CHAPTER 1.—FACTS ABOUT METHANE THAT ARE IMPORTANT TO MINE SAFETY

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In This Chapter

- ✓ The explosibility of methane gas mixtures
- ✓ Effect of pressure and temperature on explosibility
- ✓ Less common sources of methane ignitions
- ✓ The amount of methane stored in coal
- ✓ Forecasting the methane emission rate
- ✓ Layering of methane at the mine roof
- ✓ When the recirculation of mine air is hazardous
- ✓ The importance of higher air velocity in preventing methane explosions

and

- ✓ Mine explosions, barometric pressure, and the seasonal trend in explosions

Dealing with methane in mines and tunnels requires knowledge of the circumstances under which dangerous accumulations of methane are likely to occur. This knowledge involves the properties of the gas itself, an awareness of where these accumulations are likely to occur, and facts on how methane mixes safely into the mine air.

The other chapters in this handbook address the handling of methane under a variety of specific circumstances, such as at continuous miner faces or coal storage silos. This chapter addresses some broad concepts that serve as a foundation for the suggestions provided in other chapters.

THE EXPLOSIBILITY OF METHANE GAS MIXTURES

Methane entering a mine or tunnel often enters as a localized source at high concentration. Figure 1–1 depicts a cloud of methane being diluted into a moving air stream. In this illustration, methane enters the mine from a crack in the roof. As the methane emerges from the crack, it progressively mixes with the ventilation air and is diluted. In the event that this progressive dilution reduces the concentration from 100% to 1%,[2] as shown in Figure 1–1, the methane passes through a concentration range of 15% to 5%, known as the explosive range. In the explosive range, the mixture may be ignited. Above 15%, called the upper explosive limit (UEL), methane-air mixtures are not explosive, but will become explosive when mixed with more air.

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[2]Concentration percentage values refer to percent by volume.

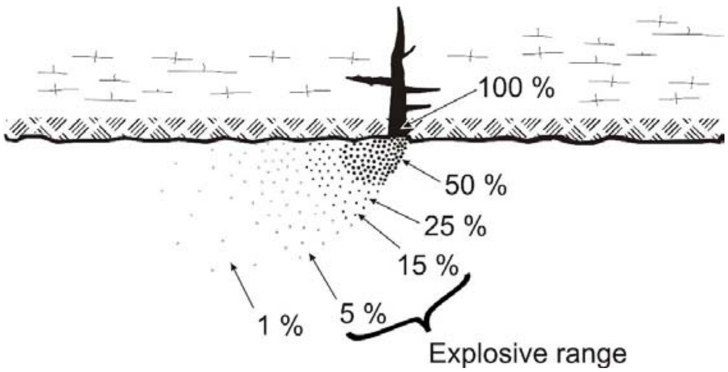

Figure 1–1.—Depiction of methane being diluted into a moving air stream.

Below 5%, called the lower explosive limit (LEL), methane-air mixtures cannot ignite.[3]

Because methane always passes through an explosive range during dilution, an effective mine ventilation system will ensure that this passage through the explosive range is as rapid as possible and that the volume of gas mixture in or above the explosive range is minimized.

Even though methane-air mixtures under 5% are not explosive, worldwide experience with methane in mines has indicated that a considerable margin of safety must be provided.

Addition of inert gases. An inert gas such as nitrogen or carbon dioxide cannot chemically react with methane. As a result, inert gases can be added to an explosive methane-air mixture to make it nonexplosive.

Explosibility diagrams are available to find how much inert gas is necessary. For example, Zabetakis et al. [1959] have provided a helpful explosibility diagram that shows whether a methane-air mixture is explosive after an inert gas such as nitrogen or carbon dioxide is added (Figure 1–2). This diagram shows that methane-air-inert gas mixtures fall into one of three categories: (A) explosive, (B) explosive when mixed with air, or (C) nonexplosive, depending on the percentage of methane and the percentage of "effective inert." Effective inert is calculated from the percentage of "excess nitrogen"[4] and the percentage of carbon dioxide in the mixture.

