrior basin of Alabama. This compilation updates the previous study because the treatment volumes are significantly larger and the injection rates are 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 (188,000 gal). Sand proppant weights were also higher, with most treatments using 18,160 kg (40,000 lbs) or more, with a maximum of 45,400 kg (100,000 lbs). 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 important, 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 pre-existing planes of weakness in the coalbeds and roof strata. These included the coal cleat and roof joints, and horizontal bedding planes along partings, the roof, and rider coals (Figure 26).

Most of the observed roof penetrations (6 of 10) observed in the smaller volume treatments (Diamond and Oyler, 1987) 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 also of greater extent than those observed elsewhere. In the recent study by Steidl (1991), similar observations were made for the generally larger volume, higher injection rate stimulations in the Blue Creek Coalbed. These roof penetrations were generally less than 0.25 cm (0.1 in) wide, with an orientation similar to the

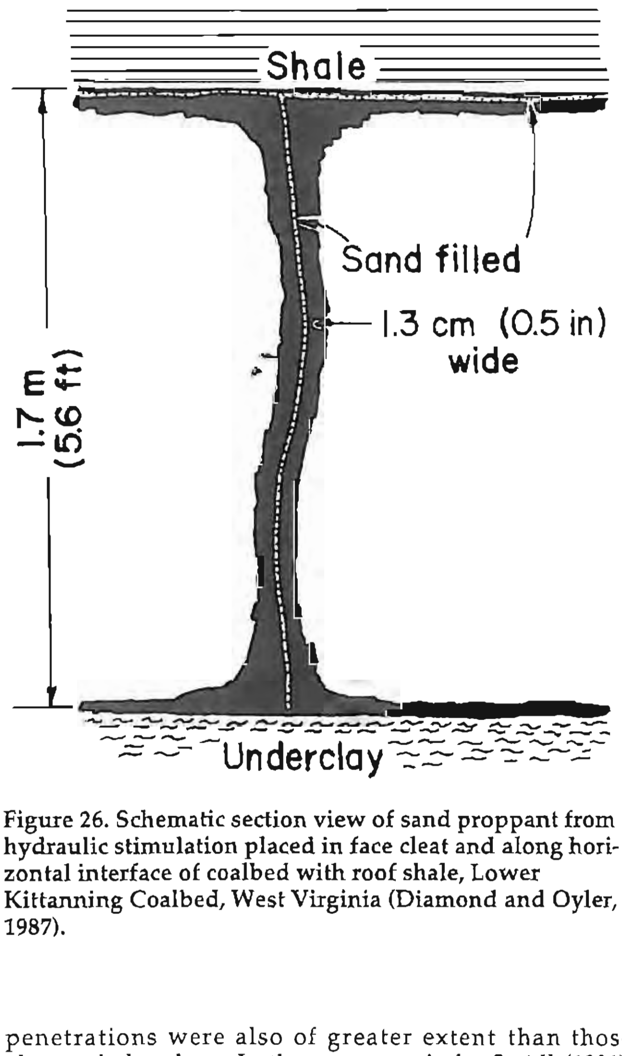

Figure 26. Schematic section view of sand proppant from hydraulic stimulation placed in face cleat and along horizontal interface of coalbed with roof shale, Lower Kittanning Coalbed, West Virginia (Diamond and Oyler, 1987).

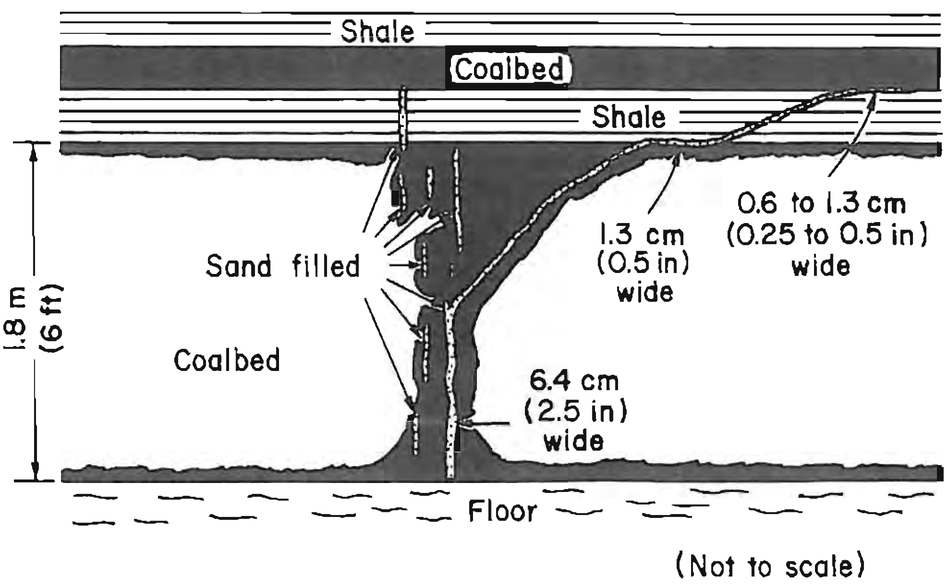

Figure 27. Schematic section view of sand proppant from hydraulic stimulation placed in face cleat, along inclined fracture in coal and shale parting, and along horizontal surfaces above and below shale parting, Pittsburgh Coalbed, Pennsylvania (Diamond and Oyler, 1987).

trend of naturally occurring roof joints. The typical roof penetrations outside of Alabama generally extended less than a foot vertically and a few feet laterally into the overlying strata (Figure 27).

