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CONTENTS

Page

ILLUSTRATIONS

ILLUSTRATIONS—Continued

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	mm	millimeter
cm	centimeter	µm	micrometer
h	hour	mm Hg	millimeter of mercury
kg	kilogram	m^3/min	cubic meter per minute
kPa	kilopascal	Pa	pascal
m	meter	pct	percent
mg/m^3	milligram per cubic meter	ppm	part per million

BLEEDERLESS VENTILATION SYSTEMS AS A SPONTANEOUS COMBUSTION CONTROL MEASURE IN U.S. COAL MINES

By A. C. Smith,[1] W. P. Diamond,[2] T. P. Mucho,[3] and J. A. Organiscak[3]

ABSTRACT

The U.S. Bureau of Mines conducted a worldwide literature review of bleederless ventilation practices to evaluate their use as a spontaneous combustion control measure in U.S. coal mines. Factors that must be taken into account in the design and use of these systems include seal construction, the use of ventilation control devices, the use of methane-drainage systems in gassy mines, and the ground control plan. Monitoring for the detection of spontaneous combustion and the control of methane when methane-drainage techniques are employed is critical to the successful use of a bleederless ventilation system. This report describes the types of ventilation systems used throughout the world and the spontaneous combustion risks associated with these systems. Methane-drainage systems used in conjunction with bleederless ventilation systems are discussed. Ground control considerations such as pillar design, entry stability, and seal usage are reviewed. Monitoring systems for spontaneous combustion detection, methane-drainage control, and behind seals are examined. Finally, methods for evaluating the spontaneous combustion hazard of a mining operation to determine when the use of a bleederless ventilation system is warranted are reviewed.

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INTRODUCTION

The primary function of mine ventilation is to dilute, render harmless, and carry away dangerous accumulations of gas and dust from the working environment. For underground U.S. coal mines, the minimum ventilation requirements were initially defined under the Federal Coal Mine Health and Safety Act of 1969 (*1*)[4] with current regulations published in Title 30—Code of Federal Regulations (*2*). The regulations stipulate that "all active workings shall be ventilated by a current of air containing not less than 19.5 volume per centum of oxygen, not more than 0.5 volume per centum of carbon dioxide and no harmful quantities of other noxious or poisonous gases; and the volume and velocity of the current of air shall be sufficient to dilute, render harmless and to carry away flammable, explosive, noxious, and harmful gases, and dust, and smoke and explosive fumes." Methane concentration is not allowed to exceed 1 pct by volume at the working area, and a worker's respirable dust exposure (particles less than 10 μm in size) cannot exceed an average of 2 mg/m^3 for an 8-h shift.

Regulations also stipulate that "bleeder entries, bleeder systems, or equivalent means should be used in all active pillaring areas to ventilate the mined areas from which the pillars have been wholly or partially extracted, so as to control the methane content in such areas." A ventilation pressure differential is required between the active working area and the bleeder system to ensure gob gas drainage through the bleeder entries. The concentration of methane in a bleeder split of air immediately before the air in the split joins another split of air, or in a return air course, cannot exceed 2 pct. Therefore, underground coal mines in the United States are designed with bleeder entries to ventilate active gob areas while mining is in progress.

With the passage of the most recent Federal ventilation regulations, bleederless ventilation systems may now be proposed as a spontaneous combustion control method. Regulation 75.371 states, "the mine ventilation plan shall contain the information described below....In mines with a demonstrated history of spontaneous combustion: a description of the measures that will be used to detect methane, carbon monoxide, and oxygen concentration...If a bleeder system will not be used, the plan shall contain the methods that will be used to control spontaneous combustion, accumulations of methane-air mixtures, and other gases, dusts, and fumes in the worked out area" (*2*).

With this development, it is necessary to have a thorough understanding of current and past experience of bleederless ventilation systems both overseas and in the United States. To accomplish this, the U.S. Bureau of Mines (USBM) conducted a worldwide literature review of bleederless ventilation practices to evaluate their use as a spontaneous combustion control measure in U.S. coal mines. The impact of bleederless ventilation practices on other mine design parameters, such as ground control, methane control, ventilation, and monitoring, is considered.

In the United States between 1978 and 1988, approximately 15 pct of underground coal mine fires were caused by the spontaneous combustion of coal (*3*). Spontaneous combustion fires usually occur in worked-out or gob areas and are not easily detected. These fires present a serious safety hazard to mine personnel and are difficult to extinguish, often requiring sealing large sections of the mine or the entire mine for long periods, resulting in severe economic losses. A spontaneous combustion fire was discovered in June 1986 in a Colorado mine (*4-5*). The entire mine was sealed and abandoned. Another heating occurred at a Colorado mine in a longwall gob that required sealing and inert gas injection to suppress the heating (*6*). Several self-heating events due to the oxidation of pyrite have also been associated with floor heave in an Alabama mine (*7*). The number of spontaneous combustion fires is expected to increase with the increased use of low rank coals, deeper mines, and the growth in longwall mining.

The self-heating of coal occurs when the heat that is produced by low-temperature oxidation is not adequately dissipated, resulting in a net temperature increase in the coal mass. Under conditions that favor a high heating rate, a fire ensues. Many factors can contribute to the self-heating process, including coal properties, geologic factors, and mining conditions and practices.

Singh grouped these factors into intrinsic and extrinsic categories (*8*). Intrinsic factors are those that cannot be controlled by the mine operator, such as coal properties and geologic and mining conditions, while extrinsic factors are those that can be controlled, such as mining practices. Generally, the most important factor is the coal's reactivity, or propensity to oxidize.

The oxidation of coal requires fuel, the coal, and an oxidizer, usually air. Thus, by limiting the amount of oxidation, and therefore the amount of heat generated, the spontaneous combustion risk can be reduced. To accomplish this, either the coal or the air must be removed. The amount of coal in a retreat longwall gob can be somewhat

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

controlled by the mining practices, such as pillar design and amount of coal left in the roof and floor. The amount of airflow through the gob can be reduced by using a bleederless ventilation system. This forms the basis of the bleederless ventilation design as a spontaneous combustion control measure.

This report will discuss the bleederless ventilation procedures used and the mining methods employed in conjunction with these procedures both in the United States and throughout the world. It will discuss bleederless ventilation design with respect to current U.S. mining practices and regulations, and the effect of a bleederless ventilation system design on spontaneous combustion, ground and methane control, and ventilation. Monitoring will be discussed in terms of early detection of spontaneous combustion and methane control. Finally, selection criteria for determining when to use bleederless ventilation systems will be examined.

This work was done in support of a USBM program to improve health and safety in the mining industry.

VENTILATION AND SPONTANEOUS COMBUSTION

In coalbeds that are reactive to oxidation, critical low-velocity airflow over the reactive coal increases the risk of coal heatings. Critical airflow is defined as insufficient airflow to remove the heat due to oxidation, but enough airflow to maintain the oxidation process (*9*). Humphreys reports that greater than 14 pct oxygen is needed to initiate a spontaneous combustion heating and oxygen levels of greater than 2 pct are needed to sustain a heating, while Liney states that heatings will occur with oxygen levels as low as 6 pct (*10-11*). Either more or less airflow than the critical amount can inhibit the self-heating of coal. Critical airflows generally exist in gobs, behind longwall supports, through crushed pillars, in intake-return air crossings, and across stoppings.

Controls for the spontaneous combustion of coal focus on either minimizing the amount of coal exposed to reactive environmental conditions or curtailing the conditions. Mine planning and production practices are of utmost importance in controlling spontaneous combustion. One of the most common methods of spontaneous combustion control used around the world is minimizing airflow to prior and active mine workings to reduce the available oxygen for spontaneous combustion. Balancing the requirements of spontaneous combustion control, ground and methane control, and the coal production plan can be very demanding because of the interdependence of each factor on the others. Therefore, a systems approach must be undertaken in mine planning to control the environmental conditions affecting spontaneous combustion (reduce fuel (coal) exposure to critical airflow conditions), to continuously assess these environmental conditions (monitoring), and to formulate alternative action plans for the existing or progressing circumstances (safety training, firefighting, and sealing).

Coal-producing countries around the world have used methods to limit the amount of airflow or oxygen to areas prone to spontaneous combustion. Great Britain (*11-13*), Germany (*14-15*), Poland (*16*), France (*17*), Australia (*10, 18*), India (*19*), Russia (*20-21*), and China (*22*) all have experience in restricting the airflow into working gob areas in coalbeds prone to spontaneous combustion. In the United States, two mines that have had spontaneous combustion occurrences have been allowed to use a bleederless ventilation system (*6, 23*).

Geologic conditions of European and Asian coalfields are notably different than those of both the United States and Australia. The European and Asian mining operations commonly extract multiple dipping coalbeds that are deeply covered (*24*). When multiple coalbeds are mined, ground and methane control problems become more complex because of the stress and multiple sources. Thus, less entry development with extensive secondary support practices is commonly used to control ground stresses, and complex in-mine methane-drainage practices are often used to control methane emissions.

Underground coal production in Europe and Asia is usually conducted with full extraction techniques or longwall mining. Both advancing and retreating longwall mining systems have been utilized in these countries. Advancing longwalls are more beneficial for methane removal from the gob area, since a negative pressure differential is created on the gob (*25*). For spontaneous-combustion-prone coalbeds, retreat longwall mining systems are more beneficial because airflow into the gob can be more easily controlled. If a large amount of methane is emitted in the gob on the retreat system, in-mine methane drainage of the gob is commonly practiced so the face ventilation system does not become overloaded with explosive levels of methane gas (*26*). In-mine drainage is generally preferred because of the depth of cover, dip of the coalbeds, multiple-bed mining practices, and surface population density. The entry that contains the methane-drainage system must be well supported so the system remains functional during the retreat of the panel. Gas monitoring of the methane-drainage system is critical so oxygen is not being pulled into the gob. The details of this technology are discussed in the methane control section of this report.

In the United States and Australia, coalbeds are usually relatively horizontal and shallow. Multiple entries are driven in the coalbed, which become the gate roads of the longwall panels. Multiple-entry developments reduce mine resistance to airflow, so higher quantities of air are more easily circulated throughout these mines and are available for the required bleeder ventilation systems. Ventilation networks of U.S. underground coal mines generally focus on distributing a large quantity of air to the working faces and through the bleeder systems, for dust and harmful gas removal. Vertical gob boreholes are commonly drilled from the surface to drain methane from the gob to supplement bleeder systems when high-gas-emission conditions are encountered (*27-28*). Since longwall mining is expanding in deeper U.S. coalbeds prone to spontaneous combustion, more heatings are expected with bleeder ventilation systems (*12*). The multiple-development entries are more prone to crushing under the higher ground stresses from deeper cover, and the current trend to larger longwall panels results in increased exposure time. These deeper coalbeds are also generally gassier than those at shallower depths. Therefore, mine design must consider all mining factors when a bleederless ventilation system to control spontaneous combustion is implemented.

BLEEDERLESS VENTILATION DESIGNS

Various ventilation methods for retreat longwall mining have been developed to control spontaneous combustion by limiting the amount of airflow into the gob. These ventilation methods must coincide with minewide planning for ground control, methane control, production, and environmental monitoring, as well as firefighting, safety procedures, employee training, and government regulations. Given the diversity in geologic conditions of various coalbeds, mine designs have to meet their unique conditional needs. Mine development planning should reach an optimum balance between conflicting design parameters, such as limiting the number of entries to reduce ground stresses versus creating more entries to improve ventilation. Since performance of various technologies is mine dependent and cannot always have universal application throughout the industry, mine planning should include alternatives to the original design.

"U" SYSTEM

The most common and effective method to limit airflow to the gob in a longwall panel is the "U" ventilation system. In this system, the air is brought up the headgate entry, across the face, and down the tailgate entry. A schematic of the "U" system is shown in figure 1.

European and Australian mines typically operate this system using single-entry development of the longwall panel. The principal advantage of this type of development is that the system does not require many seals to limit air leakage (*18*). The use of multiple-entry development requires seals between entry crosscuts, thereby increasing the risk of air leakage to the parallel entry or mined-out panel. These seals isolate the gob from the return of the next panel. The main disadvantage to the "U" system is that in gassy mines, high concentrations of methane migrate toward the tailgate corner (*10, 18, 25, 29*). An example of the migration paths of methane in the gob using the "U" system is shown in figure 2.

BACK RETURN "U"

The back return system is a modification of the "U" system that is utilized to handle dangerous methane levels in the tailgate area of the face. In this system, air is

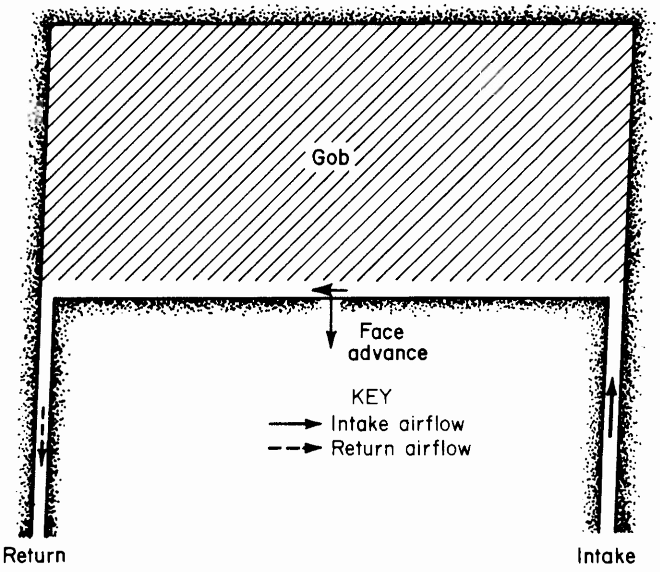

Figure 1.—"U" ventilation system on retreat longwall face (*10*).

brought up the headgate, across the face, and then directed through the tailgate corner of the gob to sweep the area of methane before it flows down the tailgate return. To accomplish this, two entries are driven as tailgates (intake and return). Methane drainage of the gob is commonly used in conjunction with this type of ventilation system, and this system facilitates methane capture by the drainage system.

The two entries required for the back return system can be predriven, as shown in figure 3. In Europe, where single entries are commonly used for gate road development, the second tailgate entry is formed upon retreat of the longwall face. A portion of the coal face is left to form a narrow pillar to create the additional tailgate entry. An example of this system and the methane migration paths is shown in figure 4.

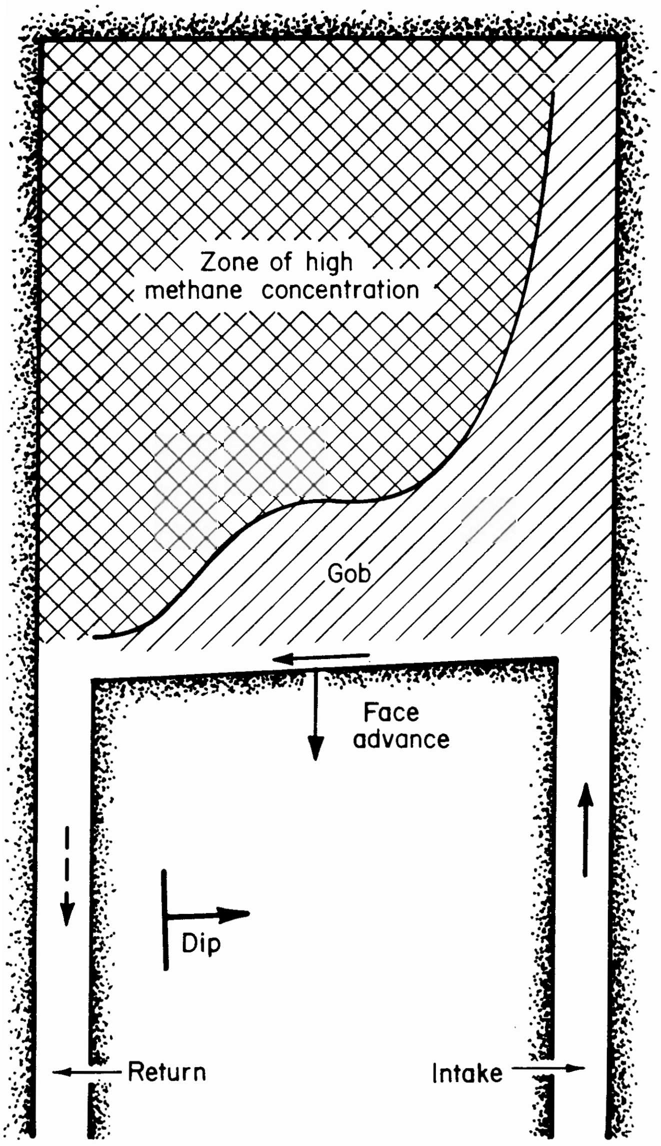

Figure 2.—Methane distribution in gob using "U" ventilation system (*16*).

"Y" SYSTEM

The "Y" system utilizes a single headgate entry with multiple tailgate entries. The air is brought up all the gate roads, across the face from the headgate to the tailgate, and removed via the outside return entry of the tailgate. An example of this system is shown in figure 5. Seals are constructed in all inby crosscuts in the tailgate except for the first inby crosscut, partially isolating the gob. The face airflow near the tailgate is allowed to migrate through the corner of the gob, passing through the first crosscut inby the face, clearing methane from this area of the gob.

Like the back return system, this design is utilized when high concentrations of methane are present, and methane drainage is usually required. One advantage of this system is that the methane-drainage systems are accessible during the life of the panel (*18*). The major disadvantages with this system are that conditions exist that contribute to the development of spontaneous combustion in the ventilated portion of the gob (*10*), and there is an absolute reliance on seals between the gob and the return airway to prevent air leakage.

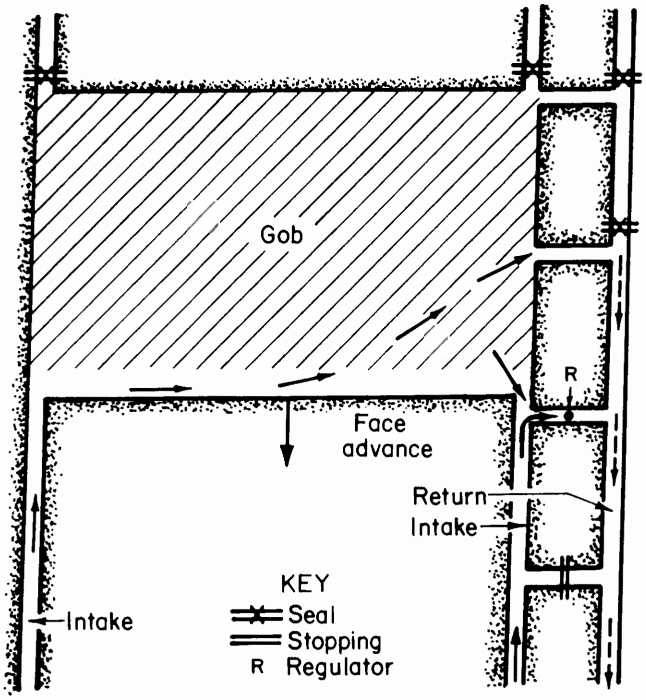

Figure 3.—"Back return" system with two predeveloped tailgate entries (*10*).