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[3]Sometimes the UEL and LEL are referred to as the upper and lower flammable limits (UFL and LFL).

[4]The percentage of excess nitrogen is the percentage of nitrogen in the sample minus the percentage of "normal nitrogen." Normal nitrogen is calculated from the ratio of nitrogen to oxygen normally found in air—a factor of 3.8. To calculate the effective inert, suppose, for example, that inert gas is added to a methane-air mixture and that a gas analysis shows that the final mixture has 6.6% oxygen, 4% carbon dioxide, 4.3% methane, and 85.1% nitrogen. The effective inert is then determined in three steps. First, in this example, the oxygen percentage is 6.6%, so the percentage of normal nitrogen is 3.8 times 6.6%, or 25.1%. Second, since the percentage of excess nitrogen is the percentage of nitrogen in the sample minus the percent of normal nitrogen, the excess nitrogen is 85.1% minus 25.1%, or 60%. Third, according to the equation shown in Figure 1–2, since the carbon dioxide in the sample is 4%, the effective inert is now 60%, plus 1.5 times (4%), or 66%. This gives the "composition point" shown in Figure 1–2. (Carbon dioxide has been found to be 50% more effective than nitrogen in inerting, so a multiplying factor of 1.5 is used).

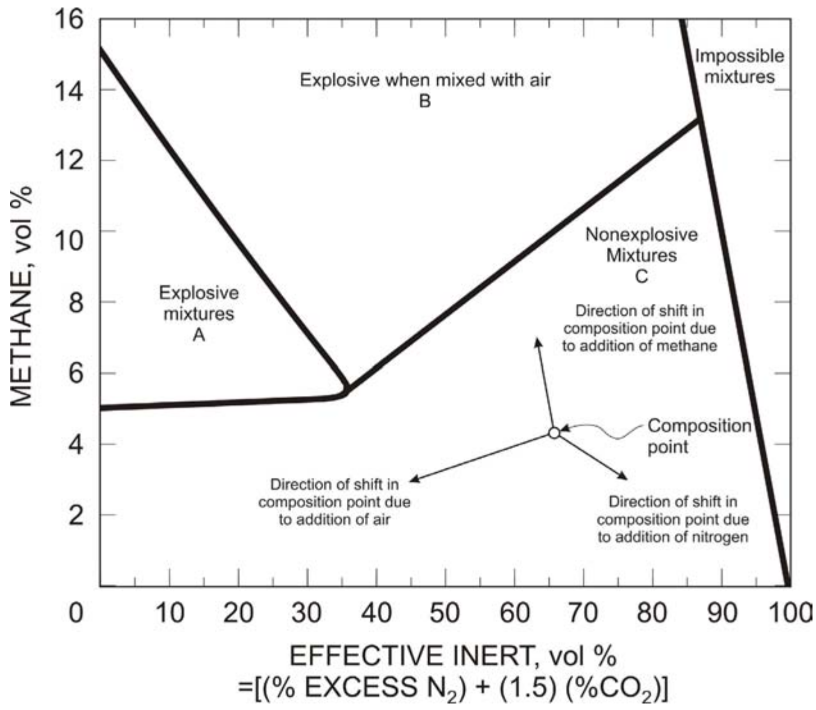

Figure 1–2.—Methane explosibility diagram (from Zabetakis et al. [1959]).

Figure 1–2 shows a "composition point" with 4.3% methane and 66% "effective inert." The arrows indicate how the composition point is shifted by the addition of more methane, more air, or more inert gas. For example, adding more air shifts the composition point in the direction of 100% air (0% methane, 0% effective inert), whereas adding more nitrogen shifts the composition point in the direction of 100% effective inert (0% methane, 0% air).