It is of particular significance that the Black Warrior coal basin has the highest incidence of roof penetrations, but is also the mining area with the greatest number of stimulated vertical wells being used for methane drainage in the United States. Most 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 also 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 tests (ISSOS) 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 measured in the coal (Popovich, 1985). 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 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 pre-stimulation geologic mapping of the mine. If roof penetrations have occurred, and if they are preferentially oriented, such as along a mine-wide roof joint system parallel to the face cleat, then it may be possible in room and pillar sections to place 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. 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 (1991) concluded that the 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 (Diamond and Oyler, 1987).

Steidl (1991) 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 a foot or more above the coalbed (Figure 28, 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 cemented casing, communication to the desired gas-bearing zone can be controlled by the use of perforations or slots (Figure 28, Coalbed B). This type of completion introduces the injection fluid into the desired zone at the wellbore, but may not influence the ultimate placement of the stimulation treatment. Steidl (1991) 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 (1992). 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

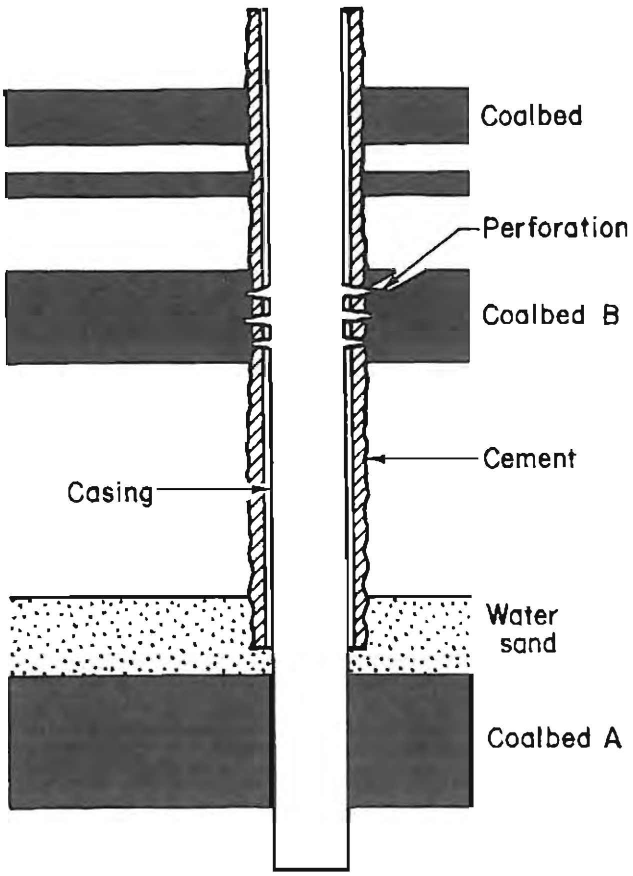

Figure 28. Schematic view of (A) open hole, and (B) cased hole completions for vertical methane drainage well.

well to the cleat system has in some cases resulted in higher gas production than that from comparison wells which were hydraulically stimulated. This completion technique may be a viable alternative for mining related methane drainage 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 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. The quicker the pressure is reduced, the sooner gas can be extracted and the coal mined.

Optimum well spacing is a particularly difficult, but important, variable to determine, since many interrelated factors must be considered. Two primary factors 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 spaced 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. Drilling vertical wells early in the life of a mine provides relief from high methane emissions at or near the initiation of mining. Subsequent wells can then be progressively drilled in advance of the mine projection. In this way only a relatively small number of holes need to be drilled in any particular year.

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 time frame (King and Ertekin, 1989). 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 site-specific conditions. Past experience with stimulated vertical wells in the same coalbed should also be considered when determining well spacing.

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 modified due to 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 have an influence on the shape of the drainage pattern in the coalbed, and hence on the basic configuration of the grid for the wells. Orientation of the cleat system and, 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 intercepted 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 (Diamond and Oyler, 1987). An example of the preference for the stimulation fluids to penetrate face cleat is shown in Figure 29. The resulting drainage pattern for a stimulated well such as shown in Figure 29 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 further apart in the face cleat direction, and closer together in the butt cleat direction.

Gas content testing of coal cores 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 (Oyler and Stubbs, 1985).