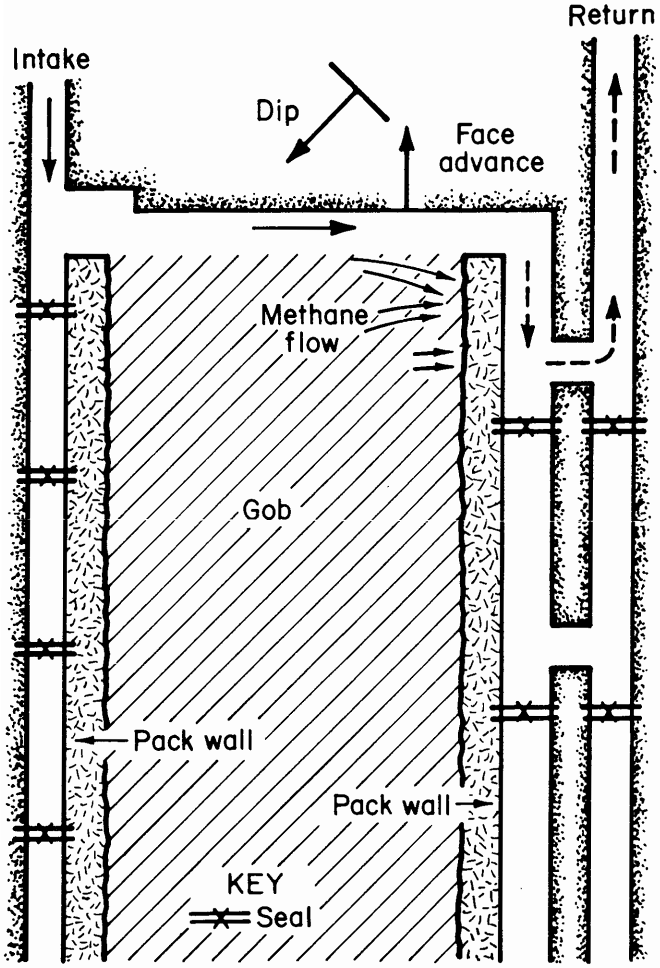

Figure 4.—"Back return" system with predeveloped entries and pack wall support (modified from Bacharach (*12*)).

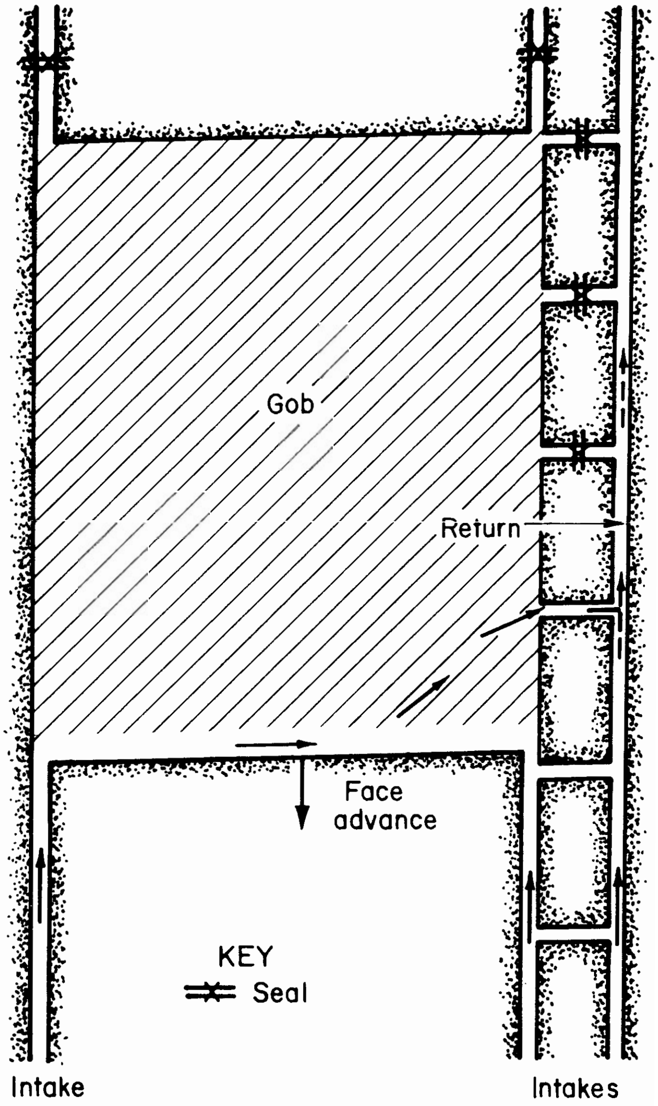

Figure 5.—"Y" ventilation system (*10*).

U.S. SYSTEMS

Two mines in the United States currently use a bleederless ventilation system (*6*, *23*). Both use a modified-"U"-type ventilation scheme with multiple predeveloped entries. Seals are constructed in entries and crosscuts to isolate the gob. Air is directed up the headgate entries, across the face, and back along the panel return. A limited amount of intake air is coursed through the headgate entry adjacent to the sealed gob to maintain access for seal examinations, monitoring, gob pressure balancing and entry maintenance. An example of a modified "U" system with two-entry development is shown in figure 6. Like the "Y" system, the major disadvantage of this system is a greater reliance on seal integrity to isolate the gob.

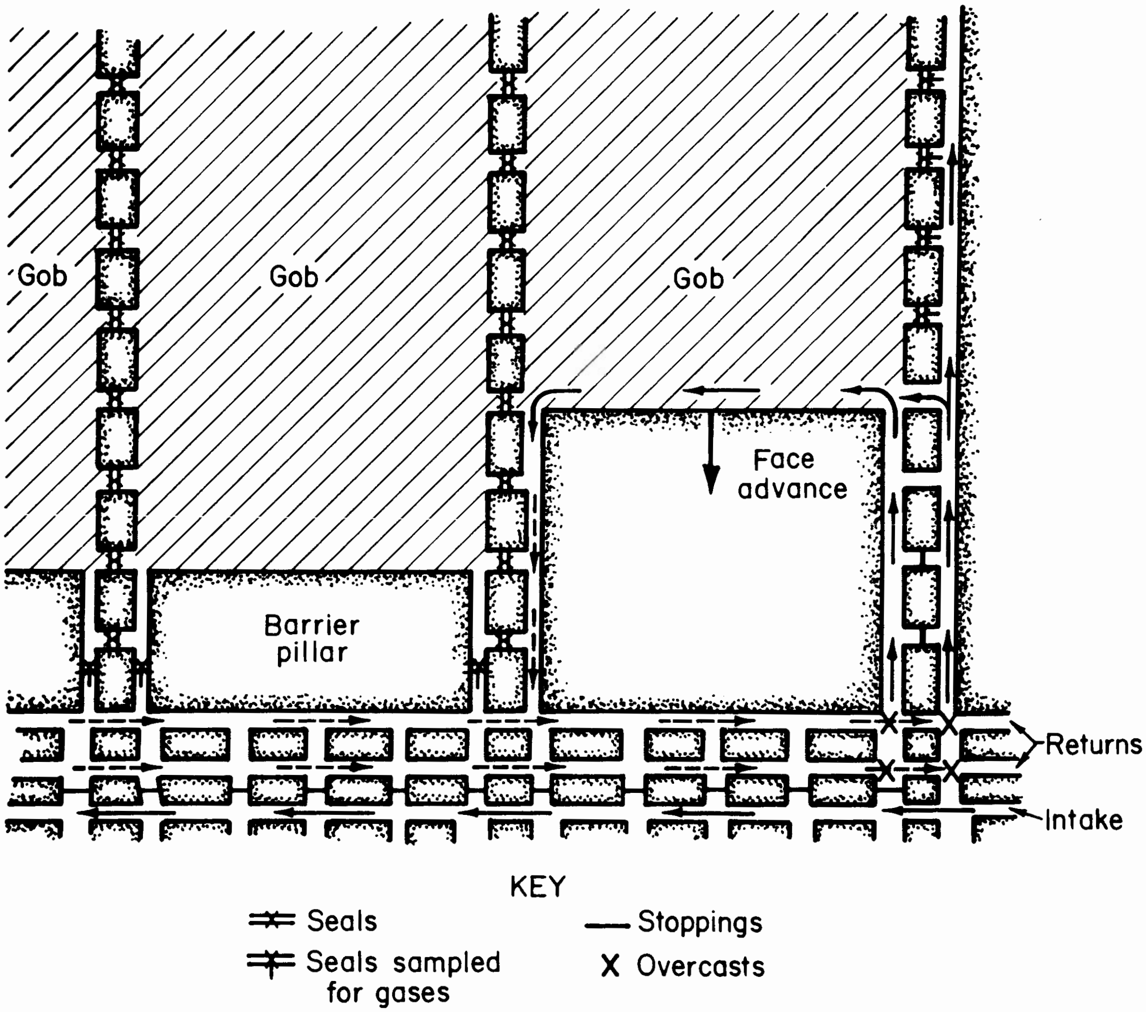

Figure 6.—Two-entry modified "U" ventilation system on retreat longwall face used in United States.

BLEEDERLESS VENTILATION DESIGN CONSIDERATIONS FOR U.S. COAL MINES

Underground coal mine design and practices in the United States are notably different than those of many other countries. One of the principal differences is the number of entries commonly developed. Most coalbeds currently mined in the United States are shallow (less than 600 m) and relatively flat with multiple-entry development within the coalbed. Three-entry longwall gate road developments are very common, with some gassy mines using four-entry developments for additional ventilation. One or more of the entries on the headgate side of the longwall become the tailgate entries on the next longwall panel, connecting adjacent gobs, which are linked to a bleeder system.

In Europe and Asia one-entry longwall gate roads are common, with some two-entry developments on the tailgate side of the longwall. Barrier pillars are left between panels, isolating individual gob areas. These one-entry or sometimes two-entry longwall development systems undergo ground convergence (mainly floor heave) inby the mining face, reducing the air pathways or increasing air resistance into gob areas on the retreat longwalls. Also, the lower number of entries reduces the number of seals to construct to isolate the longwall gob.

Multiple-entry developments in the United States reduce mine resistance to airflow, so that higher quantities of air can be more easily circulated throughout these mines and are available for bleeder ventilation systems. Higher quantities of air at the mining face are required in the United States to meet stricter health and safety standards and higher coal production levels. For example, the U.S. regulations limit the 8-h personal airborne dust exposure level of an employee to 2.0 mg/m^3 and require the mining face to be deenergized when the methane concentration exceeds 1.0 pct (*2*). In Great Britain the dust standards are 7.0 mg/m^3 measured at a point in the section return 70 m from the face and 5.0 mg/m^3 in entry roads upon development, with a methane standard of 1.25 pct before the mining face is deenergized (*30*). Also, the overall efficiency of the U.S. underground coal mining industry is notably higher than that of many other countries, so more ventilation is required to remove the dust and methane produced at a higher mining rate. Finally, the U.S. regulations with respect to belt entry ventilation to the face and escapeways require three entries for longwall development, although some petitions for modification have been granted for two-entry development.

SPONTANEOUS COMBUSTION RISKS USING BLEEDERLESS VENTILATION SYSTEM

Although a bleederless ventilation system is designed as a spontaneous combustion control measure, certain design parameters provide potential spontaneous combustion risks. The two areas with the greatest risk of heatings are around seals and behind the face supports. If high levels of methane exist in the gob (higher than the explosive range), there is the additional risk that methane concentrations within the explosive range will be located behind a leaking seal or behind the supports. If a heating takes place in these areas, dangerous methane accumulations may be exposed to a possible ignition source. Therefore, when sealing high-methane-emission gobs for spontaneous combustion control, the risks from air leakage are not only a heating but possibly an explosion hazard. Several reported cases of explosions initiated by self-heatings in the gobs of gassy coalbeds are found in reference 16.

Heating Behind Seals

In the United States the use of multiple-development entries for longwall panels leads to the extensive use of seals in a bleederless ventilation design to isolate the gob. Each seal provides the potential for a self-heating event, through air leakage around or through the seal. Also, the larger number of entries increases the number of coal pillars (additional spontaneous ignition and fuel sources) that can be exposed to critical airflows when a bleederless ventilation system is being implemented.

Heatings around seals can occur in the floor behind the seal or in the pillars and roof adjacent to the seals because of air leakage. Therefore, seal design must take into account all mining conditions and consequences that can lead to air leakage. These conditions include high pressure differentials across seals; weak floor or roof strata; fractured, weathered, or permeable coal pillars; and ground control problems and pillar stability. Seal construction must utilize appropriate materials and construction methods to meet or exceed the design specifications. Inspection and maintenance of seals is critical for continued optimum performance.

Reducing the number of entries is beneficial for bleederless ventilation systems in terms of potential sources of air leakage, but also increases the mine ventilation network resistance. A higher ventilation resistance increases the pressure differentials throughout the mine if mining faces are being ventilated with the same air quantity. Higher pressure differentials increase leakage through ventilation controls such as stoppings. Work conducted by the USBM has shown that for a newly constructed conventional block stopping (dry-stacked with mortar applied to one side) leakage was 4 m^3/min per 2.5 mm of water gauge pressure differential, and the leakage more than doubled after 1 year of use with slight roof convergence (*31*). A newly constructed universal stopping (keyed into ribs with a poured footer) leaked 1.4 m^3/min per 2.5 mm of water gauge pressure differential, and the leakage more than doubled after 1 year of use with slight roof convergence. It was shown that a stopping maintenance program could restore stopping integrity to its original effectiveness. Thus, improving the sealing of ventilation controls such as stoppings, overcasts, and seals in bleederless ventilation systems can reduce the potential for spontaneous combustion in these areas.

An example of leakage around seals was seen at a room-and-pillar mine in the Western United States. Here, seals were used to separate the intake and return airways, and there was a high differential pressure across the seals. In this case, pillars located within a 150-m burn zone near the portal of the mine were extremely weathered, and because of the high differential across the pillars, air was drawn through the pillars, causing them to heat. This is an instance where the seals were more effective in preventing air leakage than the coal itself. The problem was alleviated by reducing the differential pressure across the pillars. Although this example is not in the context of a bleederless ventilation system, the problem of air leakage and self-heating due to high pressure differentials is clearly evident.

Another mine in the Western United States that uses a bleederless ventilation scheme at its longwall operation still experienced heatings (*23*). This mine has low methane emissions and the longwalls use two-entry development. Seals are constructed in the entry crosscuts to isolate the gob as the longwall retreats. Monitoring behind these seals is conducted to measure oxygen depletion in the gob, which usually decays to below 5 pct. The oxygen content behind several seals only dropped to 15 to 20 pct because of leakage, and a heating developed. Because of the suspected air leakage, seal modifications were made on the next panel. Because the success of the seals depends strongly on ground control and mining conditions, seal design and construction need to be evaluated on a mine-by-mine basis.

Heating Behind Face Supports

Since it is impossible in practical terms to prevent face ventilation air from entering the gob behind the supports, an oxygen gradient develops. Just behind the supports, where the oxygen concentration is the highest, the air velocity is high, so that any heat generated by self-heating is carried away. Deeper in the gob, the air velocity is too low to provide sufficient oxygen to support spontaneous combustion. However, there exists a critical air velocity zone in the gob where the airflow and oxygen concentration are conducive to self-heating. This is illustrated in figure 7.

The incidence of self-heating depends on how long the coal is subjected to this critical air velocity. If the time is long enough for the heat to build up to an imminent self-heating event, referred to by the British as the "incubation period," a fire may result. Therefore, the rate of face advance is extremely important in preventing self-heating behind the supports. A similar critical area exists with respect to explosive methane concentrations behind the supports in gassy coalbeds. This makes the prevention of self-heating even more critical in this situation, since the body of methane could be ignited.

SOURCES OF AIR LEAKAGES

High pressure differentials across the gob and across seals provide the impetus for leakage. In the U.S. mines using the bleederless ventilation system, this is dealt with by attempting to pressure balance across the gob. However, because of pressure gradients in the gob, it may also be necessary to measure and adjust pressure differentials across seals. In addition, barometric pressure changes due to weather fronts can induce air infiltration into the gob, causing spontaneous combustion. These fronts can also cause outgassing to occur, producing high concentrations of methane and/or carbon monoxide in the face area.

Communication between adjoining gobs, the mine and the surface, and between mines in multiple-bed mining operations by way of overburden fracturing can also provide sources of air for spontaneous combustion in the gob. This factor also makes it difficult to characterize gob gases and maintain pressure balancing, and should be considered in the mine design and planning stages, especially for multiple coalbeds and shallow overburden conditions, to minimize these communication paths.

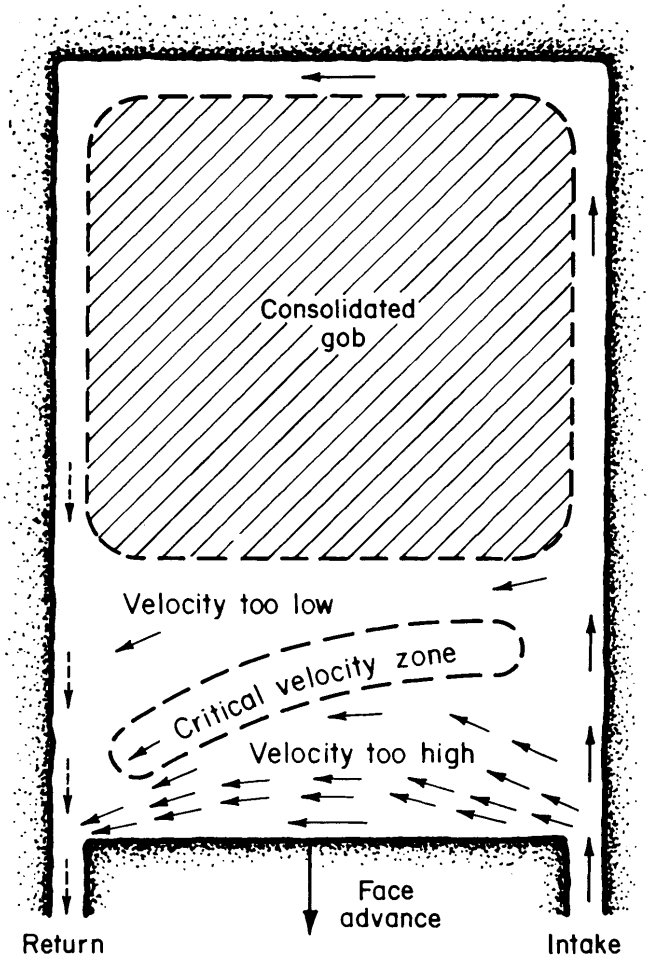

Figure 7.—Critical air velocity zone in gob (*66*).