Addition of other flammable gases to air. Mine gas mixtures can contain flammable gases other than methane, principally ethane, hydrogen, and carbon monoxide. The explosive limits of these mixtures in air are calculated using Le Chatelier's law [1891]. This law specifies that if one gas mixture at its lower explosive limit is added to another gas mixture also at its lower explosive limit, then the combination of the mixtures will be at the lower explosive limit of the combination. Mathematically,

$$\mathrm{L} = \frac{100}{P_1 / L_1 + P_2 / L_2 + \cdots\, P_X / L_X},$$

where $P_1 + P_2 + \cdots\, P_X = 100$. Here, we have gas mixtures of gas #1, gas #2, and up through gas #X. L is the lower explosive limit of the mixture, P is the proportion of each gas in the mixture, and L_1, L_2, and L_X are the lower explosive limits in air for each combustible gas separately [Jones 1929].

Combinations of both flammable and inert gases. For combinations of both flammable and inert gases in air, explosive limits can be obtained through diagrams provided by Zabetakis et al. [1959]. More explosibility diagrams are available from other sources, and Holding [1992] has reviewed the features of each of them.

EFFECTS OF PRESSURE AND TEMPERATURE ON EXPLOSIBILITY

Effect of pressure on explosibility limits. According to Kuchta [1985], the flammability limits of hydrocarbon vapor-air mixtures (such as methane-air mixtures) vary only slightly with

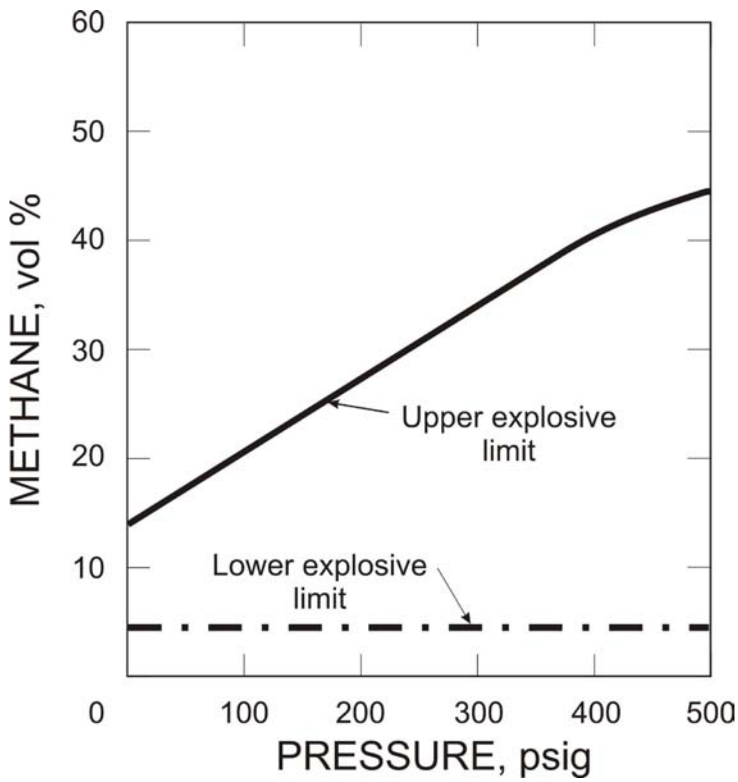

Figure 1–3.—Effect of elevated pressure on methane explosibility limits.

reduced pressure, except at very low pressures, such as below ¼ atmosphere. At elevated pressures, the lower limits of hydrocarbon-air mixtures generally decrease slightly, but the upper limits increase greatly. Figure 1–3 shows the variation in methane lower explosive limit and upper explosive limit with elevated pressure.

Effect of temperature on explosibility limits. The effect of temperature on the explosibility limits of methane is modest. For example, the LEL of methane-air mixtures at -100 °C is 5.6% methane, and at +100 °C it is 4.8% methane. The UEL of methane-air mixtures at +100 °C is 16.3% methane [Zabetakis 1965].