It is not generally necessary, or even possible, to remove all the gas from a coalbed in order to have a significant impact on mine emissions. Several examples of declining methane emissions cited in this paper are associated with

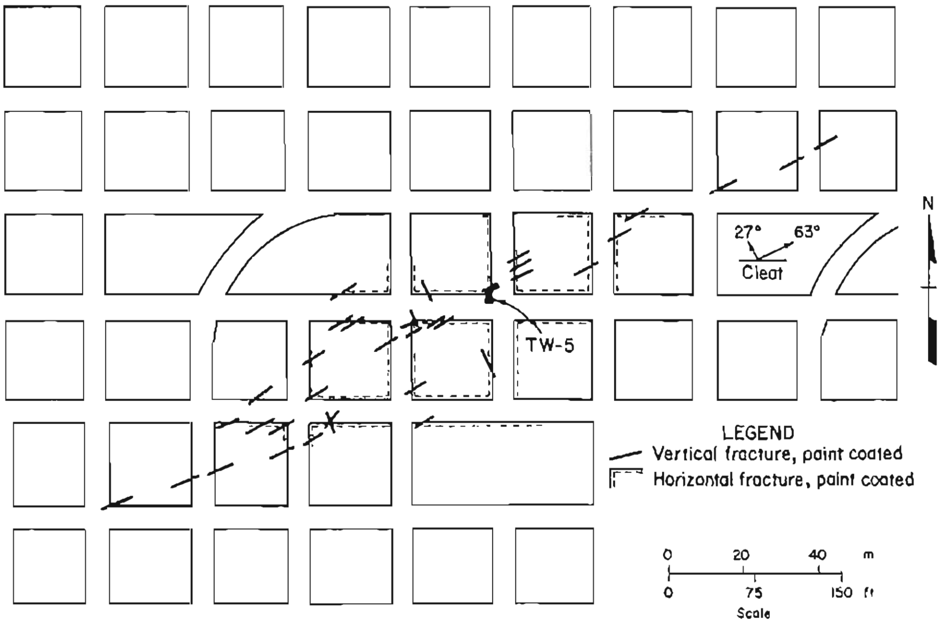

Figure 29. Plan view of elliptical placement of stimulation fluids in vertical methane drainage well, Blue Creek Coalbed, Alabama (Diamond and Oyler, 1987).

short-term methane drainage projects, where a substantial percentage of the in-place gas could not have been drained. It appears that in most coalbeds, a certain percentage of total gas content 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 (Diamond and Murrie, 1977; Diamond et al., 1989). With the gas content and/or pressure monitoring results and production data from the wells, the computer 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 into the area 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 1524 m (5000 ft) from the perimeter of the pattern (Diamond et al., 1989). The gas desorbed from this reduced pressure area outside the pattern will migrate 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 intercept wells are drilled between the mine workings and the migrating gas, 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 intercept wells just outside the actual mining area. 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 (Diamond et al., 1991). A series of new longwall panels was developed down-dip from an area of extensive old workings, some having 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 a series of gas content tests and material balance calculations, it was concluded that over the 20+ years that this area had been idle, the old workings had created a sufficient pressure sink to induce the desorption of gas from the down-dip coal reserves. This gas was migrating up-dip to the old workings. When the new longwall panel was placed in the path of the migrating gas, it provided a closer pressure sink for the migrating gas.

The direct influence of methane drainage by stimulated vertical wells on mine emissions was demonstrated by Lambert et al. (1980). 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. 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 provided a significant influence on mine emissions. The "east" entries required 70 days to mine 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 (Figure 30). The "west" entries that were driven towards 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% 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 et al. (1989). In 1976, a pattern of 23 methane drainage wells was drilled and stimulated on mine property in the Blue Creek Coalbed. The wells were drilled on a 305 m (1000 ft) square grid (approximately

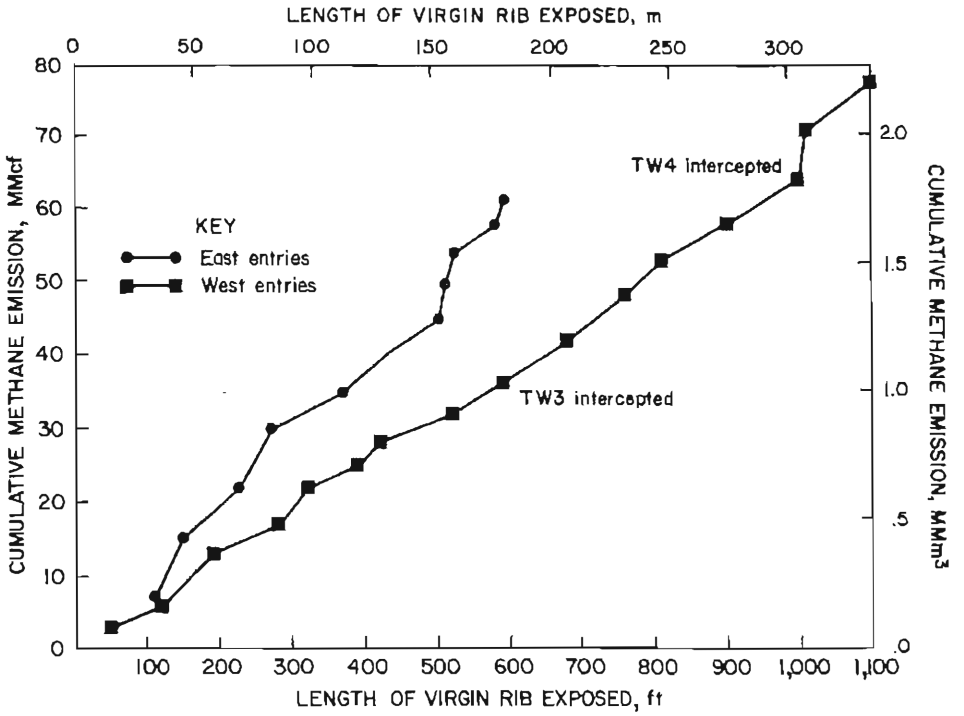

Figure 30. Comparison of cumulative methane emissions in entries developed into areas with and without stimulated vertical methane drainage wells, Blue Creek Coalbed, Alabama (Lambert and Trevits, 1980).