SEALS AND VENTILATION CONTROLS

The principle behind the bleederless ventilation design for the control of spontaneous combustion is to reduce the amount of air in the gob, thus limiting coal oxidation and the subsequent generation of heat. Bleederless ventilation systems are designed to minimize the potential for air leakage into the gob. Therefore, of critical importance in a bleederless ventilation design are the proper design and construction of seals to minimize leakage and maintain seal integrity, and ventilation planning to reduce pressure differentials across these seals.

Longwall system developments in Europe and Asia, with fewer entries, allow improved control in isolating active and inactive gob areas. A smaller number of entries reduces the number of seals that need to be constructed and maintained, making airflow isolation of mined-out areas more manageable. European and Asian mines usually drive mine entries in rock to gain access to the steeply dipping coalbeds; therefore, seals are constructed in the mined-out areas in the bedrock, reducing the risk of heating at the seal site. When the seals have to be constructed in the coalbed, they are usually constructed within a substantially sized coal pillar to reduce the crushing of surrounding coal and seal (*12*). In Australia, where mine entry development occurs within the coalbed, coal barrier pillars (or fire barriers) are designed into the mine plan so that mined-out areas can be more easily sealed or isolated from airflow to the active mining areas (*10*). Also, in Australia where pillar extraction is practiced, mining methods or sequences of pillar extraction are designed to minimize the gob's exposure to airflow. One of the key elements practiced in both longwall mining and room-and-pillar operations is that production panels are designed for quick advance rates, limiting the duration of critical airflows in active mining areas.

Seal construction is important, so various types of seals are built to meet the mine's particular requirements. Seal construction can vary from a stacked-block stopping to explosion-proof seals. Bacharach defines an explosion-proof seal as a seal composed of noncombustible material to fill the length of the entry equal to one-half the sum of the height and width of the entry (*12*). The USBM defines an explosion-proof seal as one that is able to withstand a static load pressure of 137 kPa, provided that the area to be sealed contains sufficient incombustible material to abate the explosion hazard in that area and that adequate incombustible material is maintained in the adjoining open passageways (*32*).

Seal location and design are crucial in their ability to limit air exchange. Seals should be generally located in areas where entry closure or seal crushing is minimal so airflow leakage can be minimized. Quality construction techniques can reduce leakage, such as keying the seal wall into the floor and ribs and using some squeezable material in the seal construction to accommodate some roof and floor convergence. When one or more panels are being sealed, building lightweight seals in the same entry outby the main seal is recommended to create a void space or buffer zone between the sealed area and the mine (*12*). Under stable barometric pressures the zone between this pair of seals will tend to fill with methane, nitrogen, and carbon dioxide from the sealed area. Provided the zones are made large enough, whatever breathing exists around the inner seal(s) will not be associated with an oxygen-rich atmosphere. This minimizes the risk of a heating around the inner seal.

Barometric pressure effects on seal leakage are amplified with larger mined-out areas, so a series of seals with a buffer zone also reduces atmosphere exchanges with the sealed area because the outer seal adds extra resistance to the pressure change. An improved means to reduce atmosphere exchanges in sealed areas of the mine is to construct pressure chambers at the seals or to pressure balance the sealed areas to limit atmosphere exchanges with the mine (*12, 17, 33*). This is achieved by constructing several seals with a void space in the same entry (as described above), generally on the low-ventilation-pressure side of the sealed area. The void space is then pressurized by connecting it with a duct to a high-pressure ventilation network in the mine. This is shown in figure 8. An exhaust regulator on the outer seal is then adjusted to equalize the atmospheric pressure behind the inner seal with the void space pressure. Several pipes are built into these seals for gas and pressure sampling behind the seals.

The U.S. mines with bleederless ventilation systems use wood squeeze seals and pressure balancing techniques (*6, 23*). At one mine, isolation stoppings are constructed in the crosscuts of the headgate entry prior to the longwall face passing. The stoppings consist of a wooden pack wall, a 3- to 5-m slurried sandfill, and a 1.2-m-thick wood crib block stopping. Even with this method, heatings behind the seals continue to be a persistent problem because of leakage through and around the seals. At this mine, the leakage is primarily due to the weak roof conditions, which allow leakage through the roof. At another mine, timber squeeze seals are built in advance of the face. As the longwall passes the seal, ground convergence "squeezes" the timbers, isolating the gob. No self-heatings have been reported at this mine using this type of seal in a bleederless system.

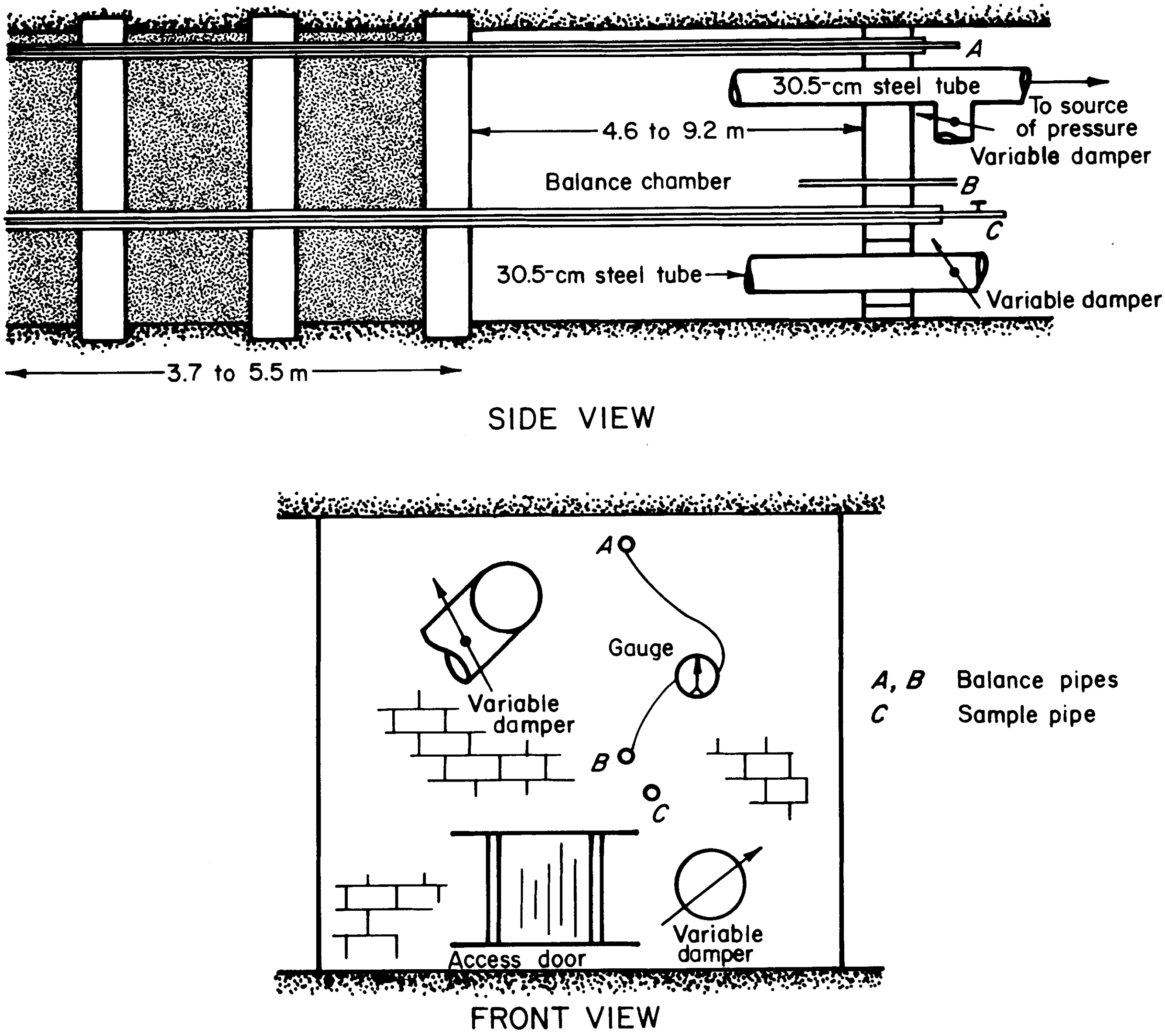

Figure 8.—Pressure balance chamber to minimize seal leakage (*12*).

Ventilation control devices such as stoppings, man doors, regulators, and overcasts create air pressure differentials within the coalbed. Fractures and cleat in the coal around these control devices are conduits for critical airflows through the coal, creating the potential for a heating. Proper location, improved design, and quality construction of these devices can decrease the amount of critical air exposure of coal and/or reduce pressure differentials around these devices. The coalbed airway surfaces around these ventilation control devices can be sealed or coated and the coal itself injected with an inorganic sealant to restrict airflow through the fissures. Coal pillars in mine airways should be properly designed to reduce crushing or sloughage, using pillar bolting if necessary. Pillars that crack can be surface coated and/or injected with an inorganic sealant.

The mine plan should be designed to minimize ventilation control devices, and the sealed mine areas should be located on the low-pressure side of the ventilation network. Also, pressure differentials can be reduced through better location of the control devices, or through alternative pressure reduction techniques. For example, regulators, in some cases, can be located outby overcasts or air crossovers. Auxiliary fans can be used with stoppings to reduce the air pressure differential between air crossover entries. Double doors can be constructed to create an airlock. If possible, all these control devices should be keyed into the floor, roof, and coal pillars. Finally, a compromise between the number of air entries, entry dimensions, and exposed coal surfaces in the ventilation network design should be considered while minimizing the mine's ventilation pressure characteristics (*12*).

METHANE CONTROL ASPECTS OF BLEEDERLESS VENTILATION DESIGN FOR LONGWALL SPONTANEOUS COMBUSTION CONTROL

Spontaneous heatings can be a serious mine safety problem because in addition to the obvious fire hazard, they can potentially ignite methane accumulations with disastrous consequences (*16*). The preponderance of literature that addresses the problem of spontaneous combustion in the presence of methane during longwall mining recommends or describes using retreat mining and preventing the penetration of ventilation air into the gob (*10, 13, 15-16, 18, 25, 34-35*). Humphreys points out that "wherever ventilation air is permitted to pass along the edge of a goaf or is forced to pass through the goaf, there will be areas in which there is sufficient oxygen to support oxidation, and insufficient air movement to carry away the heat generated." He further states that "it is much easier to ensure no air reaches these places, than to ensure that all the potentially hazardous areas are adequately ventilated" (*10*).

In mines where methane drainage has been used to supplement bleeder entries, excluding ventilation air from the gob will make drainage the primary methane control measure. Methane drainage may also be required with bleederless ventilation systems in mines where ventilation by bleeder entries alone could have controlled the methane accumulations. Humphreys states that "when dealing with a spontaneous heating, the source of ignition is ever-present and therefore emphasis must be placed on preventing accumulation of explosive mixtures." He further states that the key element of a methane-drainage system is to establish "an extinctive atmosphere in the goaf, that is neither potentially explosive nor aids the oxidation of coal" (*10*). Relatively low levels of methane emissions that would otherwise have been swept out of the gob could eventually build up to the point where they could inundate the face as a result of falling barometric pressure, or large roof falls.

The effectiveness of methane drainage is important beyond the obvious explosion risk when spontaneous combustion is also a concern. One spontaneous combustion control strategy is to mine at rates sufficiently fast so that any ventilation of the gob that does occur is sustained for a time interval less than the coal's spontaneous combustion incubation period. Thus mining delays due to high methane levels not effectively controlled by ventilation and methane drainage can potentially expose ventilated gob areas to spontaneous combustion conditions past the incubation period. This is a particular concern when the "Y" or "back return" bleederless ventilation systems are used, since they are specifically designed to ventilate the return corner of the longwall face.

HISTORICAL AND CURRENT METHANE-DRAINAGE PRACTICES

Ventilation is the primary methane control measure in coal mines throughout the world. However, when ventilation alone cannot control methane levels underground, supplementary methane drainage must be used. Methane-drainage practices are generally different in the United States than in other countries. Methane drainage for longwalls in the United States is primarily accomplished by the drilling of several vertical boreholes into the gob from the surface. These vent holes are generally equipped with surface vacuum pumps to draw gases from the gob. In most applications, the pumps are set to draw the maximum volume of gas possible. Minimal monitoring or control of the gas production is attempted. Secondarily, horizontal methane-drainage holes are used underground to drain gas in advance of mining from the coalbed being mined.

The primary methane-drainage technique used on longwalls outside the United States is cross-measure boreholes. These holes serve a similar function as the vertical gob gas vent holes used in the United States. The cross-measure holes, however, are drilled underground from the entries adjacent to the panel. The holes are usually drilled at an angle into the roof, over the longwall panel to intercept the "destressed" zone by the retreating face. Methane drainage of gob areas through pipes installed in seals is also practiced. Methane-drainage holes are also drilled in advance of mining to other horizons (usually other minable coalbeds), particularly in steeply dipping multiple-coalbed mining operations.

The selection of methane-drainage techniques depends on several factors, including mining depth, mining methods, number of coalbeds being mined, degree of dip, and cultural development on the surface. Methane drainage outside the United States is predominantly conducted underground. This is due to the longer history of mining, which results in mining at greater depths, increasing the cost of drilling from the surface, and the lack of surface drill sites due to habitation density. Conversely, in the United States, most of the longwall mines that require methane drainage are relatively shallow and are located in sparsely populated areas.

A common method to ensure the effectiveness of any methane-drainage system is to identify the source of the gas that enters the mine atmosphere. Generally, this will include the coalbed being mined, as well as surrounding strata, particularly other gassy coalbeds that are influenced or distressed by longwall mining (*36*). Once the source of the gas has been determined, then the appropriate methane-drainage technique can be selected and designed for the particular site-specific conditions.

Methane-Drainage Systems

The greatest volume of literature concerning ventilation and methane control relative to spontaneous combustion originated in Great Britain. Coal mining was practiced in Great Britain for many years before coal mining began in the United States, and longwall mining was used in British mines before it was introduced in the United States. Historically, longwall mining in Great Britain has been by advancing methods into the solid coal, which requires the construction of pack walls and the use of extensive roof support and floor grading to maintain open entries for ventilation, transport of the mined coal, and movement of equipment and personnel. An advancing longwall, shown in figure 9, presented an ideal situation for methane control since the pressure differential between the intake and return sides tended to direct gas accumulations in the gob away from the face and into the return. However, as gassier coalbeds were mined, it became necessary to supplement the ventilation system with methane-drainage holes to control methane at the face. Cross-measure holes, shown in figure 10, were the most common drainage system employed. These holes are drilled from the return side over (or under) the pack wall or cribs into the destressed zone over (or under) the extracted panel. The holes are drilled from the return side to take advantage of the pressure differential between the intake and return.

While the ventilation and methane-drainage attributes of the advancing longwall system shown in figure 9 are advantageous for methane control, the system is not desirable for control of spontaneous combustion in the gob, since the gob is continuously infiltrated by the ventilation air. A gradual shift to retreat longwalls began in Great Britain in the 1960's, primarily to increase coal production. Because of the past successes with a "U" ventilation system

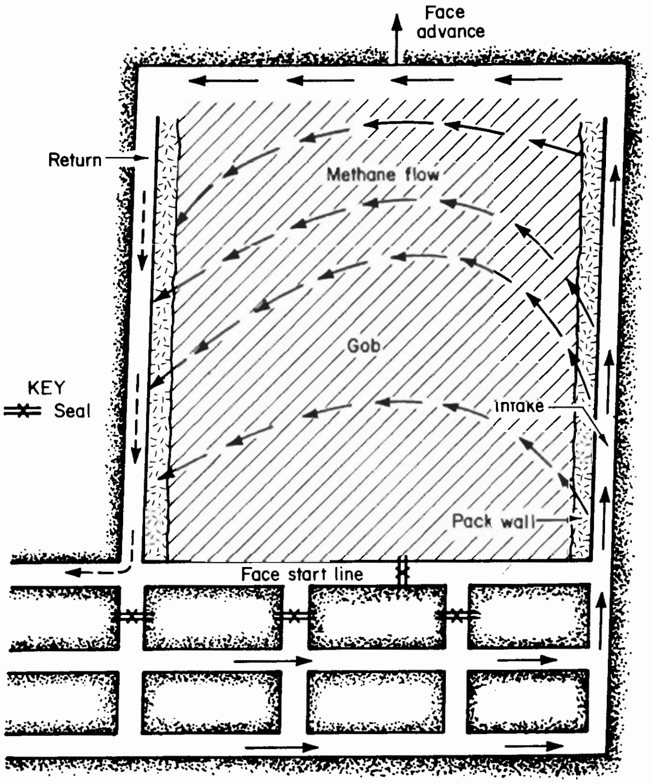

Figure 9.—"U" ventilation system on advancing longwall face (modified from Humpreys (*10*)).

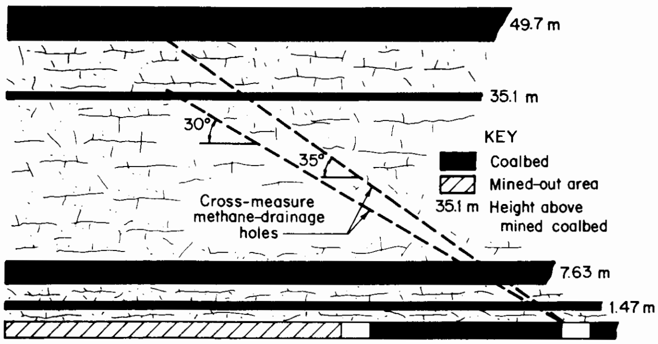

Figure 10.—Section view of cross-measure methane-drainage holes (modified from McKensey (*18*)).

on advancing longwalls, a similar system was used on the retreat longwalls. As can be seen in figure 1, single entries were developed in the coal block before longwall mining started, and the overburden was allowed to cave without maintaining the entries as the face was mined. This bleederless ventilation system was also advantageous from a spontaneous combustion control standpoint; however, in gassier conditions, methane emissions became a problem at the return corner adjacent to the gob, figure 2. Since entries were not maintained adjacent to the gob, the traditional cross-measure boreholes could not be used for methane drainage.