LESS COMMON SOURCES OF METHANE IGNITIONS

There are many well-known methane ignition sources in mines, ranging from frictional ignitions caused by cutting bits (Chapter 3) to open flames, explosives, and electrical sparking. However, there are other less recognized ignition sources. A review of these is worthwhile here.

Hot solids. The temperature at which a hot solid can ignite methane is quite high. Coward and Ramsay [1965] report that the minimum ignition temperature in a closed vessel is about 675 °C, but when the hot surface is exposed to convection currents, the minimum temperature is higher. For example, ignition from a hot steel bar requires 990 °C. Kuchta [1985] found that ignitions by any heated surface depend on the dimensions of the surface. He reports methane ignition temperatures ranging from 630 to 1,220 °C.

However, when an ignitable dust is present on the hot surface, this dust is more readily ignited than methane. The burning dust can then ignite the methane. Kim [1977b] reported laboratory studies in which the spontaneous ignition temperature of coal dust layers was as low as 160 °C. As a result, Mine Safety and Health Administration (MSHA) regulations require that the surface temperature of permissible electrical equipment and diesel equipment[5] in coal mines[6] not exceed 150 °C.

Thermite sparking from light metal alloys. When light metal alloys strike rusty steel, the resulting sparks can ignite methane. This so-called thermite sparking can appear in different ways. Thomas [1941] showed that striking aluminum-painted rusty iron with a tool could ignite methane. Margerson et al. [1953] readily ignited methane by dropping a piece of magnesium alloy onto a rusty steel plate. Findings such as these have inhibited the use of light metal alloys in mines.

Today, sparking from light metals is minimized by using less incendive alloys. For example, MSHA[7] requires that aluminum fan blades contain no more than 0.5% magnesium.

Adiabatic compression. McPherson [1995] has proposed that adiabatic compression of methane-air-coal dust mixtures by falling roof can be responsible for some methane ignitions in coal gobs. A theoretical model indicates that the temperatures attained are adequate to ignite such mixtures if the roof fall is extensive in plan area, but not necessarily of large thickness. In a later laboratory study by Lin et al. [1997], an experimental apparatus was built to simulate the adiabatic compression that might result from roof falls. This apparatus, which dropped a 1,320-lb weight, ignited the methane and dust when they were in the proper concentration range.

Sliding (or impact) friction between blocks of rock or between rock and steel. Sliding friction between falling blocks of sandstone or pyrites, or between hard rock and steel, can produce incendive streaks that ignite methane [Powell and Billinge 1975].

According to Coward and Ramsey [1965], methane ignitions from rock falling onto rock were reported as early as 1886. Laboratory experiments confirmed this effect. The higher the quartz content, the more likely an ignition; however, the necessary rubbing distance was always greater than could be envisioned from a fall underground. Ignitions from rock falling onto steel were reported as early as 1908 and seen throughout the 20th century, both underground[8] and in the laboratory. Today, the most likely source of steel-rock ignitions are cutter picks on mining machines, a topic covered in Chapter 3.

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[5]The MSHA 150 °C requirement applies to diesel equipment intended for use in areas of the coal mine where permissible electrical equipment is required. Some state regulations require a surface temperature maximum of 150 °C for all diesel equipment in coal mines.

[6]In gassy metal/nonmetal mines, the diesel surface temperature limit is 204 °C (400 °F).

[7]Per 30 CFR 57. *Code of Federal Regulations.* See CFR in references.

[8]These ignitions were not always in coal mines. For example, an explosion in a Detroit water intake tunnel on December 11, 1971, killed 22 workers. The ignition was attributed to sparks caused by dropping a 23-in-diam drill bit a distance of 16 ft onto the concrete tunnel floor [Detroit Water and Sewerage Department 2005].