100×10^3 m^2 [25 ac] spacing). After 10 years, the wells 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 core holes in and around the 23-well pattern after 10 years of gas production were tested for gas content and compared to samples obtained from the same area prior to the start of methane drainage. Inside the pattern, 73% of the original gas in place had been drained from the Blue Creek Coalbed that had been completed for production. Similar gas reduction results were measured in the overlying Mary Lee and New Castle Coalbeds, 1.5 and 13.7 m (5 and 45 ft), respectively, above the Blue Creek Coalbed. The same naturally occurring roof joints in the strata above the Blue Creek Coalbed that were penetrated by the stimulation treatments observed underground likely provided the conduits for gas flow to the completions below.

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 from these wells through the third quarter of 1991 was 1.19×10^9 m^3 (42 BCF) of gas (McBane, 1992). At a nearby mine operating in the same coal interval, Mills and Stevenson (1991) reported a decrease of about 50% 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 Holes

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

The first experimental directional holes drilled for coalbed methane drainage were long radius, turning from vertical to horizontal at a rate of about 6°/30 m (100 ft) (Oyler et al., 1979). These well paths required about 305 m (1000 ft) of depth (Figure 31). Down-hole motors and various configurations of drilling assemblies are used to drill the directional holes and control the well path. In a directional hole system drilled into the Pittsburgh Coalbed, Pennsylvania, three long horizontal holes (539 m [1767 ft]; 912 m [2993 ft]; and 977 m [3207 ft]) were drilled from the bottom of a single well path to the coalbed (Figure 32) (Oyler and Diamond, 1982). Sloughing of the bottom portion of the uncased part of the well in the roof shale above the Pittsburgh Coalbed and dewatering problems severely limited the gas production from this hole.

Alternatives 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 (Logan, 1988; Nazzal, 1990) (Figure 33). Medium radius systems are turned at a rate of 8–20°/30 m (100 ft), which requires 91 to 213 m (300 to 700 ft) of vertical section. Short radius systems can turn at a rate of 1.5–3°/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. Nazzal (1990) reports that holes can be drilled up to 305 m (1000 ft) horizontally using the short radius system.

This new technology in directional drilling, especially the short radius holes, may have significant applications to coalbed methane drainage. The shorter radius holes reduce