In an attempt to keep the positive attributes of the "U" ventilation system, but to incorporate methane drainage, the back return ventilation system was developed (*13, 26, 37*). This is primarily a bleederless system with only the return corner of the gob ventilated. With this ventilation system, as the longwall retreats down the panel creating a larger gob area, the resistance of the ventilation path decreases. This is advantageous in gassy conditions since greater air volumes are progressively supplied to dilute the increasing gas emissions of the larger gob area. In this system, spontaneous combustion should only be a problem in the limited gob area near the tailgate. As long as mining progresses at a rate sufficient to ventilate this area for a period of time less than the incubation period for spontaneous combustion, heatings should be avoided.

As shown in figure 4, the back return system provides a supported entry from which the traditional cross-measure methane-drainage holes can be drilled. The gas produced by these holes is collected in an underground pipeline and transported to the surface where it is generally utilized.

The back return airway is generally kept relatively short, requiring that seals be periodically constructed to isolate the gob. In the first experiments with this system, the cross-measure holes into the roof and floor were not left connected to the pipeline after seals were installed outby their location (*37*). Apparently the holes were allowed to bleed under natural flow into the sealed chambers. Open-ended methane-drainage pipes were left behind the seals to provide drainage of these chambers, shown in figure 11.

Even with this drainage system in place, the gas pressure behind the seals eventually became sufficient to leak gas at high rates into the returns. Subsequently, the cross-measure holes were left connected to the underground pipeline after the seals were constructed, and this successfully controlled the methane leakage problem. No access was possible to these cross-measure holes behind the seals, and the only control of their gas flow was by adjustments to the amount of suction applied to individual pipelines. The holes behind the seals could only be shut in by closing valves on the pipelines outby the last seal.

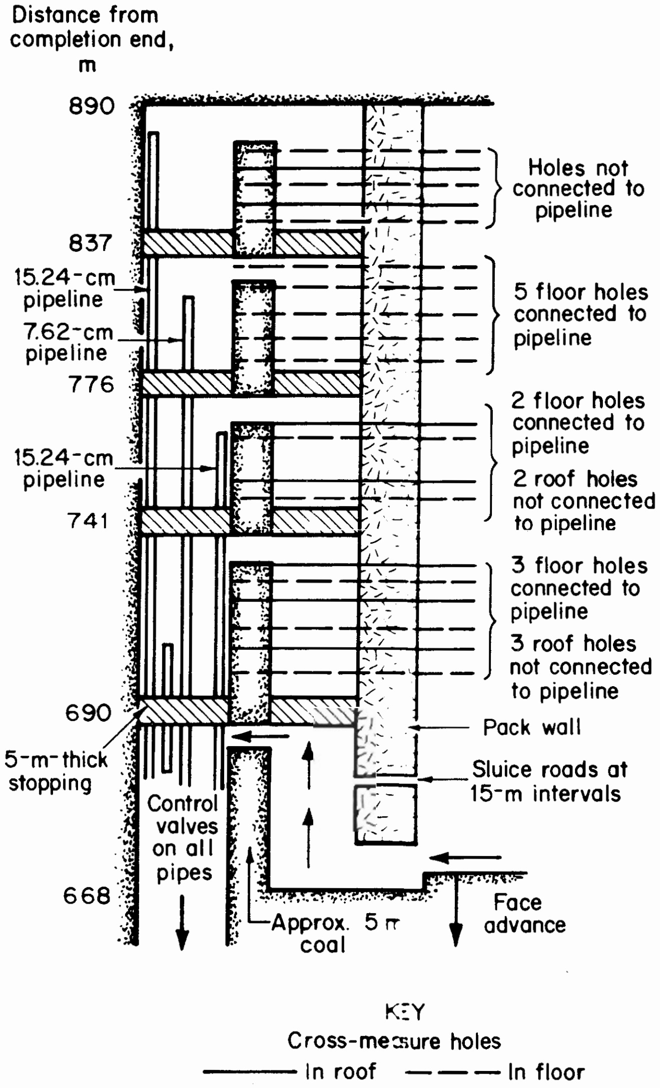

Figure 11.—Methane-drainage system used with "back return" ventilation system (modified from Highton and Cunliffe (*37*)).

Such methane control measures would most likely not be acceptable in U.S. coal mines. When underground methane-drainage systems have been utilized in the United States, many ventilation plans have required that they be installed in accessible entries where repairs could be made in the event of leaks (*38*). The USBM has developed a fail-safe protection system to automatically shut in underground pipelines and the methane-drainage holes connected to them in the event of methane leaks (*39*).

Highton recommends that two methane-drainage pipelines be maintained in the sealed return airway (*13*). This is to make it more likely that one pipeline would survive and continue to produce gas from the gob in the event of a roof fall. Each pipeline would, however, be connected to different sets of cross-measure holes, and the consequences of losing one set of drainage holes would vary depending on their location. Highton reports that even when one pipeline has been damaged and shut in, the remaining methane-drainage holes have captured a portion of the gas previously drained by the holes connected to the damaged system (*40*). A decrease in the percent methane from a pipeline is generally the first indication of a leak. Under most circumstances, it is likely that drainage holes from only a limited number of sealed chambers in a back return ventilation system would be kept on production as the longwall retreats. Eventually the pipeline connected to holes farther back in the gob would be cut off, and a new pipeline connected to holes closer to the face would be started. In this way, the recommended two pipelines would be preferentially draining the gob closest to the longwall face. It has also been a practice to leave a pipeline active to the holes near the start-up end of the panel, especially when it is updip of the retreating face.

Another version of the modified "U" ventilation system has been used in gassy coalbeds subject to spontaneous combustion in Australia. It is quite similar in design and function to the British back return system. The primary difference is that the Australian system uses two entries on the tailgate side driven on development, shown in figure 12, instead of leaving a line of small pillars and constructing a pack wall to create two entries as the British do. However, as the longwall retreats, two entries are maintained with the British system, whereas one entry is sacrificed in the Australian system. The Australian system would probably be less labor and time intensive than the British back return system, making it more attractive to U.S. coal companies. The Australian modified "U" system also provides for two intake airways, which would be advantageous in gassy U.S. coalbeds.

Methane drainage with the Australian modified "U" ventilation system is similar to the back return system used by the British. A system of cross-measure holes is drilled into the roof from the return airway. However, fewer holes are used (one per pillar versus every 9 m), and they are drilled in advance of the face instead of after. Also, no floor methane-drainage holes were reported. These differences may be due to site-specific methane conditions, and not to any fundamental difference in the ventilation system. The cross-measure holes are connected to an underground pipeline hung from the ceiling, and the gas is transported to the surface with the aid of vacuum pumps. In addition to the cross-measure holes, an open-ended pipeline is also installed through the seals to a point near the gob at the highest point in the return airway. This pipeline is also connected to the vacuum pumps on the surface.

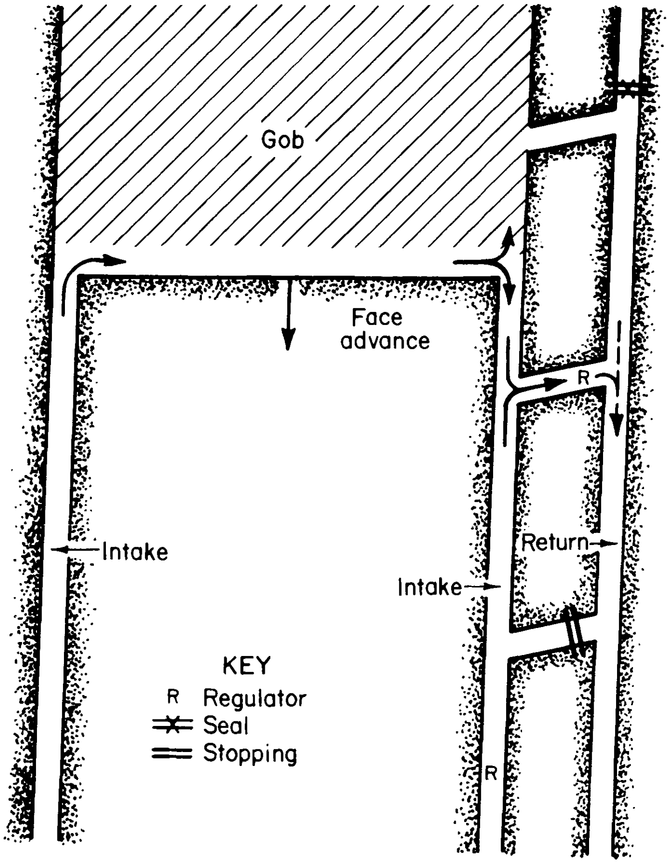

Figure 12.—Australian "modified U" ventilation system (*18*).

The basic British back return ventilation system with modifications to include two intake entries and "auxiliary diagonal air raises" (fig. 13) is used by the Russians to control methane emissions on longwall panels susceptible to spontaneous combustion (*21*). This ventilation plan diverts gas emitted from broken coal on the belt line through the diagonal, thus bypassing the face. The methane hazard is reduced along with the air velocity at the face, which aids the basic back return system in spontaneous combustion control. As in the other countries discussed previously, methane drainage by cross-measure holes (both above and below the extracted panel) is commonly practiced. However, Smorchkov also mentions the use of "ventilation holes drilled from the surface to the drainage gate," and "gas drainage of contiguous seams" using boreholes from the surface without giving specifics as to the configuration of these holes (*21*).

Spontaneous combustion and concurrent methane drainage is also a considerable problem in Poland (*16, 29*). The ventilation systems developed by the Polish are most

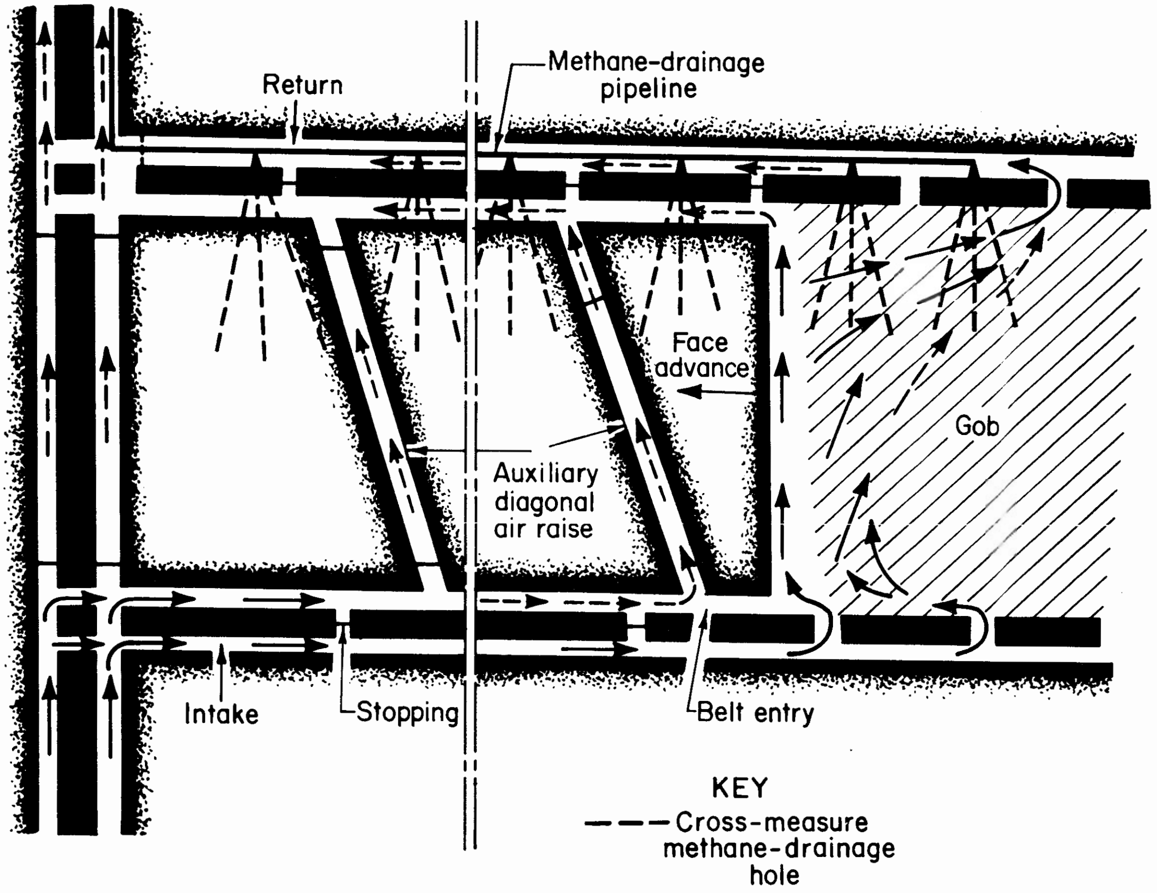

Figure 13.—Russian "modified U" ventilation system with "auxiliary diagonal air raises" (modified from Smorchkov (*21*)).

remarkable for their great number of variations, including several variations of the basic "U" and back return systems. Methane control systems are also quite varied, utilizing several variations of the cross-measure concept. Methane drainage in advance of the face is more commonly practiced than in other countries, primarily from underground, but in some instances from the surface. Krzystolik states, in reference to surface drainage in advance of mining, that in no case did it "avoid the necessity of methane drainage from the excavation after beginning the exploitation process" (*41*).

Methane drainage in many Polish mines is an integral part of the drivage of development entries. Shallow-angle holes are drilled from specially constructed drilling "caves" to drain gas from the strata in front of and adjacent to the advancing entries as shown in figure 14. Because of the steep dip of the strata in many of the Polish mining districts, cross-measure-type holes are also drilled from drainage entries driven in rock above or below mined coalbeds (fig. 15). Because of the prevalence of multiple-coalbed mining, similar holes are also drilled from existing entries in other coalbeds in preference to driving entries in rock. The more traditional cross-measure holes are also used during the mining of longwall panels. These holes are drilled both above and below the panel, in advance of the face and into the destressed zone immediately before the longwall face. Additionally, when the mined coalbed is a major contributor to the gas emission problem, horizontal holes are drilled into the unmined panel to drain gas. This is one of the few instances of a foreign country's using a gas-drainage technique commonly used in the United States.

Drainage entries and the remaining entries around completed panels are generally sealed, especially when spontaneous combustion is likely. These seals, shown in figure 16, are equipped with open-ended methane-drainage pipelines and gas sampling ports to monitor the gas composition behind the seals. Krzystolik also mentions a

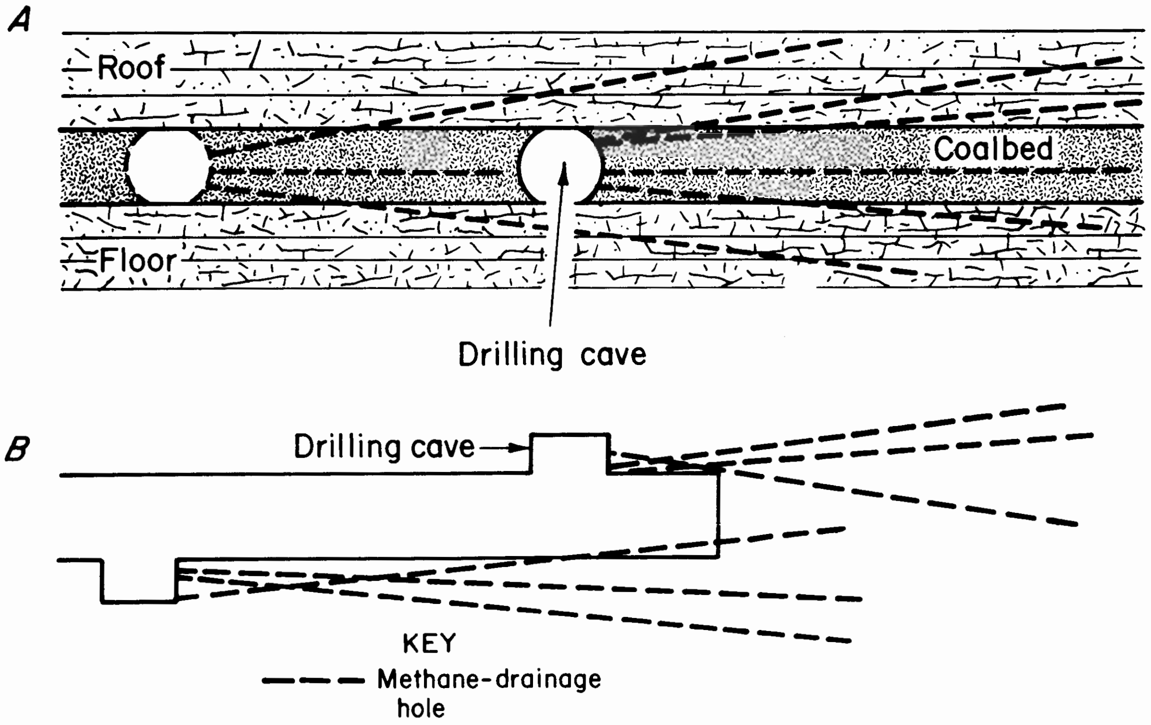

Figure 14.—Shallow-angle methane-drainage holes drilled in advance of entry development. *A*, Section view; *B*, plan view (modified from Krzystolik (*41*)).

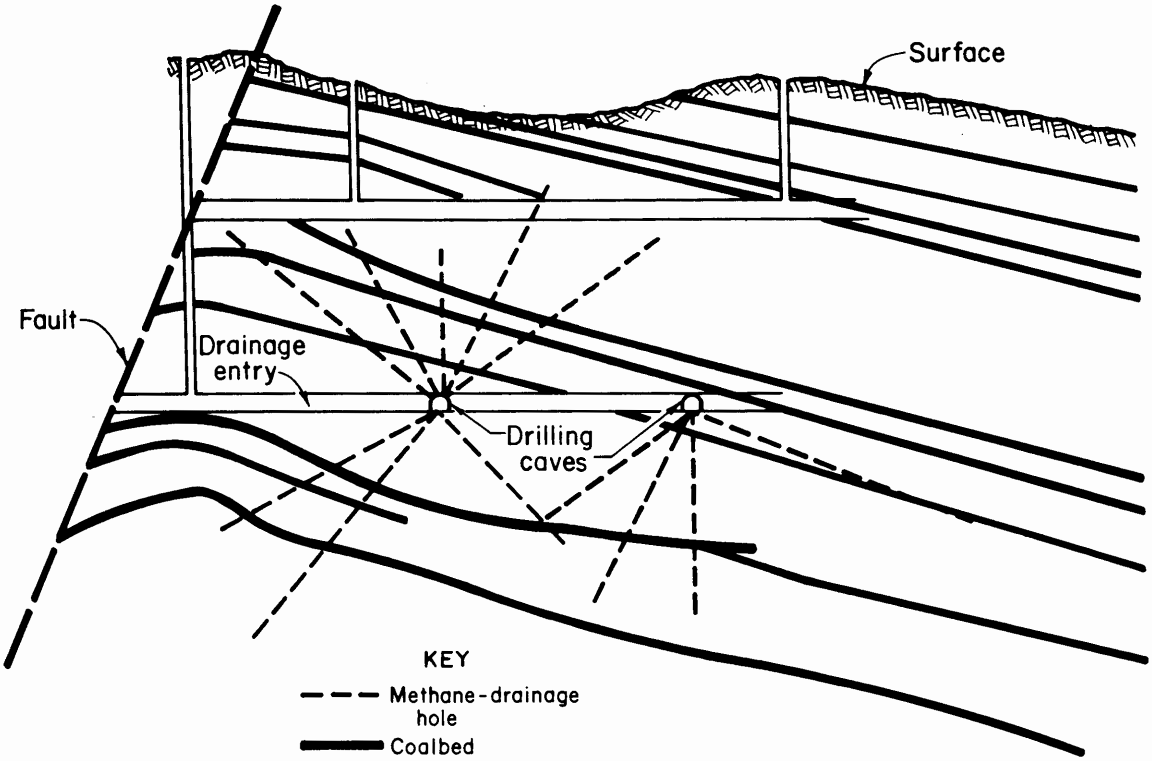

Figure 15.—Section view of cross-measure-type methane-drainage holes drilled from drainage entries into surrounding coalbeds (modified from Krzystolik (*42*)).