Static electricity. Protection against discharges of static electricity is a common feature of mine regulations. Precautions are required for electrical equipment, for explosives loaded into blastholes (30 CFR 57.6602), for nonmetallic rotating parts such as belts (30 CFR 18.26), for venturi air movers powered by compressed air, and for similar circumstances where static charges are likely to collect. The National Fire Protection Association [NFPA 2000] and many Internet sites have more information on how to prevent static electricity.

Although controlling static electricity in mines is important, it has not been a common source of methane explosions in underground mines, possibly due to higher humidity underground. Nevertheless, extra precaution should be taken where acetylene is used, since acetylene is much more easily ignited by static electricity than methane.

Lightning. The South African underground coal mining industry has seen many incidents related to the passage of lightning storms on the surface. These incidents included electrical shocks, visible sparking from mining equipment, premature detonation of explosives, and methane explosions. The majority were in shallow mines at depths of 300 ft or less. Precautions to prevent these lightning-related incidents included lightning warning techniques, the use of less sensitive detonators, modified blasting practices, and improved electrical grounding of mining equipment [Geldenhuys et al. 1985].

In the United States, lightning has been reported as the explosion source at two mines in Alabama [Checca and Zuchelli 1995]. Both mines had been worked since the 1970s and had large sections that had been abandoned and permanently sealed. The mines were deeper (500 and 1,200 ft) than those in South Africa. However, in the investigation following each of the explosions, it was found that the lightning strike occurred at a location where there was a convenient conduit for electrical current into a sealed area of the mine. In one instance, it was an old capped shaft; in the other, it was a test well with a metal casing that extended from a foot below the surface to a foot above the mine roof. On the surface, this test well was located in a fenced area that enclosed a methane-pumping unit.

More recently, Novak and Fisher [2000] conducted computer simulations of lightning propagation through the earth to confirm whether lightning could penetrate a 600-ft-deep mine with enough energy to trigger methane explosions. They found that the presence of a steel-cased borehole dramatically enhances the possibility of lightning starting an explosion. With a steel-cased borehole, the calculated voltage difference between a roof bolt adjacent to the borehole and a section of rail on the floor was 15.6 kV.

THE AMOUNT OF METHANE STORED IN COAL

Coal is the major source of methane gas in mines. Smaller (but still dangerous) amounts of methane are found in oil shale, porous rock, and water. Methane in oil shale has been measured by Kissell [1975], Matta et al. [1977], and Schatzel and Cooke [1994]. Methane stored in porous rock and water is of most concern in tunneling and has been discussed in some detail by Doyle [2001].[9]

Methane in coal. The amount of methane in coal is measured by using the "direct-method" test during exploration drilling from the surface, or it is estimated from the properties of the coal and the gas pressure or depth of the coalbed. The direct-method test for surface exploration drilling was first used by Kissell et al. [1973]. Improvements to the method were made by others [Diamond and Levine 1981; Ulery and Hyman 1991; Diamond et al. 2001]. McLennan et al. [1995] have written a thorough description of how to conduct a direct-method test and analyze the results.

In the direct method, a drill core of coal is brought to the surface, it is enclosed in an airtight container, and the methane emitted from the core is measured. The amount of gas that escaped the core as it was being brought to the surface is calculated. Later, the core is crushed and the residual gas given off during crushing is measured. Added together, these allow one to estimate the amount of gas in the coalbed.

A considerable amount of direct-method testing has taken place, so it is usually possible to get gas data for most U.S. coalbeds. For example, Diamond et al. [1986] have given the results of 1,500 direct-method tests on coal samples from more than 250 coalbeds in 17 states.

If direct-method results are not available, the amount of gas in coal may be roughly estimated from adsorption data. This estimate requires knowledge of the proximate analysis of the coal, assumes a standard moisture and ash content, and uses the hydrostatic head to estimate pressure [Kim 1977a]. Figure 1–4 summarizes methane content data for different rank coals at various depths using the hydrostatic head assumption.[10] However, because the actual pressure is often less than the pressure of the hydrostatic head,[11] the methane content values shown in Figure 1–4 are very much an upper limit.