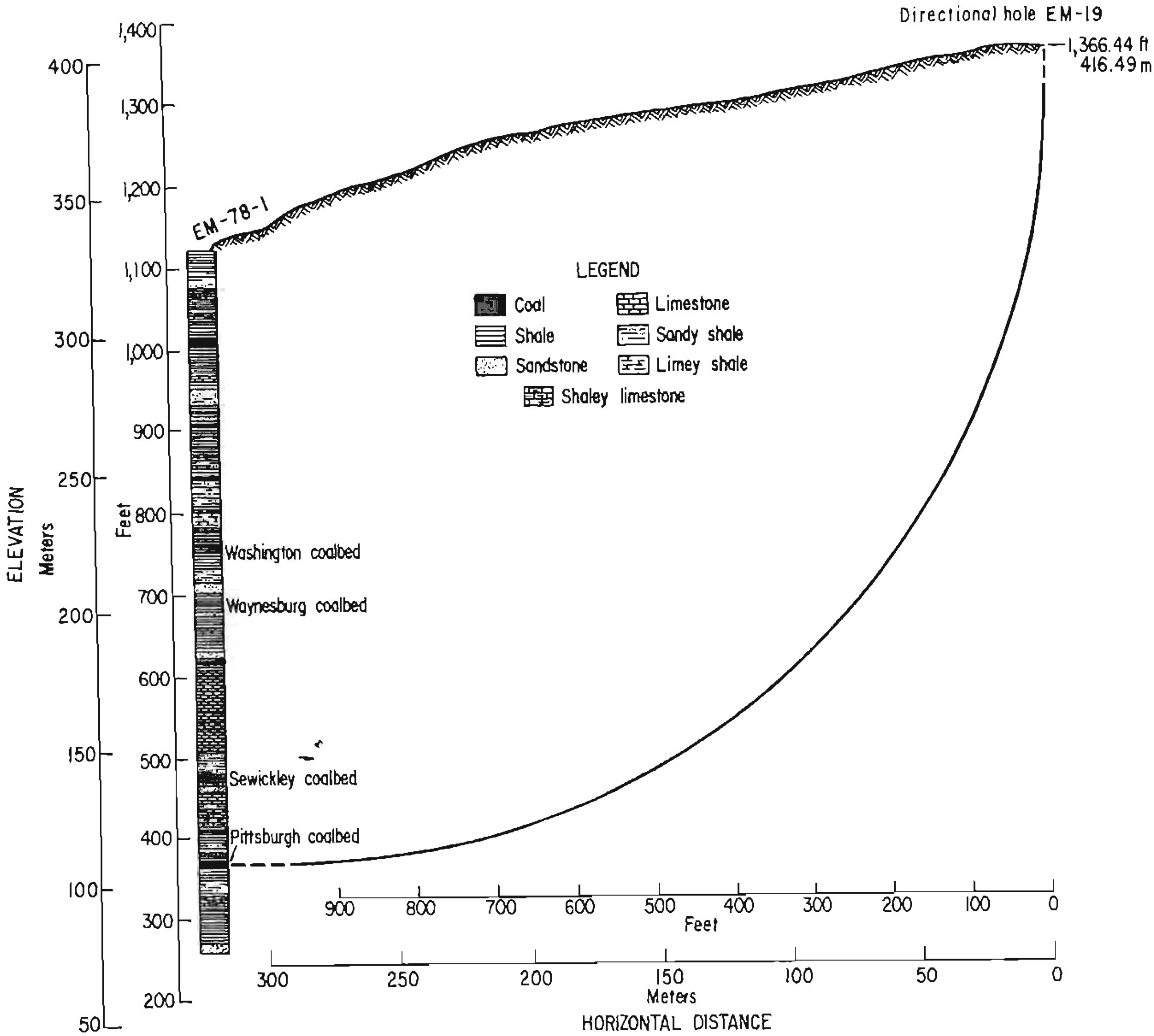

Figure 31. Section view of long radius directionally drilled well path to intercept the Pittsburgh Coalbed horizontally from the surface, Pennsylvania (Oyler and Diamond, 1982).

the length of unproductive directional hole drilled 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 hole section below the kick-off point of the directional hole (Figure 33). This pump configuration may provide more effective dewatering than was previously possible in the long radius holes. This proven directional drilling technology with off-the-shelf components has a greater potential for successful implementation in coalbed methane drainage than the experimental slant holes drilled in the 1970s that required in-the-field development of prototype tools and drilling procedures.

Longwall Gob Gas Vent Holes

Vertical gob gas vent holes 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 miners and equipment on the face. Gas-bearing strata, particularly overlying gas-bearing coalbeds, are either 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 (Figure 5). Gas-bearing strata below the mined bed may also contribute methane 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 are permitted to dissipate from the working area. Gas-related mining delays are becoming an increasingly common occurrence, even with the use of vertical gob gas vent holes. 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 vent holes is most common in the United States, probably due to the greater ease of