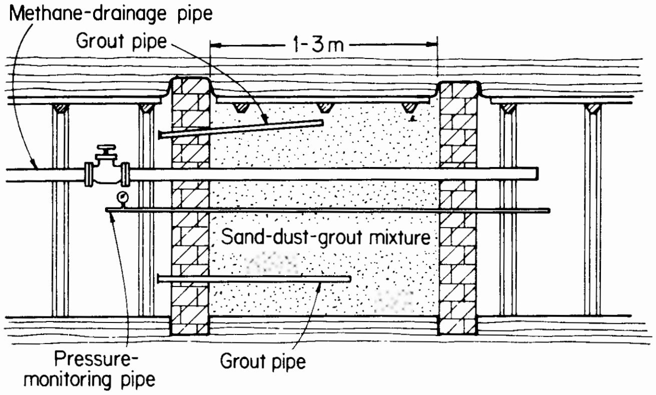

Figure 16.—Methane drainage behind seals (*24*).

spontaneous combustion control measure of inerting the gob by using pumps to divert methane from the methane-drainage pipeline "to the piping led out the gob seals in the bottom roads" (*16*). This is a spontaneous combustion control practice that would most likely not be permitted in U.S. mines. Nitrogen and carbon dioxide are the most common gases used to artificially inert the gob atmosphere for spontaneous combustion control (*10, 19*).

In coalbeds with significant dips, the geometry of the longwall panel and the direction of mining in relation to the structure can influence the effectiveness and selection of methane-drainage systems. This is generally of greater concern outside the United States. Commonly in areas of steep dips, longwalls are oriented with the face parallel to the strike and mining progresses downdip (*18, 40*). This enhances methane control by the ventilation system in that the buoyancy effect of methane tends to keep it in the gob updip of the face (*26*). Methane drainage of sealed chambers created by the back return ventilation system is also enhanced by placing the intake of the open-ended drainage pipeline at the highest elevation in the individual chambers. Thorp observed that retreat mining downdip is less conducive to spontaneous combustion (*25*). A disadvantage of mining downdip is that if water is present, it will continually accumulate at the working face.

While retreating downdip can be advantageous, it is not without potential problems. Highton reports that because of the buoyancy effects of the methane in the gob, it was generally found that when retreating downdip, the oxygen content is generally higher behind the seals in a back return ventilation system (*13*).

"Overdrainage" of the gob will tend to move the interface between methane-rich and oxygen-rich air farther back into the gob, creating conditions ideal for spontaneous combustion over a more extensive area. Swift describes a longwall panel where "overdrainage" from cross-measure holes at the highest point in the sealed return created a migration path from the active face, along the collapsed intake side of the gob, and then across the gob to the cross-measure holes (*26*). This infiltration of ventilation air initiated spontaneous combustion, as evidenced by an increase in carbon monoxide levels in the pipeline connected to the initial cross-measure holes drilled near the face startline. By regulating the suction applied to this pipeline, the flow of ventilation air into the gob was reduced, and carbon monoxide levels in the gas stream declined.

It is also possible to retreat a longwall face updip using the back return ventilation system in a gassy mine subject to spontaneous combustion. In this longwall configuration, with the gob gas downdip of the active face, the buoyancy effect will initiate gas migration to the face, which is obviously undesirable. Swift stated that under such circumstances, "the ventilation pressure drop in the back return circuit must be sufficient to counter the buoyancy and also to facilitate the movement of firedamp (methane) into the zone influenced by the firedamp drainage holes." He reports on a case study of a longwall retreating updip (fig. 17) where "by adjustment of the firedamp drainage system, it was possible to quickly create an extinctive atmosphere behind the newly constructed seal, thus minimizing the risk of spontaneous combustion" (*26*). The risk of spontaneous combustion on this panel retreating updip was further controlled by never allowing a back return to be open and exposed to the air current for more than half the estimated incubation period. However, Highton also states that the "length of the back return is more critical on faces retreating to the rise (updip), and this length should be kept as long as possible in order to maintain access to a maximum number of boreholes on the methane drainage system" (*13*).

Longwalls are also oriented with their faces parallel or subparallel to the dip. In this orientation, the gate roads are then parallel to the strike, and successive panels are placed downdip of the previous panel. The intake airway is on the downdip margin of the panel, and the return is on the updip margin. This is also an advantageous arrangement for cross-measure methane drainage when the back return ventilation system is used for spontaneous combustion. The buoyancy effect of the methane helps to move the methane updip to the cross-measure methane-drainage holes in the return airway on the updip margin of the panel.

Another ventilation system used for spontaneous combustion control in the presence of methane is the "Y" system (fig. 5). This system has been used in Australia on longwalls retreating downdip (*18*). As with the back return ventilation system, the "Y" system is designed to

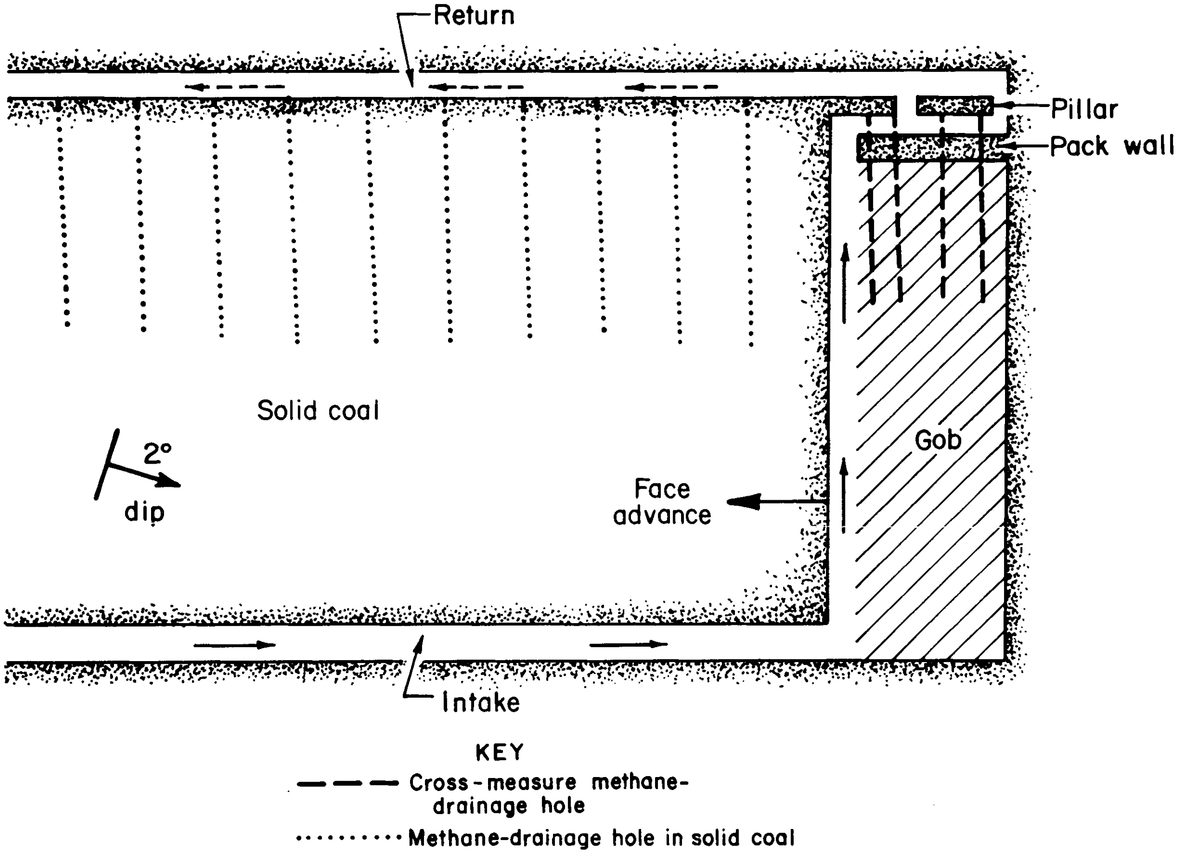

Figure 17.—Horizontal and cross-measure methane-drainage holes used on "back return" ventilation system (*26*).

ventilate the gob in a limited area at the return corner as well as the tailgate. The advantage of this system is that three intake airways are used, which allows for greater volumes of air to reach the face and return corner. The back return system with a pack wall, as utilized by the British, uses only a single intake airway. Another advantage of the "Y" system is that the return airway adjacent to the gob is always accessible, permitting access to the methane-drainage system. The disadvantage from a methane control standpoint is that as the panel retreats and the gob area increases, the volume of air decreases because of a longer return airflow path with greater resistance. With greater volumes of gas being diluted in less airflow, the methane concentration in the returns increases, placing more reliance on the methane-drainage system for methane control. The "Y" system is probably best suited for mines operating with low to moderate methane emission problems.

Methane drainage is achieved in the "Y" system by drawing gas from the gob through an open-ended pipeline installed through the sealed crosscut at the highest elevation in the gob. In addition, cross-measure holes are drilled over the gob from the return airway that is maintained for ventilation. These cross-measure holes are then connected to a separate pipeline to transport the gas out of the mine. There are several notable differences in methane-drainage practices relative to the cross-measure holes described by McKensey for the "Y" system versus the back return system utilized by the British (*18*). With the Australian "Y" system the cross-measure holes were drilled in advance of the longwall face, and the holes were farther apart (120 m versus 9 m). Also, the British utilized drainage holes into the floor beneath the panel.

In the United States, the primary methane-drainage technique employed on longwalls is vertical gob gas holes drilled from the surface in advance of the longwall, as shown in figure 18 (*42-44*). This technique is generally preferred because of the shallow depth of U.S. mines that results in relatively low drilling costs. Also, because of subsidence-related problems, longwall mining is generally practiced in areas with sparse development on the surface, which makes it easier to acquire drilling locations. Drilling on the surface is also more desirable than in the more restrictive underground environment, where logistics are

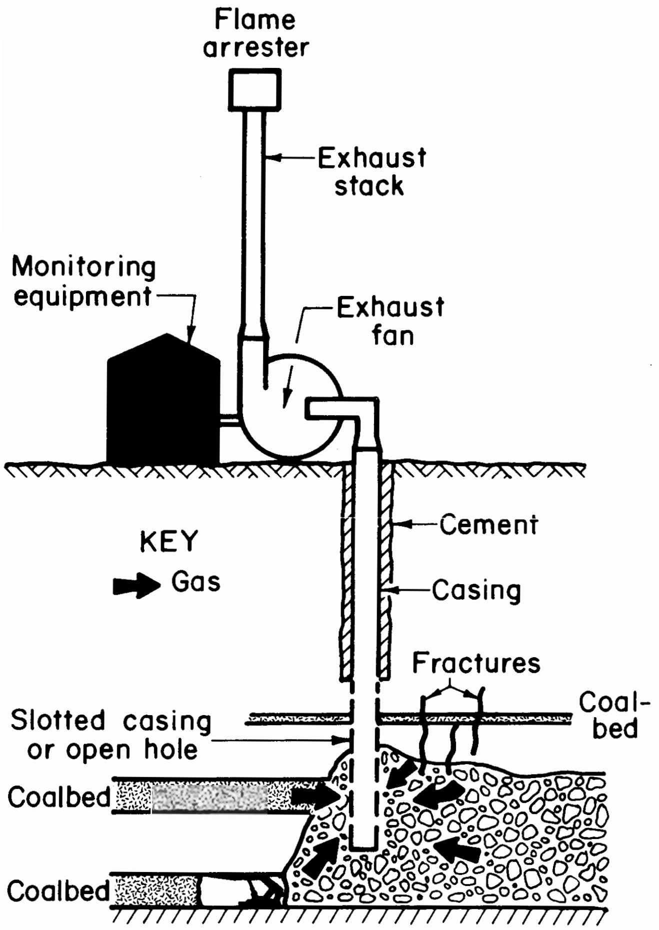

Figure 18.—Schematic section view of complete longwall gob gas vent hole system commonly used in United States.

more cumbersome and more stringent safety regulations must be observed.

The vertical gob gas vent holes function very much like the cross-measure holes most commonly used on longwalls outside the United States. The major difference (other than drilling location) is that the vertical gob gas vent holes are usually drilled near the centerline of the panel, whereas the cross-measure holes are drilled from entries along the panel margin. Also, fewer vertical gob gas vent holes (two to four per panel) are generally required on a panel, whereas cross-measure holes are spaced as close as every 10 m.

These differences in methane-drainage technologies potentially have some significance relative to their use in mines that have spontaneous combustion potential. Humphreys, Muller, and others note the importance of not "overdraining," since this can pull mine air into the gob and potentially initiate spontaneous combustion (*10, 45*). Since the cross-measure holes are drilled from mine entries underground, there is a higher risk of air infiltration on a bleederless entry ventilation system. Air infiltration can occur if the annulus between the drilled hole and the standpipe is not grouted properly, or if it is too short. Humphreys recommends that the standpipes be at least 6 m long and be grouted with impermeable materials. He also recommends that the holes be completely grouted at the end of their productive life (*10*). This of course would not be possible if they were allowed to remain on production after the entry was sealed with a stopping, as is commonly practiced with the back return ventilation system outside the United States.

Mine air infiltration into the gob can also occur through fractures in the roof or pillars as a consequence of too much suction applied to the cross-measure holes. A final consideration is that since a relatively large number of cross-measure holes are drilled on a panel, there are numerous sites for potential air infiltration into the gob.

Cross-measure methane-drainage holes have been used on an experimental basis at only one mine in the United States (*46-49*). This technique has never gained support from the mining industry in the United States. This is primarily due to the general success and ease of drilling vertical gob gas vent holes from the surface, the general unfamiliarity with the cross-measure technique, and the logistics of drilling near the active face.

The vertical gob gas vent holes would seem to have several advantages relative to their use with bleederless longwall ventilation systems in the presence of a potential for spontaneous combustion. First, since the gob gas vent holes are generally drilled near the centerline of the panel, they are as far from the mine airways as possible. Second, there are generally only two to four vertical gob gas vent holes drilled per panel, so there are fewer sites that could potentially leak air into the gob because of incomplete cementing of the annulus between the hole and the casing. Third, there is greater length of cemented casing; therefore, it is less likely that a leak will occur between the surface and the gob. If leaks were discovered, there is a greater chance that they could be corrected, since access to the hole is always possible on the surface, as opposed to the underground cross-measure methane-drainage holes.

Even with the apparent positive attributes of the vertical gob gas vent holes, it is still possible to "overdrain" and pull mine air into the gob. It is essential that the amount of suction applied to the gob gas vent hole be controllable so that the infiltration of mine air into the gob is minimized. Also, monitoring the gas compositions in the vent holes is necessary to detect overdrainage.

On longwalls in the United States that use bleeder entries, there is generally little, if any, control over the suction applied to a gob gas vent hole. The intent of most mine operators is to produce the highest volume of gas possible with the highest capacity blower available at the mine. This policy is relatively harmless early on in the panel extraction, since most gob gas vent holes reach their highest production volume in the first week or two after being intercepted by mining. The methane concentration generally increases into the high 90-pct range in this same early timeframe. However, if the large blowers are left in place for an extended time, the methane concentration gradually decreases as mine air is drawn through the gob, probably partially because of the active bleeder system and the suction applied to the vertical gob gas vent hole itself. The methane concentration commonly stabilizes for some extended period of time in the 50- to 80-pct range. Commonly when the methane concentration drops below 25 pct the blowers are shut off as a safety precaution, and the holes are allowed to free flow (*50*). In many cases, the only control over the gob gas production is by moving the large blower installed at the beginning of the panel to a newer hole and replacing it with one of lower capacity. This movement is done to keep the capital outlay low by having the fewest number of large blowers possible.

Implicit with control of the suction on gob gas vent holes to prevent infiltration of mine air into the gob is monitoring of the gas stream. Practices in monitoring gas flow and composition are quite variable in the United States. In general, only those mines producing gob gas commercially, where a high methane concentration (greater than 95 pct) is desirable, have comprehensive monitoring (and suction control) capabilities. A mine operating in the Mary Lee and Blue Creek Coalbeds of Alabama has been producing gas commercially from vertical gob vent holes for many years (*43*). The monitoring system at this mine continuously measures the oxygen concentration with an automatic oxygen analyzer at each gob gas vent hole. The data are relayed to a central monitoring station at the mine office. When the oxygen concentration increases to 0.3 pct, an alarm is sounded, and field crews are dispatched to check the overall system at the hole. The system is adjusted, primarily by decreasing the suction applied to the hole. This in turn eventually decreases the infiltration of mine air into the gob, and the oxygen content of the produced gas. In addition, this mine uses a bleeder-type ventilation system that effectively excludes oxygen from the old gobs, which aids spontaneous combustion control as well as the commercial production of pipeline quality gob gas (*51*).

A gas chromatograph lab at the mine is used to routinely check the oxygen concentration in gas samples from the gob gas vent holes to calibrate the oxygen analyzers. Gas samples from various locations are also analyzed in the on-site lab for carbon monoxide concentrations as part of the mine's spontaneous combustion detection program.

It has recently been reported (*52*) that a mine operating in the Pocahontas No. 3 Coalbed, Virginia, has begun to produce gas commercially from gob vent holes. Monitoring and suction control to maintain a high methane concentration in the produced gas are also part of this system. During informal discussions with USBM personnel, it was reported that in addition to remotely monitoring the oxygen concentration in the produced gas, the suction on individual holes could be controlled by changing the voltage to the blower. The flow could also be remotely controlled by adjusting valves in the surface production facility to increase or decrease the back-pressure on the system. Such a monitoring and control system would be required on any facility draining gas from gobs using bleederless ventilation systems for spontaneous combustion control. In addition to monitoring oxygen and/or methane, carbon monoxide should be monitored in the methane-drainage system for early warning of spontaneous combustion.