FORECASTING THE METHANE HAZARD

Additional hazard calls for additional precaution, so an estimate of the expected methane emission is valuable for both new and existing mines.

Coal mines. When an active mine is nearby, the most effective way to forecast the methane emission rate for a mine under development is to use the emission rate from a nearby mine (or section) where similar mining methods are used under similar geological conditions. Corrections can be made for those factors that are likely to shift the emission rate. Such factors are

[9] Doyle [2001] also provides a helpful discussion of methane in coal.

[10] The adsorption of mixed gases (methane and carbon dioxide) on coal has been measured by Lama [1988].

[11] Kim [1977a] has compared the actual pressure to the hydrostatic head pressure for several U.S. mines. The results varied from 50% to 100% of the hydrostatic head. For Australian mines, Lama and Bartosiewicz [1982] estimate gas pressures ranging from 50% to 90% of the hydrostatic head. For U.K. mines, Creedy [1991] reports that gas pressures are generally less than 20% of the hydrostatic head.

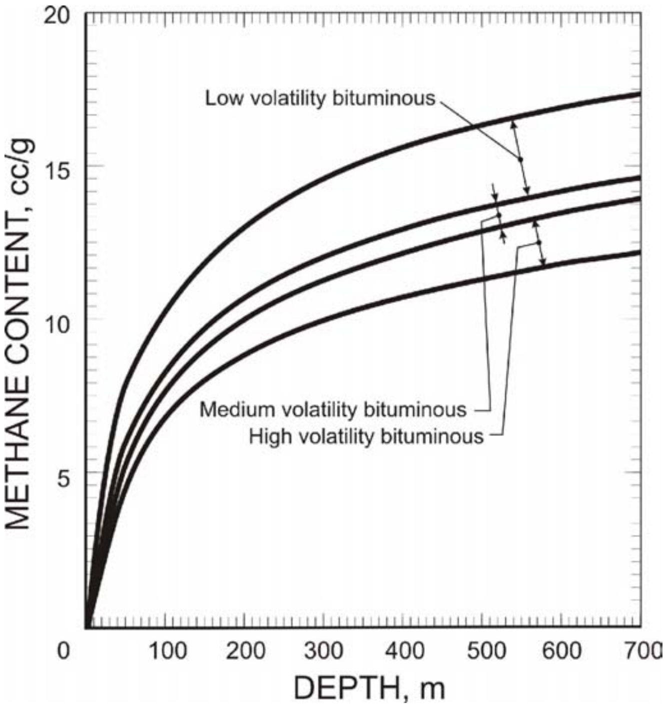

Figure 1–4.—Estimated methane content of coal versus depth and rank. Values shown are an upper limit.

differences in coalbed depth, differences in production rate, and geological anomalies[12] such as faults. Some of these corrections are simple, if inexact.[13]

When no other mine is nearby, a very rough emission forecast for the entire mine may be obtained using the gas content of the coal. For example, Saghafi et al. [1997] have reported the relationship between gas content and mine emission for Australian mines (Figure 1–5). The amount of methane released from the mine exceeded the methane in the mined coal by a factor of 4. This differs from the results of Kissell et al. [1973], who measured a factor of about 7 for some U.S. mines. The difference is probably due to methane emissions from adjacent coalbeds and porous rock. Other associations between mine emission and gas content have been made without using production data. Grau and LaScola [1984] have correlated the mine emission of some U.S. mines in cubic feet per day with the in situ gas content in cubic feet per ton.[14]

Much more on forecasting for coal mines is covered in the coal mine forecasting chapter (Chapter 8). Forecasting for metal and nonmetal mines is covered in this section. Forecasting for tunnels is covered in the tunneling chapter (Chapter 14).

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[12]The effect of geological anomalies is discussed in Chapter 7.