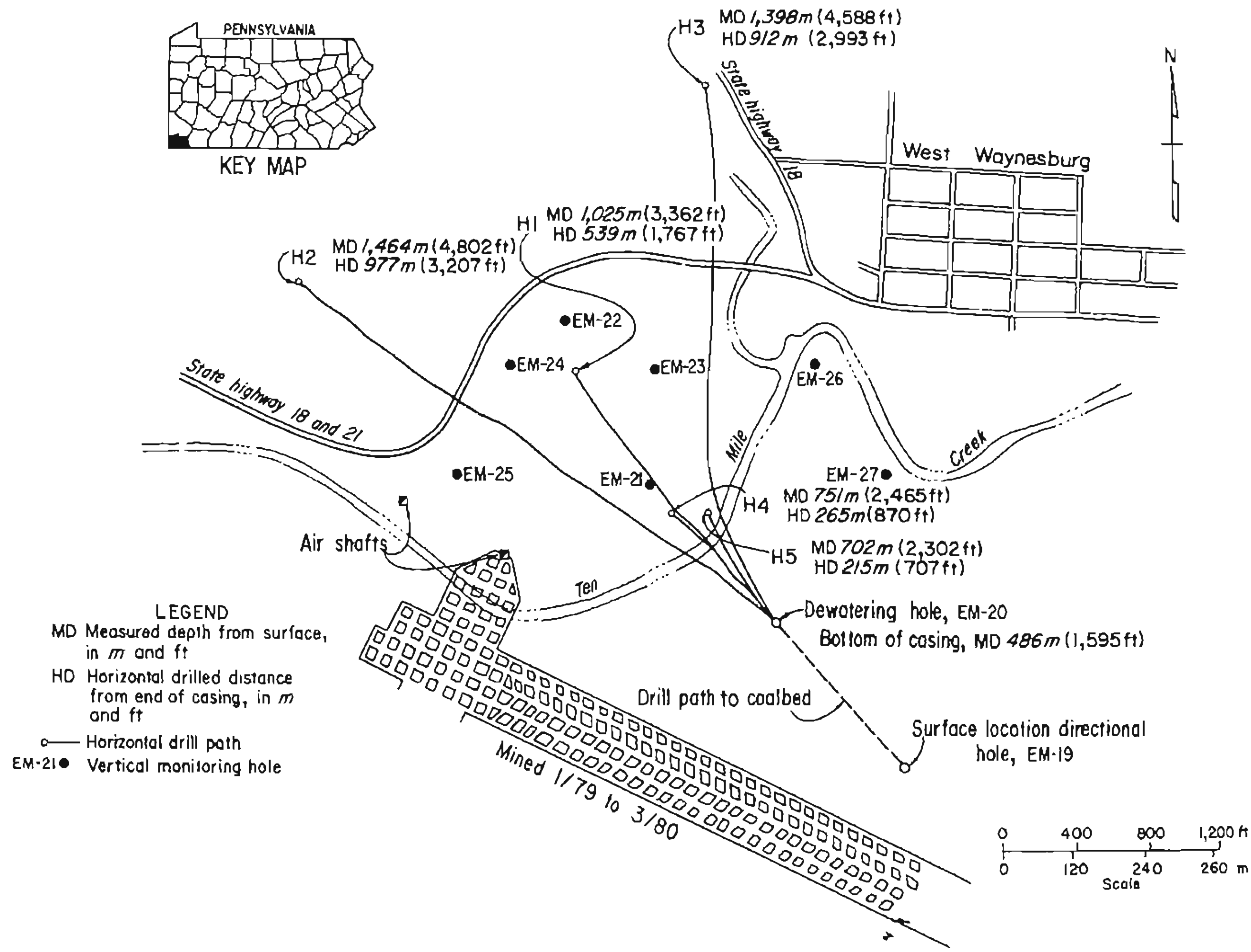

Figure 32. Plan view of multiple horizontal methane drainage holes drilled from a directional surface hole, Pittsburgh Coalbed, Pennsylvania (Oyler and Diamond, 1982).

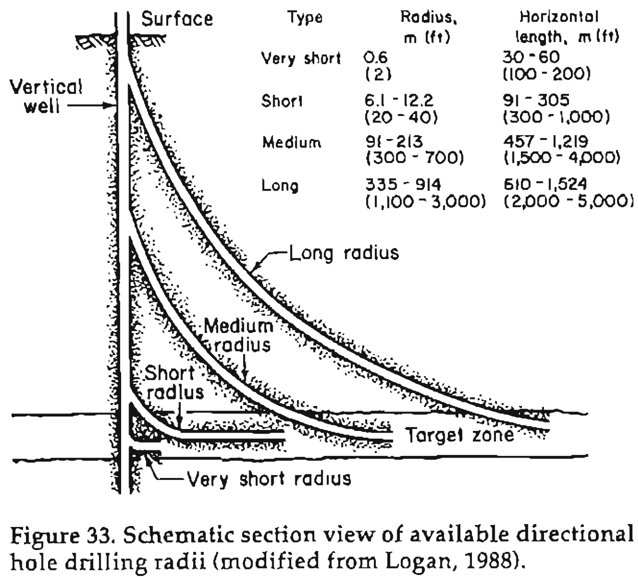

Figure 33. Schematic section view of available directional hole drilling radii (modified from Logan, 1988).

obtaining surface drill sites than in the more mature mining districts elsewhere. The relatively shallow depth of the longwall mines in the United States also makes the use of gob gas vent holes more cost effective. The first experimental vertical gob gas vent hole was drilled at a mine operating in the Lower Kittanning Coalbed, Pennsylvania, in the late 1960s (Elder, 1969). 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 initial 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 vent holes 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 1960s, gob gas vent holes have been drilled and completed in several different ways. Completion techniques are determined by site-specific conditions as determined by trial and error (Mills and Stevenson, 1991). Once a successful drilling and completion

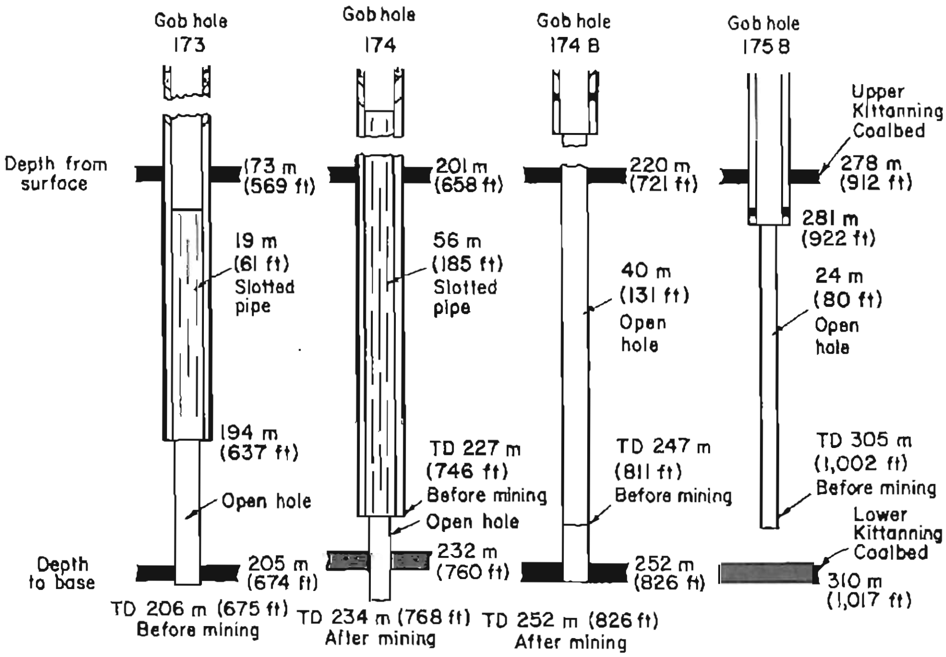

Figure 34. Schematic section view of various longwall gob gas vent hole completion designs.

design is found that keeps the methane concentrations within the regulatory limits, few if any changes in the design are initiated.