The USBM has developed a monitoring and data collection and transmission system for vertical gob gas vent holes. This system monitors methane concentration in the produced gas, along with atmospheric pressure, ambient temperature, and gas temperature, to correct the measured flow rate to standard temperature and pressure. Data from the system can be accessed remotely via phone lines. While this system was not designed to control the flow of gas from the hole, it was set up to shut down the blower if the methane concentration was below 25 pct continuously for 10 min. If the blower shutdown is due to low methane percent (or for any other reason such as a power failure), an alarm is triggered in the mine office.

One way to minimize mine air infiltration, thereby controlling spontaneous combustion in the gob, is by "pressure balancing" the gob with the mine ventilation system (*10-11, 21, 53*). Pressure balancing is a rather complex procedure requiring comprehensive control of the ventilation system in response to many factors, including changing differential pressures, ventilation changes, gob gas composition, and the effect of mining rate on the volume of gob created and methane released. One of the biggest problems is the effect of methane drainage on the gob when pressure balancing is being practiced. While methane drainage of the gob can help achieve the desired pressure balance, it is another variable to be considered. Uncontrolled methane drainage could easily overwhelm a traditional pressure balancing system.

Because of the many variables, the Coal Mining Research Center of Japan has developed an autocontrolled gas-drainage system in connection with pressure balancing of sealed gobs for spontaneous combustion control (*53*).

The methane-drainage technique practiced is open-ended pipes installed through seals. Pressure balancing is achieved through the control of gas extraction from the gob by controlling valves on the gas-drainage pipelines underground. The system is multicomponent, consisting of monitoring, data storage, judgment, control, and alarm. Extensive use is made of minicomputers and expert systems to evaluate and respond to the many variables involved in the control of atmosphere behind the seals. In field trials of the system for 2 years, it was able to maintain the desired differential pressure range of 0.5 to 2.0 mm Hg and a nearly constant methane concentration of 98 pct, both advantageous conditions for spontaneous combustion control. While this system was designed for control of underground methane-drainage pipelines, there is no reason why it could not be adapted to control surface gob gas vent holes and underground monitoring of sealed areas.

Methane Drainage in Advance of Mining

Control of methane emission or spontaneous combustion problems individually is reasonably straightforward. However, when both problems must be dealt with simultaneously, control becomes more difficult and complicated. One approach to address this situation is to remove one of the problems in advance of mining. Methane is probably the problem most amenable to control prior to mining. Methane drainage in advance of mining is especially important in mines having high gas emission where ventilation pressure is being minimized for spontaneous combustion control. Liney reports that in Great Britain "it is becoming extremely difficult to adhere to previously accepted limits on ventilating pressure—for example, 50 Pa across the waste" because of "production limiting levels of methane" (*11*).

Methane drainage in advance of mining is less frequently practiced than drainage during and after mining, both in the United States and elsewhere. This is primarily because of the reluctance to commit the capital necessary to drain gas from coal reserves several years prior to mining. Many companies would rather commit capital when a problem has reached the point of interfering with production. In view of the complexity and severity of the combined problems of methane and spontaneous combustion control, methane drainage in advance of mining may be the key to safe and productive longwall mining under these conditions. If a substantial portion of the methane problem is eliminated, then a bleederless entry ventilation system may be easier to implement and an atmosphere in the gob less conducive to spontaneous combustion easier to maintain.

The basic technology for methane drainage in advance of mining from underground has been discussed previously. These techniques consist of drilling methane-drainage holes into the strata identified as gas-bearing zones that will contribute methane to the longwall or development mining. The most common techniques applied in the United States are the drilling of multiple horizontal holes from the tailgate entries into the virgin coal adjacent to the panel currently being mined or developed, and the drilling of holes into the panel ready for mining (fig. 19). These holes generally require a year or more of drainage to provide significant reduction in methane content and emission upon mining (*44, 54*).

Horizontal holes can successfully drain gas from the coalbed to be mined, but they do not address the problem of gas in the surrounding strata. It is this gas that in most cases accumulates in the gob and causes the methane emission problems underground (*36*). While the coal mines in other countries have used horizontal and cross-measure-type holes underground to drain methane from other gas-bearing horizons, the gas production from such systems has generally been limited because of the lack of permeability in the surrounding strata. In fact, the standard cross-measure holes were found to generally be effective only when they were drilled into the "destressed" zone behind the longwall face.

The technology most amenable to drainage from multiple horizons in advance of mining is the use of hydraulically stimulated vertical boreholes drilled from the surface (fig. 20). These holes have the advantage over underground drainage techniques in that they can be drilled many years in advance of mining to drain gas from large areas. Multiple gas-bearing horizons can be completed for production, and the gas can easily be captured for sale to help defray the cost of the methane-drainage system. An important advantage of these vertical wells is that individual gas-bearing zones can be stimulated to enhance their permeability and increase gas production. The technology is successfully being used in the mining district of the Black Warrior Basin of Alabama (*42, 55-56*), the Central Appalachian Basin of Virginia, the San Juan Basin of Colorado, and in New Mexico in the West (*57*). This technology is quickly gaining popularity in many U.S. coal basins, including some mining areas, but primarily for commercial production of the coalbed methane (*56*).

There is one cautionary note relative to the use of stimulated vertical wells. Existing planes of weakness, primarily the coal cleat, but also bedding planes and rock joints, are enhanced and propped with sand as a result of the stimulation treatments (*58*). As discussed previously, with "overaggressive" methane drainage, mine air could be drawn into a spontaneous-combustion-prone area through

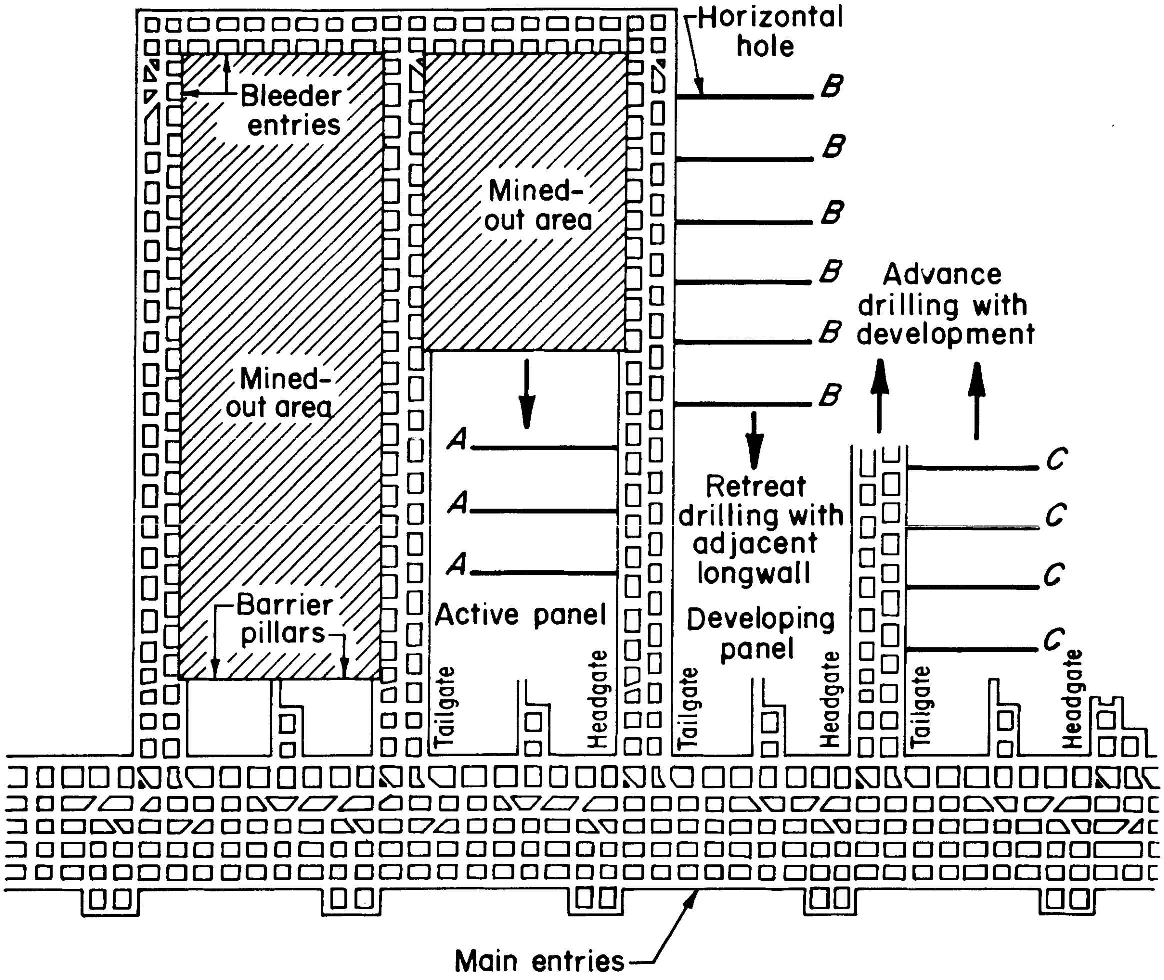

Figure 19.—Schematic plan view of short horizontal holes used for draining gas from longwall panels. *A*, On active panel in advance of face; *B*, on developing panel adjacent to active panel; *C*, from advancing entries.

naturally occurring or mining-induced fractures and joints in pillars and roof and floor strata.

There is some possibility (although no published literature suggests that this has ever occurred) that mine air leakage could also occur through the enhanced permeability of the propped fractures of stimulated vertical wells. The most likely problem area would be a propped fracture that extended from the gob into a mine airway, either through a pillar or through the surrounding roof or floor strata, in association with a bleederless ventilation system. Provisions would have to be made to seal such exposed fractures that are encountered with an impermeable coating.

Mine air could also infiltrate into the solid coal if wells were left on production after mining had occurred close to their location. This potential problem could be dealt with by plugging the hole with cement prior to mining if it was in a location such as a pillar or rib, where it would provide no further benefit. If the hole was located in the panel where the intent was to use it for gob gas venting, then production could be suspended, or the exposed strata infused with water to block gas flow during any critical time identified by experience as hazardous for mine air leakage.

One final concern relative to methane drainage in a spontaneous-combustion-prone coalbed was raised by Humphreys (*10*). He states that "coal which has been drained of gas is susceptible to oxidation" and "the reduction of the natural moisture content accompanying gas drainage increases the coal's susceptibility to oxidation." The concern appears to be generally related to "overaggressive" methane drainage that may pull mine air through solid coal that has previously been drained of gas. While no examples of spontaneous heatings of solid coal resulting from the effects of methane drainage were given, the potential is probably plausible enough to warrant vigilance.

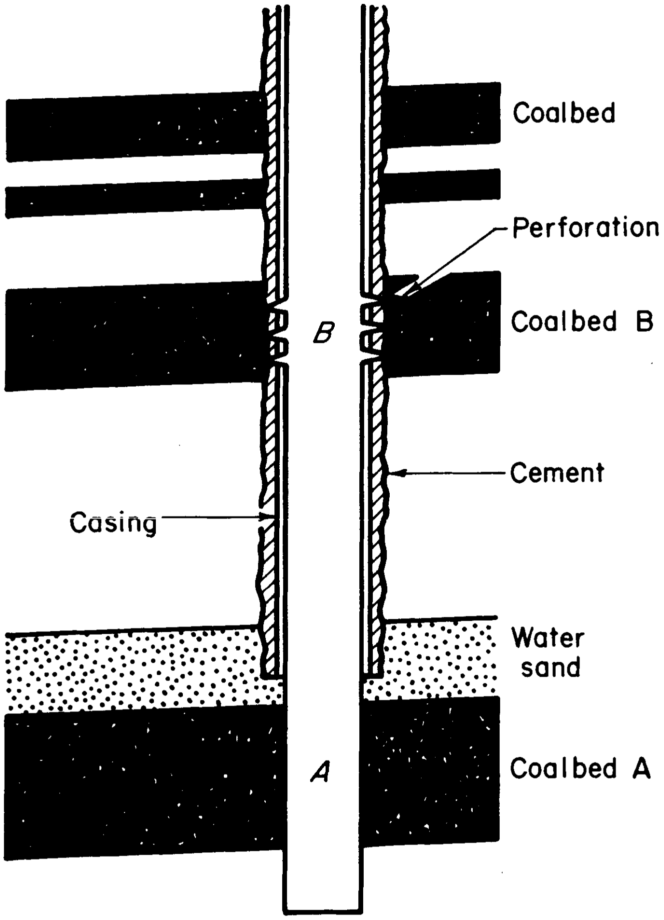

Figure 20.—Schematic view of open hole (*A*) and cased hole (*B*) completions for vertical methane-drainage well in advance of mining.

METHANE-DRAINAGE CONSIDERATIONS FOR USE OF BLEEDERLESS VENTILATION SYSTEMS IN THE UNITED STATES

Controlling methane emissions in longwall mines prone to spontaneous combustion is a complicated problem. In other countries where considerable experience with this problem has been gained, excluding or minimizing the infiltration of air into the gob by some type of bleederless entry ventilation system is generally the preferred method of spontaneous combustion control. Since bleederless entry ventilation systems can result in high methane emissions on the face, methane drainage of the gob directly through cross-measure holes or by open-ended pipes extending into the gob through sealed entries is commonly practiced. Every effort is made to ensure that the methane-drainage system is not "overaggressive," thereby pulling mine air into a spontaneous-combustion-prone zone. The methane-drainage holes themselves are drilled and completed so that they are not a conduit for mine airflow. Additionally, the seals, pillars, and ribs in common with the gob and the mine ventilation system must be of sufficient integrity to resist an exchange of atmospheres through them. Finally, the underground atmosphere is fine tuned by pressure balancing, and comprehensive monitoring of the methane-drainage system and the atmosphere behind sealed gob areas is required to detect and monitor the early stages of oxidation.

If bleederless entry ventilation systems are used in the United States for spontaneous combustion control, it is most likely that methane-drainage systems similar to those already being practiced will be the technology of choice. This would most probably be vertical gob gas vent holes.

Problems with cross-measure drainage may also arise if access is required to any active drainage holes. To be effective, cross-measure holes should be on the return side of the panel. Most bleederless entry ventilation systems actually allow mine air to ventilate the gob directly behind the face on the return corner to control methane emissions in that area. Maintaining accessible and ventilated entries on the return side of a panel that is commonly adjacent to the previous panel's gob is difficult because of abutment loading. In fact, to do so may require substantial additional roof support and ventilation capacity. Even if an entry on the return side was maintained, and not progressively sealed as with the back return bleederless entry system practiced outside the United States, it would in effect become a bleeder entry.

Methane drainage in the presence of potential spontaneous combustion will require greater preplanning, and monitoring and control after implementation, than is generally practiced in the United States. Instead of waiting until a methane problem is encountered, the probable sources of gob gas should be determined early in the design stages of a new mine (or a mine contemplating switching to a bleederless entry ventilation system) so that effective methane-drainage systems can be incorporated into the overall mine design. To successfully utilize a bleederless entry ventilation system to control spontaneous combustion in high-gas-emission longwall mines, some form of methane drainage in advance of mining will probably have to be practiced. By reducing the volume of methane contained in the coalbed being mined as well as that in the surrounding strata, control of the underground atmosphere should be considerably less difficult. Once methane drainage and mining are underway, monitoring and control of the underground environment is essential to ensure a safe and productive mining operation.

GROUND CONTROL ASPECTS OF BLEEDERLESS DESIGN FOR SPONTANEOUS COMBUSTION CONTROL

INITIAL PLANNING AND EVALUATION

Once a bleederless ventilation system has been chosen as the primary means to control spontaneous combustion, a comprehensive geotechnical evaluation of the mine property needs to be made. In addition to the geotechnical data directly related to spontaneous combustion, such as coal rank, self-heating susceptibility, seam pitch (*23*), and the proximity and susceptibility of accompanying rider seams (*9, 16*), the evaluation should also include the vital information that will serve as the basis for an integrated ground control plan. The ability to control the ground, especially to limit leakage through seals, strata, and pillars, will govern or at the very least impact the success and safety of bleederless ventilation as a spontaneous combustion control measure.

The information assembled needs to be as complete as possible so that a ground control plan that has a high chance for success may be devised. Collecting the required data is easier if the property is in operation. In this case, much of the information may already be available and only need to be compiled and molded into a comprehensive control plan. However, if the operation is a greenfield site, especially if there are few or no neighboring operations in the same or similar conditions, the gathering of the information will involve greater effort and expense. Also, the inability to observe the ground control plan in practice will require some assumptions that may need to be modified once actual conditions are encountered and can be documented.

The geotechnical evaluation should include information on a number of major areas that need to be assessed for their impact on ground control's role in a bleederless design for spontaneous combustion control and resultant issues such as leakage; stress concentrations; coal friability (*9*); and entry, pillar, rib, and floor stability. Some of the areas that should be addressed are as follows:

1. Floor, roof, and coal stratigraphy, strength of units, and general uniformity. The roof should be classified by an accepted system.
2. The direction and magnitude of the principal stresses of the horizontal stress field.
3. Depth of cover over the property and its impact on ambient temperature (*15*), stresses, pillar behavior, entry stability, pillar fracturing (*23*), rib sloughage, and potential surface leakage (if depth is shallow).
4. Discontinuities of the roof, floor, and/or seam, such as bedding, joints, cleats, faults (a particular problem that may need to be avoided (*9, 23*)), clay veins, and other unfavorable geologic conditions.
5. Caving characteristics of the immediate and main roof: impact on methane liberation, profile in the gob, and variance of gob line direction with cleat and the horizontal stress field. (The British feel that cleat direction is important, but recent research suggests that the observed relationship may have been more a result of the direction of the principal horizontal stress field than cleat direction.) Also important are the length of gob line, gob consolidation characteristics, and the impact on room-and-pillar mining method (interplay of pillar design).
6. Multiple coalbed effects—which should be minimized through the overall design. These include mining coalbeds systematically in a downward direction (*16*), considering impact of gob and barrier areas in other coalbeds, superimposing pillars and gate roads, and considering the direction and angle of approach to upper coalbed gobs and barriers.
7. Quantification of the ground movements of selected pillar, entry, and support designs in anticipated and/or actual geological and stress environments. This information would be used to design these mine structures as well as to match the critical seal design(s) to the ground control plan.