Most gob gas vent holes 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 (Figure 34, Hole 173). In some cases the hole is 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 casing to the coalbed (Figure 34, Hole 175 B). Numerous variations on these basic designs are possible, as illustrated in Figure 34, which represents the trial and error design process to find a more productive design on a single longwall panel in the Lower Kittanning Coalbed, Pennsylvania (Diamond et al., 1991).

The distance between the gob gas vent holes, like the basic drilling and completion design, is determined by experience and by 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 vent hole to a typical depth of 229 m (750 ft) is only a few days. The gob gas vent holes will usually produce only a small volume of gas under natural flow conditions. The holes are typically equipped with exhausters to draw gas from the gob (Figure 35). The installation of the surface equipment requires about a day. In most cases, a gob gas vent hole can be drilled and put in operation in less than a week.

Individual gob gas vent holes over longwalls in the Lower Kittanning Coalbed have produced nearly

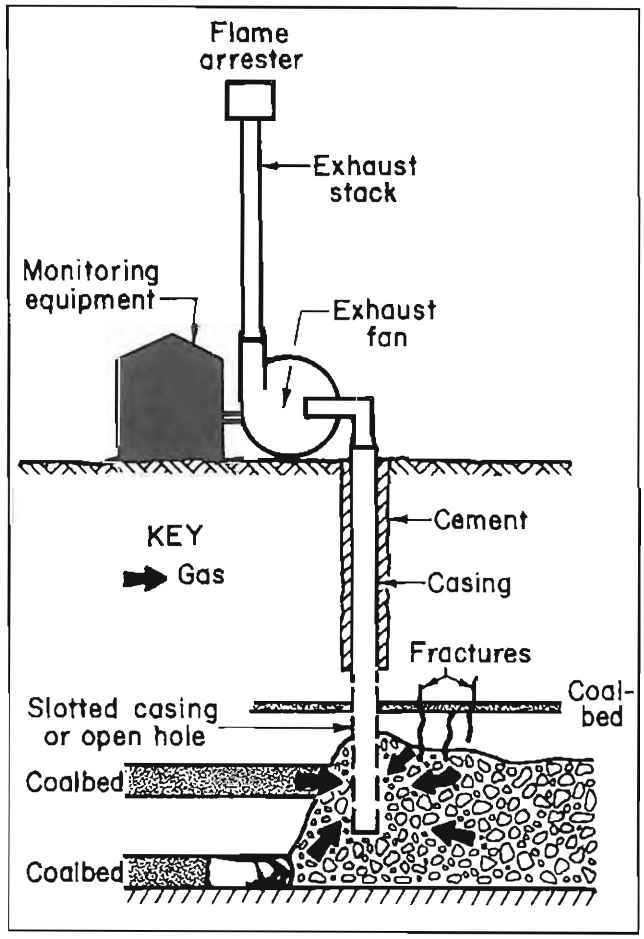

Figure 35. Schematic section view of complete longwall gob gas vent hole system.

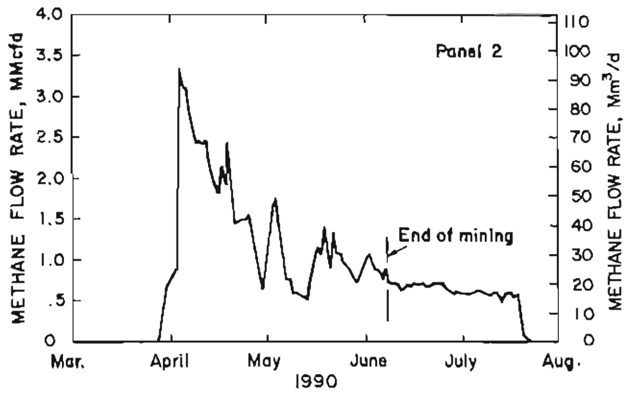

Figure 36. Daily methane flow rate, gob gas vent hole 178, Lower Kittanning Coalbed, Pennsylvania.

8.5×10^6 m³ (300 MMcf) of methane over their productive life (Diamond et al., 1991). A single hole in the Pocahontas No. 3 Coalbed has produced nearly 17×10^6 m³ (600 MMcf) of methane during mining of that coalbed (McCall and Garcia, 1991). Maximum daily methane production usually 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 (Figure 36), or in some cases for a few months. 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%) and remains relatively high for several months after mine-through. The methane concentration usually declines gradually with time. When the methane concentration reaches 25%, the exhausters must be turned off as a safety precaution, because the explosive range of methane in air is 5 to 15%. The holes are generally allowed to free flow after the exhausters are turned off.

Gob gas vent holes are an effective technology to drain gas from longwall gobs. Mills and Stevenson (1991) reported that approximately 30 to 40% of the total gas liberated from several mines operating in the Mary Lee/Blue Creek coal interval was produced by gob gas vent holes. Dixon (1987) stated that the mines could not operate at economic levels without gob gas drainage. Dixon (1987) also reported that the methane level in the mine bleeder entries can be reduced by as much as 80% using gob gas vent holes. In some cases, the methane produced from the gob gas vent holes 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 (1991) reported that 0.48×10^6 to 0.65×10^6 m³/d (17 to 23 MMcfd) of methane from gob gas vent holes at two mines in the Mary Lee/Blue Creek coal interval was sold to a commercial gas pipeline.

Methane production rates have been reported as high as 0.14×10^6 m³/d (4.9 MMcfd) for Lower Kittanning gob gas vent holes (Diamond, 1991), 0.17×10^6 m³/d (6 MMcfd) for the Mary Lee/Blue Creek Coal interval, Alabama (Mills and Stevenson, 1991), and 0.26×10^6 m³/d (9.1 MMcfd) for the Pocahontas No. 3 Coalbed, Virginia (McCall and Garcia, 1991). It is important to 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 (Figure 37). Some of the variability can be

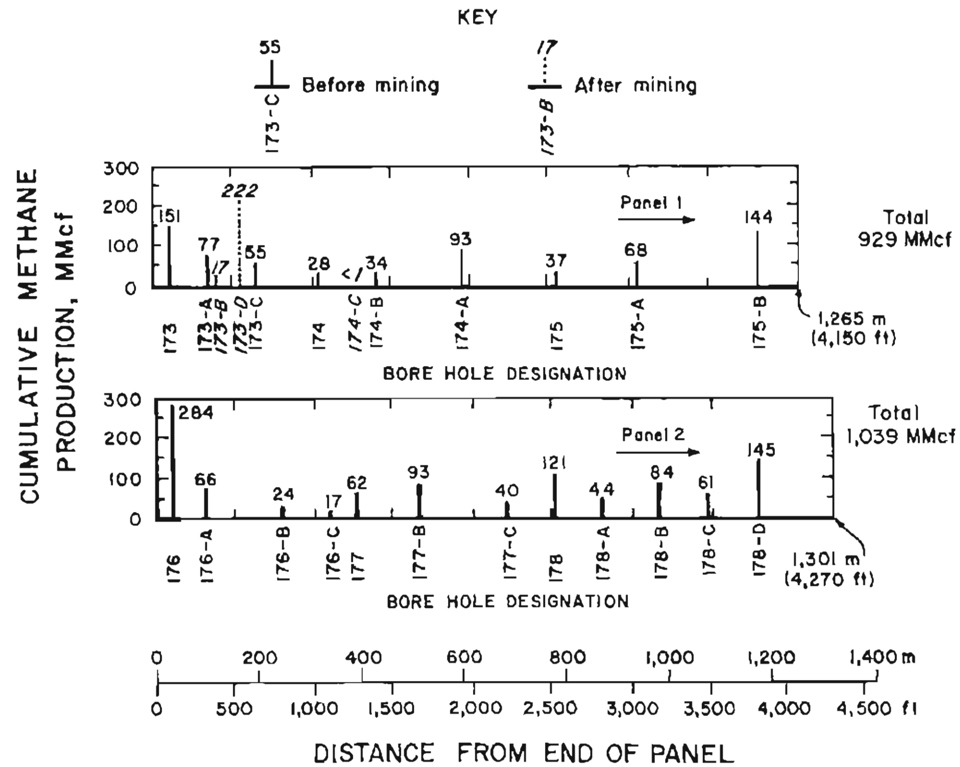

Figure 37. Total methane production through 12 months after panel completion from individual gob gas vent holes on adjoining longwall panels, Lower Kittanning Coalbed, Pennsylvania.

due to completion problems, such as inadvertently cementing fractures during the setting of casing in holes drilled after mining (Figure 37, Hole 174C). 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 vent holes (Diamond et al., 1991).

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 vent holes drilled on either end of the panels tended to have the highest cumulative production (Diamond et al., 1991) (Figure 37). The reason for this may be related to the subsidence mechanics of longwalls. At the ends of the panels, the overburden strata are partially supported on three sides by the surrounding pillars of the development entries. 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 for a longer time than those in the center of the panel, where complete subsidence and recompaction occurs relatively quickly. The longer the fracture permeability is maintained, the longer the gob gas vent holes remain on production, and hence the higher 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 (Mills and Stevenson, 1991).

Strata along the margin of the panels are also draped into the subsidence trough, and should have enhanced fracture permeability. It is possible that the customary practice of placing the gob gas vent holes along the center line of the panels may not be the optimum location for gas production. Holes placed along the margin of the panels may produce more gas for a longer time. 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 the magnitude of vacuum applied to the system is necessary for the holes to operate at maximum efficiency.

Since gob gas vent holes are not stimulated, there is generally only a small flow of gas, if any, from the holes prior to being 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 vent holes, it may be possible to use fewer holes per panel, thereby offsetting the added cost of 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 shorten the time required for their 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 due 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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Dudley D. Rice

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On the cover: cleat system in the Upper Cretaceous Cameo coal, Williams Fork Formation, Piceance basin, Colorado, U.S.A.; photo by Ben Law, U.S.G.S. Inset photo: tectonic thickening of the Lower Cretaceous Jewel coal seam, Gates Formation, Cardinal River Mine, Inner Foothills Belt, Alberta, Canada; photo by Wolfgang Kalkreuth, Geological Survey of Canada.