While many of the above are required or prudent ingredients for a mine plan for any underground operation, many of these areas assume roles of greater importance when spontaneous combustion and bleederless design as a control measure are considered. For instance, other coalbeds above or below the mined coalbed that would be exposed by caving or bottom heave could contribute to or be the source and fuel for spontaneous combustion events. Likewise, short- and possibly long-term rib, entry, pillar, and floor stability during development and retreat mining will be very critical if the spontaneous combustion control plan includes limiting the amount of coal as a fuel or minimizing leakage paths to a gob.

Once all required geotechnical information has been accumulated, the comprehensive ground control plan can be developed. If the operation is existing, past ground control experience at that mine will be the cornerstone of the plan. Experience from neighboring mines or mines with similar conditions would also be helpful inputs, especially if the operation is a greenfield site. Because of the impact that the ground control plan has on a major safety issue of the bleederless ventilation system (i.e., assisting to maintain the integrity of the sealed gobs by minimizing or eliminating leakage paths through floor or roof strata, through pillars, or through seals stressed by ground movements), accepted ground control techniques and designs should be utilized in the plan.

The ground control plan should revolve around a focused design philosophy as to how the ground will be controlled in and around the bleederless gobs. There are two basic choices: to design a stiff, stable system that will carry anticipated loads with little or no ground movement, or to employ a yielding design that permits a controlled amount of ground movement. There are also hybrids of these two extremes. The choice made will then define the roles of gate roads and barrier and chain pillars (in the case of room-and-pillar mining). Within the ground control plan, pillar and opening dimensions should be derived using accepted design methods and should complement the overall concept, whether yielding or stable.

Likewise, the artificial support system(s) used should also complement the overall ground control goals. In addition to the design methods used to accomplish the basic philosophy, the ground control plan should also contain sufficient information detailing how known or anticipated special problem areas will be addressed. For example, bottom heave or rib control measures would be detailed if pillar sloughage or floor leakage paths were viewed as presenting abnormal safety risks.

GENERAL GROUND CONTROL CONSIDERATIONS

As noted earlier, ground control considerations may change remarkably when designing for spontaneous combustion control through implementation of a bleederless ventilation plan. The following is a discussion of some of the major issues that should be considered in the ground control plan.

Number of Openings

A general goal of the plan should be to limit the number of openings into and around the gob areas that will be isolated and the number of openings between intake and return airways where associated leakage paths may present a potential problem. Obviously, the fewer the number of openings, the less the number of leakage paths, the less the chances for incidents of abnormally high leakage, and the lower the sum of the total volume of leakage. Limiting the number of openings is also beneficial when sealing areas or panels according to the mine plan or if necessitated during a heating. Using fewer openings reduces the number of seals required and speeds the sealing process in emergencies. To limit the number of openings, extensive use of barrier pillars and long pillars should be made in the mine design (*59*).

Coal Barriers

Coal barriers can be left between main intake and main return entries, with only a few interconnections between the two. Usually, this requires that these entries be driven as separate sets of entries and then converted to an intake use or return use after their development is complete. Coal barriers should also be extensively used to separate longwall or room-and-pillar panels from main and submain entries. Openings through these barriers should be minimal and only made for emergency or other practical measures.

Coal barriers can also be used to separate longwall or room-and-pillar panels into districts of a limited number. Reasons why this may be done include the following: to maintain districts that meet methane control capabilities; for ground control considerations, such as to control periodic large abutments; or as insurance to limit the area that would or could be sealed in the event of a heating (*11, 35*). In all cases coal barriers should be large enough to carry the expected loading and provide long-term stability (*10*). Where used to isolate bleederless gobs, barriers should also be explosion proof.

Long Pillars

Where barrier pillars are impractical to separate intakes and returns such as gate roads, panels, or some main-submain drivages, long pillars can be used to at least minimize the number of openings and seals. To develop long pillars to separate intakes and returns in these drivages, the mining and ventilation plans need to be integrated to create the longest distance prior to holing through without outstripping the mining or ventilation system capability.

Number of Entries

A corollary to limiting the number of openings is to limit the number of entries. With fewer entries there are fewer openings to leak when sealing entire panels. Also, when difficult ground conditions are encountered, a limited number of entries may permit the use of different ground control techniques than are presently possible or practical. As U.S. mines increase in depth, corresponding increases in stress will likely lead to the same ground control problems currently experienced in the rest of the world. Most older coal mining countries limit the amount of drivage, commonly to one entry on each side of a panel. However, current regulations, especially those regarding escape, prohibit the use of these ground control designs in the United States.

Floor Heave

While a minimal amount of floor heave may not have a great impact on the operation of some mines, it can present a major problem in coal mines susceptible to spontaneous combustion. Floor heave can provide leakage pathways through the floor or damage seal integrity, allowing oxygen to contaminate gob areas. It can also expose reactive coalbeds in the floor to the atmosphere (*7, 60*).

Where these conditions exist, the control of floor heave may be a major consideration and, therefore, dictate the general approach of the overall ground control plan. This is especially true if mine structure control techniques are used to control floor heave. Mine structure control techniques are those where the parameters of the major mine structures, such as entry opening geometry and pillar geometry, are varied to accomplish specific ground control objectives. One example of this would be using a larger size pillar to provide more bearing surface area if "pillar punching" into a weak floor was the source of the floor heave (*61*). Another would be using small, yield pillars to decrease the level of stresses in the immediate floor when high stresses and a weak floor were the cause of the heave (*62-63*). Narrowing entry width may also help to control floor heave (*64*).

Other floor heave control techniques that may be employed in the ground control and mine plan are minimizing water on the floor by using the minimal amount required for dust suppression, and a well-maintained sump and pumping system for ground water inflows; considerations made for the orientations of the mine workings to the direction of the principal horizontal stress; rib softening techniques; and supplemental support techniques such as floor bolting, cementitious lining, and polyurethane injection (*64*). The results of the geotechnical evaluation would provide insights into the source(s) of the floor heave and may suggest appropriate control techniques. Some of the control techniques listed may be rejected because of their inability to be practically incorporated into the mine plan.

Rib Sloughage

Rib sloughage, existing or anticipated, needs to be assessed as to whether it should be a consideration in the ground control plan. Excessive rib sloughage can detrimentally impact a coalbed susceptible to spontaneous combustion by providing ventilation leakage paths through pillars or by providing a ready fuel that increases heating potential. Since rib sloughage is a result of perimeter yielding of the coal pillar, one control method is to vary the geometry of the mine structures as discussed in the section "Floor Heave." The goal would be to lessen the magnitude or location of stress loading on the pillar. One problem with this approach is that there is a practical limit in a given physical environment to the extent that pillar perimeter yielding can be minimized. Another problem with this approach is that this technique may require the exact opposite parameters to other more important aspects of a ground control plan aimed at facilitating bleederless ventilation for the control of spontaneous combustion. For instance, control of floor heave, which may be more important, may require the use of thin yield pillars.

Another rib sloughage control approach is to orient pillar edges as near as possible to 45° to the cleat (*12*). Other methods to reinforce the rib include the use of rib bolting or banding, meshing, posts, and other passive restraints, such as cementitious linings. As with the floor heave control measures, the applicability, practicality, and contribution to minimizing the sloughage hazards need to be assessed for any of these techniques to be a component of the plan.

Entry Stability

As with any mining, entry stability will be at the core of the ground control plan. In a bleederless design, and especially for a mine with high methane emissions, the importance of entry stability is even greater. This is due to its impact on leakage, stability and integrity of seals, methane drainage, and monitoring.

Entry stability is dependent upon the physical nature and the interactions and interrelationships of the surrounding mine structures—the roof, floor, and coal pillar—relative to the imposed stress field. The magnitude and pattern of the stresses, the absolute and relative strength and the geometry of the mine structures, and the installed support are the elements that will dictate entry stability (*61*). Those controllable parameters will be varied within practical limits in the ground control plan to create serviceable entries for their required life span. As a result, some of the mine structures may behave undesirably because of the higher priority given to entry stability, because of their own physical inadequacies, or because of practical mining considerations such as entry width.

The resultant stability of the entry will then impact the particular bleederless design concerns. Leakage paths and the resultant leakage through the mine structures will be a function of entry stability. Entry stability will also dictate the loading and stresses on seals. If cross-measure holes or another type of in-seam methane drainage is used, those involved entries must remain accessible for a time period required by the methane-drainage scheme (*25*).

Similarly, the entries must provide and maintain access to key points of the bleederless system to meet the maintenance requirements of methane, carbon monoxide, or any other monitoring system(s). This access may be required for people, instruments, conduits, or all three. Because of the time interval required by these functions and their physical locations within the system, entry stability will need to be maintained in areas subjected to gob abutment loading.

Seal Design

A special concern of the ground control plan is the interrelationship of the seals. Since the intention of the bleederless design is to limit airflow through the gob as a spontaneous combustion control, the success and safety of this control technique is measured by how well this is accomplished (*18, 60*). Control of the airflow through the gob becomes even more critical in gassy mines, where an accumulating methane body must also be flawlessly controlled. Consequently, the hermetic sealing of the gob is of paramount importance, and seals must perform with a high degree of reliability (*65*). The loading and ground movements in and around the seal locations must be anticipated to select seal strength, flexibility, size, material, and need for sealants (*65*). The seal performance and design, therefore, must be a major consideration of the ground control plan (*10*).

THE GROUND CONTROL PLAN

Once the geotechnical information has been gathered and evaluated, and the general considerations for ground control contemplated and assessed, the ground control plan can be devised. This plan, of course, would need to complement the general mine plan and the plan to control spontaneous combustion through bleederless mine design. In many cases, it will not be possible to maximize all of the desirable aspects of bleederless design in the ground control plan. Some features may even conflict. In such instances, decisions need to be made as to the ground control approach that best addresses the most salient requirements of the overall plan. The highest priority requirements will be those tied most directly to the most likely and major hazards of spontaneous combustion and the bleederless control approach.

Of these ground control decisions, probably the major decision is whether to use a stiff design or yielding design in and around the gob areas. Experience around the world acknowledges that small ground movement is much preferred (*11, 18, 65*). Rigid ground eliminates many of the major concerns of bleederless design and spontaneous combustion control. Rib sloughage, floor heave, leakage paths through strata and pillars, lack of seal stability and integrity, inaccessibility of methane-drainage and various monitoring systems, exposure of roof and floor coalbeds, and coal remnants in the gob are eliminated or minimized if there is little ground movement (*10*). Therefore, rigid ground should be the first goal of the ground control plan and every effort should be made to investigate methods to utilize a stiff, stable design. This includes exploring various mine structure geometries, support types or methods, and mining methods.

Where it is not possible to design or maintain stiff mine structures because current control techniques are either ineffective or impractical, an approach that permits one or more of the mine structures to yield is the alternative. However, whether the focus of the ground control plan is stiff or yielding, all elements of the ground control plan should be directed to accomplishing predictable ground movements. Those elements not totally controlled by the overall design approach that still represent substantial concerns or hazards may be addressed by specifics of the plan. As an example, if an unacceptable amount of rib sloughage exists, rib bolting could be incorporated into the plan. There is, of course, a wide variety of primary and secondary support schemes and methods that can be used to add stability to the ground. These techniques are generally known to the industry or can be easily researched if not known.

Stiff Design

In a stiff design the goal is little or no movement of the roof, pillars, or floor. Pillars should be large enough to carry the original development loads and the later abutment loads due to pillar mining. As a result, there would be minimal pillar crushing, rib spalling, convergence of the ground on the seals, and floor heave. The primary and secondary support should also be stiff to complement and assist the overall design. Additional support should be added in the seal construction area if needed to keep the mine structures stable with little movement (*18*).

The seals used in this design should also be stiff and rigid, perhaps even providing some of the support to the immediate area. They should be able to withstand the rather small ground movements and still preserve their hermetic seal. However, even with a stiff, stable design, the mere proximity of seals to the gob area will expose them to ground movements. If these movements are of such a magnitude that a rigid seal will fail, some flexibility can be built into the design through elements that readily crush yet remain airtight. However, ground movements may be so extreme that, even in the case of a conceptually stiff ground control design, the seal may need to be flexible to allow convergence of the roadway (*18*). This flexible philosophy is discussed more fully under "Yielding Design."

The length of time that the seal must maintain its integrity would also affect its design. Therefore, seals to isolate a panel, mined-out areas, or a mains or gob cut through, which are usually more long term in nature, may be required to be substantially constructed. Seals used to separate a longwall panel gob from an entry used initially for methane drainage and monitoring on a current panel, and then as a return on the next longwall panel, would only need to successfully function until the successive panel is mined and may not need to be as substantial. However, if these seals are subjected to large abutment loading and severe ground movements as a result, the opposite case could exist. If the opportunity exists, the seals should be tested in the same or similar conditions prior to their being employed in a bleederless plan.

Yielding Design

A yielding design usually employs small pillars that are unable to carry the total imposed load and begin to fail and deform. As a result, they then pass some of their load onto surrounding structures such as longwall panels, barriers, or larger pillars. Ideally, in a bleederless design, these pillars are small enough to yield, thereby relaxing the immediate roof and floor and providing the desired stress relief, but not so small as to become excessively crushed and create leakage paths through the pillar and/or excessive rib spalling. The goal of the yielding approach is also stability. However, unlike the stiff concept, yielding permits deformation of the mine structures to obtain this goal.

Because of the inherent benefits of using a stiff design already noted, the use of a yielding design should be limited to those areas where a stiff design cannot be practically maintained. Generally, the most severe problems with stiff design will occur upon retreat abutment loading. In these cases, if a yielding concept is required, it should be limited to those areas subjected to this type of loading, such as longwall gate roads. However, high vertical loads, high horizontal stresses, physical inadequacies of the mine structures, or combinations of these could render stiff designs incapable or impractical on a broad scale (*66*). This would require a more widespread use of yielding design throughout the mine (*60*). Still, because of the benefits, a stiff design should be implemented to the greatest extent practical where it impacts the bleederless system.

As with stiff, stable design, it is extremely critical that the seal design be harmonious with the ground control design. The yielding ground control design should be aimed at a consistent, predictable, and fairly uniform ground convergence on the seal that in turn could be incorporated into the seal design (*26*). Most current seal designs of this type allow for and generally require consistent and uniform ground convergence for their own design to be an effective deterrent to leakage. For instance, a U.S. coal mine that uses bleederless design in deforming ground conditions has used seals made from 3-ft wooden blocks stacked and filled with rock dust or sand. The ground convergence compresses the wood and that, combined with the rock dust or sand filler, creates the seal (*6, 9*).

An Australian mine, also in deforming ground conditions, reports successful performance with a flexible seal design built around anchored steel straps to which expanded steel mesh is attached. A fiberglass reinforced cement grout is then sprayed onto the mesh. The cured grout and the surrounding 1-m perimeter of mine entry are then oversprayed with a 3-in covering of polyurethane foam. These flexible seals have bulged out up to 500 mm without losing their effectiveness (*18*). However, large ground movements, such as the pillar deformation and yielding, may create leakage paths around these types of flexible seals. Therefore, more extensive sealing and grouting techniques may be necessary for acceptable seal performance.

However, the meshing of an acceptable seal design with deforming ground is probably the biggest obstacle for yielding approaches for bleederless design. Because of the limited experience in the United States with seals requiring these design parameters, this topic should be investigated further for bleederless applications. If possible, like the stiff seals, the yielding seal design(s) should be constructed and tested in ground conditions similar to those anticipated. This will permit seal integrity to be checked and design improvements, if needed, to be made prior to reliance on their performance.

Combination Design

In some cases, the best ground control plan may be to combine the two design approaches, for example, by using yield-abutment and yield-abutment-yield schemes. Experience in Great Britain with the small pillar used to create the back return ventilation system has indicated that a yield pillar next to the gob may be beneficial if cross-measure methane drainage is practiced (*13, 29*). When yield-abutment and yield-abutment-yield designs are used, seal design problems should be eased if the seals are located between the more stable abutment pillars (*10, 23*).

MONITORING

The revised Federal regulations require that, in mines with a demonstrated history of spontaneous combustion, the ventilation plan provide a description of the measures that will be used to detect methane, carbon monoxide, and oxygen concentrations in worked-out areas (*2*). This is in addition to those requirements for air quality and quantity in work or travel areas. The use of a bleederless system places extra demands on the monitoring plan, especially in terms of spontaneous combustion detection, maintaining safe air quality at the face, pressure balancing, methane-drainage monitoring, and seal integrity. A thorough understanding of the methods currently used in these areas, and of the additional monitoring requirements imposed by the use of a bleederless system with respect to methane and dust, is required.

SPONTANEOUS COMBUSTION DETECTION

Early detection is critical for the prevention and control of spontaneous combustion. The analysis of gaseous products of combustion is the primary method used in underground coal mines for early fire detection. The use of gas analysis and various ratios of these gases in the detection of gob self-heatings was recognized and evaluated early in this century. However, only in cases of advanced heatings were gas analysis data able to identify heatings (*67*). Considering the state of gas analyses at the time, this is understandable. More recently, Chamberlain (*68*) showed that carbon monoxide is the most sensitive indicator of the early stages of self-heating and recommended that continuous monitoring of this gas would provide the earliest detection of spontaneous combustion. Figure 21 shows the evolution of carbon monoxide and some other gases as a function of temperature.

Other gases have been investigated as indicators of spontaneous combustion, such as carbon dioxide, methane, hydrogen, and higher hydrocarbons. However, carbon dioxide and methane are usually present from other sources, and hydrogen and higher hydrocarbons are usually not produced until much higher temperatures are reached, making the use of these gases unreliable.

Various ratios have been investigated, including $CO/\Delta O_2$, CO/CO_2, and $CO_2/\Delta O_2$. Thorough discussions of the use and advantages and disadvantages of the $CO/\Delta O_2$ ratio are given by Humphreys and Greuer, among others (*10, 69*). Recently, the USBM developed the R ratio to evaluate the atmosphere of sealed mines for safe reentry (*70*). This ratio compares the carbon monoxide concentration with respect to the residual gas concentration (all gases except ambient air, methane, and ethane). These ratios were evaluated by the USBM in a large-scale experiment using 11,000 kg of coal. Although all the ratios indicated a heating after thermal runaway was underway, only the $CO_2/\Delta O_2$ ratio gave an early warning of the heating in the coalbed (*71*).

Continuous monitoring of carbon monoxide levels is the preferred method of spontaneous combustion detection worldwide. The most popular methods are telemetry or tube bundle systems (*10, 12, 65*). With the telemetry system, electrochemical sensors located at key sites in the mine are wired to a computer on the surface for analysis, alarming, and recordkeeping (*10, 23, 65*). The tube bundle system collects samples underground and delivers them to a central analyzer, usually aboveground. The main advantage of the telemetry system is that the information is gathered instantaneously. However, these systems are costly, must be relatively durable, require calibration, and are dependent on the mine's power system. The main

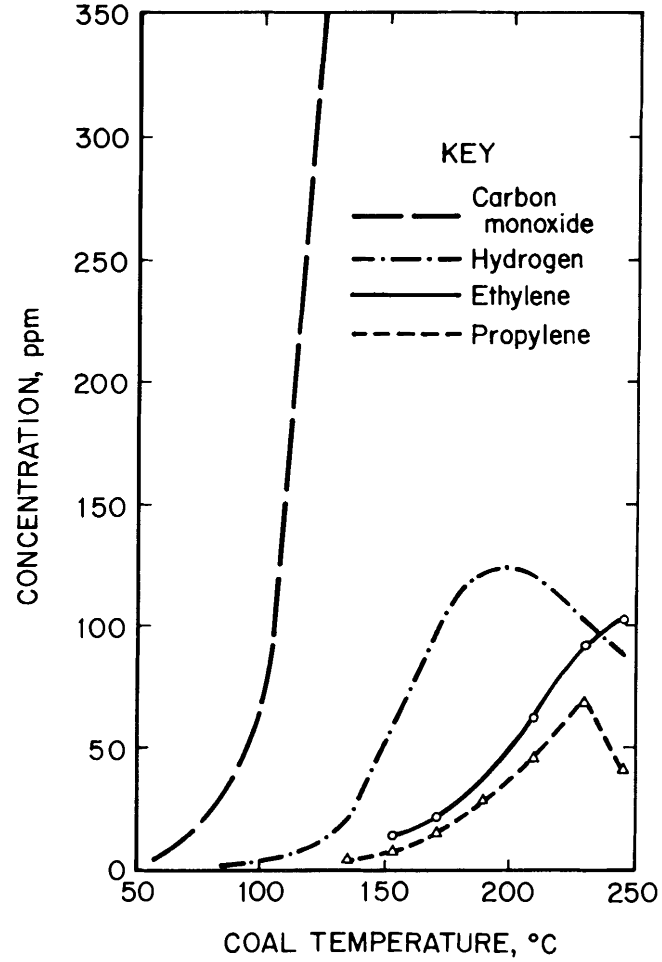

Figure 21.—Evolution of detector gas in laboratory tests (*68*).

advantages of the tube bundle system are the lower cost, lack of dependence on the mine power system, and relative ease of calibration. The main disadvantage is the time delay in sampling. Humphreys and Bacharach provide thorough discussions of these systems (*10, 12*).

A significant problem in the detection of spontaneous combustion is in recognizing when a heating is developing. U.S. regulations require mines that utilize a bleederless-type ventilation system to monitor for the detection of self-heating. The monitoring requirements will probably be based on carbon monoxide measurements and require action plans or alert levels for self-heatings. The monitoring plans should be proposed and reviewed on a mine-by-mine basis.

The ambient levels of carbon monoxide in a mine depend on the type of coal, the rate of mining, and many other factors. Transient spikes in carbon monoxide can be caused by diesel machinery and changes in ventilation, as well as other factors. A new method that has been used by some mines with spontaneous combustion problems is that of trending. Data are accumulated over a period of time to establish normal ambient carbon monoxide background levels. Averaging methods are employed to compare the continuous monitoring analyses to the ambient background levels. A Wyoming mine that relies heavily on the use of diesel equipment has developed a method to deal with transient spikes called wave trend crossing. This method uses two carbon monoxide sensors sampling the same gas stream at different locations, along with computer analysis, to constantly update the ambient carbon monoxide background level (*72*).

METHANE DRAINAGE

Monitoring of methane-drainage systems in the presence of a spontaneous combustion potential has been touched on previously, primarily relative to automated underground methane-drainage pipeline control and pressure balancing systems described by Deguchi (*53*). This system monitored methane and carbon monoxide concentrations in the various methane-drainage pipelines, the flow rate, and the pressure on both sides of seals in real time.

Computer-based expert systems were used to evaluate the many variables from multiple data collection sites and to adjust automated valves to control the amount of suction applied to the methane-drainage pipelines. With the system in operation, the atmosphere in the gob behind the seals of a bleederless ventilation system was maintained at optimum conditions (low pressure differential and high methane concentration) for spontaneous combustion control.

McKensey (*18*) describes an automated control system that operates in conjunction with the surface production facilities connected to the various underground pipelines. This system is fully automatic and controlled by a Programmed Logic Control (PLC) unit and automatic sensors. A predetermined operating pressure is set (0 to -50 kPa) and then the PLC controls "the total plant outflow by either controlling the number of exhausters operating or altering the quantity of gas being recirculated through the plant." Monitoring includes pressure, methane concentration, gas flow, and temperature at the inlet of the underground pipeline and methane concentration, temperature, and pressure at the outlet on the surface. In addition to the monitoring of the methane pipelines, a "tube bundle system" is used to monitor gas concentrations in return airways and inside gob seals. This monitoring system is interfaced with the PLC unit to "assist in the control of the mine environment both inside and outside sealed goaf areas." For spontaneous combustion control and avoidance of explosive mixtures, total plant outflow is automatically adjusted whenever low methane concentrations (less than 40 pct) are detected at the inlet monitor. If the methane concentration falls below 30 pct, the plant is "isolated" from the methane-drainage system. The PLC system in conjunction with gas monitoring via the tube bundles is also used to detect and monitor spontaneous combustion incidents and balance the pressures around sealed gob areas for additional control.

Gas compositional monitoring of individual methane-drainage holes or at least monitoring of several locations along pipelines to which drainage holes are connected is recommended by many authors (*11, 18, 45*). Monitoring can be beneficial in detecting increasing levels of oxygen that may indicate "overaggressive" methane drainage that is pulling mine air into a potential spontaneous combustion zone. Swift provides examples of case studies that document such occurrences (*26*).

Monitoring of carbon monoxide levels (or the CO/O_2 deficiency ratio) (*11*), or carbon monoxide, oxygen, hydrogen, and methane for calculation of the fire index (*45*), combined with sufficient background "norms" can provide early warning of a developing problem. In fact, Highton states that gas compositional monitoring of methane-drainage pipelines give "the first indication of an increase in oxidation" (*13*). With a sufficient number of monitoring sites, it may be possible to locate the area of infiltration or oxidation. The more specific the identification of the problem area or methane-drainage holes causing the problem, the more quickly and efficiently remedial actions can be initiated.

SEALS

Another important place for monitoring for the detection of spontaneous combustion in a bleederless ventilation system, in addition to monitoring returns and working areas, is behind seals. Continuous monitoring behind each seal constructed in the headgate entry is impractical, because of the large number of seals. In the two U.S. mines that are currently using a bleederless ventilation system, gas sampling tubes are installed in each seal so that periodic gas samples can be withdrawn and analyzed by gas chromatography. Samples are analyzed for oxygen, carbon dioxide, carbon monoxide, methane, hydrogen, and some higher hydrocarbons. A recent paper by Koenning describes the use of these samples at one of the mines to detect two spontaneous heatings behind seals (*23*). Information on the techniques and gas analyses at the other mine employing a bleederless system is, at this time, unpublished.

As bleederless ventilation systems become more accepted and utilized by mines, the importance of detection of spontaneous combustion will become greater. This is particularly true in methods to monitor behind seals to check seal integrity and to minimize both the spontaneous heating potential and the explosion potential. Research is strongly needed in the areas of improved and novel detection methods and guidelines.

ADDITIONAL CONSIDERATIONS

The use of a bleederless ventilation system will require additional monitoring in the face and travel areas, especially in gassy mines. Current U.S. regulations stipulate that measures to detect oxygen, methane, and carbon monoxide must be provided in the ventilation plan (*2*). Because the gob is sealed, combustion gases and methane can flow from the gob into the work areas and returns because of massive caving, barometric changes due to weather, and unexpected methane emissions leading to an overloading of the methane-drainage system. This places an increased reliance on the monitoring systems.

It is anticipated that additional monitoring along the face for methane and carbon monoxide emissions, and around the seals for pressure balancing of the gob, will be required. Research is necessary to develop more reliable criteria and guidelines for these areas.

SELECTION CRITERIA FOR BLEEDER-BLEEDERLESS VENTILATION SYSTEM

An important issue that will need to be considered is determining when the spontaneous combustion hazard potential in a mining operation is severe enough to warrant the use of a bleederless ventilation system as a control measure. This section will review the use of risk analyses available to assess the spontaneous combustion potential of coal.

USBM research on the prediction of the spontaneous combustion potential of coal dates back to 1928. Davis concluded that two available methods, the rate at which coal absorbs oxygen and the rate of heating of coal under adiabatic conditions, were reliable for distinguishing relative self-heating tendencies with respect to coal. He also concluded that all coals, with the exception of anthracite, can self-heat under favorable conditions and that, in general, lower rank coals have higher self-heating susceptibilities (*73*). These findings have not changed over the years, but the methods have improved, and as recently as 1987 and 1991, Smith and Miron published reports on the use of an adiabatic oven and oxygen adsorption apparatus to evaluate the relative self-heating potential of coal (*74-75*).

In 1972, Nandy published a paper describing the use of the crossing point method to classify Indian coals with respect to their relative self-heating potential. In this test, the temperature of a coal sample is monitored with respect to a constantly increasing oven temperature, and the temperature at which the sample temperature overtakes the oven temperature is measured. The lower the crossing point temperature, the higher the self-heating potential (*76*).

Up to that time, no methods to classify self-heating risks took into account the role that mining factors or other mining conditions play in self-heating. In 1973, Feng developed a risk index that considered a coal's liability to self-heat, as well as the mine environment. The liability index was a variation of the crossing point method that assigned a risk based on the heating rate and ignition temperature. The mine environment index assigned risk based on the coal loss, fissuration, and ventilation pressure differential (*77*). Canada still uses the liability index to characterize the self-heating potential of coals (*78*), but reference to the environmental index has disappeared from recent publications.

In 1978, an extensive study of spontaneous combustion was made under a U.S. Department of Energy contract by Bacharach (*12*). Included in this study was a risk analysis that considered the rank of the coal, pyritic sulfur, hardness, humidity, strata temperature, and unworked roof coal thickness. The analysis was called "Rapid Appraisal of

Spontaneous Combustion Assessed Liability," or RASCAL, and claims to give "only a very generalised indication of susceptibility and should never be used as the sole measure of risk." This risk analysis was unique in that it did not require laboratory tests.

In 1982, Bhattacharya described a classification system based on a coal factor, a geological factor, and a mining factor (*79*). The coal factor was dependent on the crossing point temperature, while the geological factor considered coalbed gradient, thickness, depth, faulting, and structure, and the mining factor was determined from ventilation, depillaring time, and type of explosives used. No information was given on how the factors were determined, and no follow-up publications were found.

At about the same time, Banerjee published the first description of a risk analysis that is still being used and refined (*80-82*). The method considers 22 parameters with subjective assessment of the influence of 8 factors that affect spontaneous combustion. This method provides criteria for assigning high or low risk values for each of the 22 parameters.

Banerjee also refers to a Polish risk index, the "Oplinski Method," that considers the spontaneous heating susceptibility of the coal, the amount of coal left in the gob, the mining method, ventilation method, amount of leakage in the gob, wetness of the coalbed, depth, and ventilation pressure. However, all references are to private communications, and no literature was found for this risk analysis.

Researchers in Great Britain have also been actively involved in the development of a risk index throughout the 1980's (*8, 59, 83*). They were among the first to attempt to computerize the method by using an expert system format (*84-85*). The index is based on laboratory adiabatic oven tests to assess the spontaneous combustion potential of the coal, combined with a modified risk classification system of Bystron and Urbanski (*86*) that evaluates the contributions of some geologic and mining factors.

The USBM developed a risk assessment method to evaluate the self-heating potential of coal, based on the coal's minimum self-heating temperature, a measure of the coal's relative reactivity, in adiabatic heating experiments (*74*). These results were correlated with oxygen adsorption experiments, and a prototype sealed-flask test apparatus was developed to evaluate the relative self-heating tendencies of coals in the field (*87*).

A statistical analysis of the adiabatic oven results also showed that the relative reactivity of a coal was strongly dependent on the coal's dry ash-free oxygen content, a number readily available from a routine coal analysis. These results were incorporated into an expert system computer program that allows for the prediction of a coal's relative self-heating potential without the need for laboratory experiments (*88*).

While the USBM's methods are widely used in the United States to assess the relative reactivity, or susceptibility of coal to self-heat, they do not consider other factors that contribute to self-heating, such as geologic factors, mining conditions, and mining practices. A prototype expert system is currently being developed to take into account these other factors.

As described in a previous section, there are currently two mines in the United States operating with a bleederless ventilation method, and one other mine has used a bleederless system at least temporarily. In these instances, the case for the bleederless ventilation system as a spontaneous combustion control measure depended primarily on establishing a spontaneous combustion risk based on a history of self-heating events (*6*). Until a ranking criteria or risk analysis is developed that accurately describes the self-heating risk of a mining operation, it is likely that spontaneous combustion history will remain as a primary determinant in the justification for the use of a bleederless system. Since the successful use of a bleederless ventilation system is more likely when the system is designed into the mining plan from the start of an operation, it is essential that the development of a ranking criteria be a priority.

CONCLUSIONS

A worldwide literature review of bleederless ventilation practices for spontaneous combustion control in coal mines was conducted to examine the impact of bleederless ventilation systems on U.S. coal operations. The literature study reflected that restricting airflow into mined-out areas (bleederless ventilation) is recognized worldwide as a spontaneous combustion control measure. However, successful application of this concept involves systematic minewide design of ventilation, methane, and ground controls with a reliable monitoring system for detecting uncontrolled or unexpected circumstances leading to a heating. The literature reflected that bleederless ventilation systems reduce the risk of spontaneous combustion, but the potential still exists. This is evidenced by the continued occurrence of reported spontaneous combustion mine fires associated with these ventilation systems.

The main difference between implementation of bleederless ventilation in Europe and Asia as compared to the United States is in the design of mining operations. Europe and Asia commonly develop one-entry longwalls (sometimes two entries on the tailgate side of the longwall) with a solid barrier pillar between prior and active longwall sections. This type of design isolates gob areas and minimizes the number of seals constructed.

Multiple-entry longwall development in the United States is common (two-, three-, and four-entry systems) with existing gate road entries reused when mining the adjacent panel. Two multiple-entry, low-gas-emission coal mines in the United States have used bleederless entry ventilation systems to control spontaneous combustion occurrences. Seals are constructed in entry crosscuts to isolate longwall gob areas. This type of bleederless design places its reliance on a large number of seals to isolate the gob, and these seals are constructed between coal pillars subjected to highly stressed ground control conditions. Seal leakages and heatings were reported in one mine that has used this type of bleederless design. Mines with high methane emissions have an additional risk of a potentially explosive atmosphere developing near a leaking seal where an oxygen-enriched atmosphere can initiate a heating that becomes an ignition source.

Ventilation control of spontaneous combustion must coincide with minewide planning for ground control, methane control, production, environmental monitoring, and compliance with all government regulations. Given the diversity in geologic conditions of various coalbeds, mine designs have to take into account their unique conditions. Plans should optimize a balance between conflicting design parameters, such as limiting the number of entries to reduce ground stresses as opposed to creating more entries to improve ventilation. Since performance of various technologies is mine dependent and cannot always be universally applied throughout the industry, mine planning should also include alternatives to the original designs.

Methane drainage will be a key factor in the successful use of bleederless ventilation systems for spontaneous combustion control in mines with high gas emissions. Even mines that can control methane by ventilation alone may need to use supplemental methane drainage if a bleederless ventilation system is adopted. Methane drainage with a bleederless ventilation system will require more preplanning, monitoring, and control than most U.S. mining companies currently practice. It will be necessary to more accurately determine the source of the gas that accumulates in the gob so that the most efficient methane-drainage system to handle site-specific conditions is employed. If sufficient time is available, methane drainage can be started several years in advance of mining to minimize the impact of methane emissions on a bleederless ventilation system.

It is important that a methane-drainage system employed in a spontaneous-combustion-prone mine using a bleederless ventilation system not over- or underdrain the gob. If the methane-drainage system is not sufficiently effective, high methane emissions may be experienced on the face. Conversely, "overaggressive" drainage can pull mine air into the gob, causing spontaneous combustion problems. The composition of the gas produced from a methane-drainage system must be sufficiently monitored so that changes in the atmosphere in the gob can be detected as early as possible. Monitoring of the gases produced from the methane-drainage system may also provide an early warning of the presence and location of a spontaneous heating. Finally, the methane-drainage system must be designed so that it can be sufficiently regulated to control the atmosphere in the gob in spite of changing conditions underground.

The ground control aspects of bleederless design for spontaneous combustion control are central to a safe comprehensive mine design. A thorough geotechnical evaluation needs to be done as a basic input to the ground control plan. Once this information is gathered, optimum pillar designs such as stiff, yielding, or a combination of both can be formulated. Stiff, stable ground minimizes many of the concerns of a bleederless spontaneous combustion control system. Taking into account the special demands of a bleederless system, such as minimizing number of openings, floor heave, rib sloughage, maximizing entry stability, and incorporating a complementary seal design, the elements of a ground control plan can be formulated.

The use of a bleederless system places additional demands on the monitoring plan, especially in terms of spontaneous combustion detection, maintaining safe air quality at the face, pressure balancing, methane-drainage monitoring, and seal integrity. The analysis of gaseous products of combustion, particularly carbon monoxide, is the primary method used for the detection of spontaneous combustion.

The determination of when the spontaneous combustion hazard potential of a mining operation is severe enough to warrant the use of a bleederless ventilation system as a control measure is an important issue. Many methods to determine the self-heating potential of coals are in use throughout the world, including the United States. Some methods depend on laboratory tests to determine the liability of a coal to self-heat, while other methods use empirical data. Some methods consider mining conditions and practices, while others do not. Many of the criteria used are subjective in nature. It is apparent that no method at this time provides a clear and definitive evaluation of the potential for self-heating.

When a spontaneous combustion risk is present, critical attention must be given to mine design, seal construction, methane drainage, regulations, monitoring, and emergency procedures. However, several of these areas have limited technology that needs further development. The mine can be designed to minimize entries and isolate each gob with barrier pillars. This reduces the reliance on seals, which can leak. Seal construction can vary to accommodate local mine conditions. To minimize seal leakage, entry closure must be reduced and pressure balancing should be practiced. However, pressure balancing is complicated, since the mine resistance is dynamic and is responsive to changing barometric pressures. An automated pressure balancing system under human surveillance would be an improvement; however, research still must be conducted to develop reliable alternative systems. Methane drainage must be closely monitored when used so that air is not drawn into the gob. Automated methane-drainage systems need to be developed to control, in real time, the drainage rate from the gob. Mine gas monitoring systems exist, but research is needed to improve system performance, sampling strategies, and data interpretation.

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