[13]Sometimes very inexact. For example, the methane emission can be assumed as roughly proportional to depth. However, Diamond and Garcia [1999] compared the methane emission rates of two longwall panels a mile apart. The second panel was 37% deeper than the first, but gave 61% higher emissions. The emissions were much higher because the elapsed time between development of the panel and retreat of the longwall face was much less in the second panel. Thus, there was less time for the second panel to drain gas into the returns, so when it was mined the emission was higher than expected.

[14]Grau and LaScola report 1980 mine emission data. Reliable U.S. data after 1980 are not available. As degasification programs became widespread, the degas quantities were retained as confidential information by coal companies.

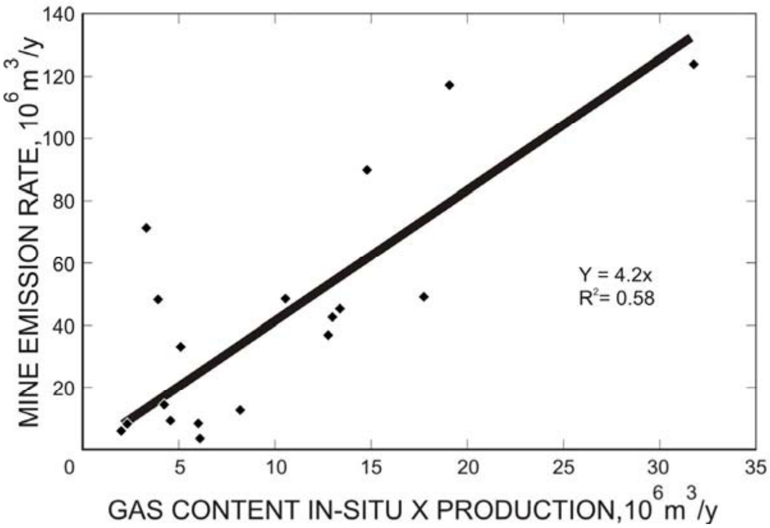

Figure 1–5.—Original gas content of mined coal versus mine emission. (Mines producing less than 10^6 tons/yr were omitted.)

In the last 25 years, sophisticated computer models have become available for coalbed methane forecasting. Most of these are driven by the need to estimate how much gas can be extracted to generate revenue. Chapter 8 deals with coalbed emission forecasting. Also, Creedy [1996] has provided a comprehensive report on methane prediction for coal mines.

Metal and nonmetal mines. Metal and nonmetal mines that encounter methane emissions are placed by MSHA in a special regulatory category that requires extra precautions against methane explosions. Placement in these special regulatory categories (30 CFR 57, Subpart T) is usually triggered by a specific incident, such as measurement of a methane concentration of 0.25% or more, an ignition of methane in the mine, or an outburst in the mine if it is a salt mine.

Most of these incidents are probabilistic in nature. For example, as the methane hazard level increases, the chance of an ignition goes up, but an ignition (especially a small ignition that can serve as a warning) is by no means certain.

How then does the operator of a metal or nonmetal mine estimate the methane hazard level without waiting for such an incident to take place? Thimons et al. [1977] established a simple guideline that would enable mine personnel to evaluate the methane hazard. In their research, they measured trace methane concentrations in 53 metal and nonmetal mines. They found that mines with a return concentration exceeding 70 ppm of methane were inevitably classified as gassy.[15] Although a measurement of concentration alone is not the complete methane story,[16] a return concentration exceeding 70 ppm should serve as an alert to the presence of gas that has not yet shown itself in other ways.

[15]In 1977, the MSHA classification system for mines with methane was different from the one in existence today. However, the triggers that lead to extra precautions (such as measurement of 0.25% or an ignition in the mine) are similar.

[16]See the section in this chapter on the importance of air velocity in preventing methane explosions.

LAYERING OF METHANE AT THE MINE ROOF

The density of methane is roughly half that of air, so methane released at the mine roof may form a buoyant layer that does not readily mix into the ventilation air stream. Such layers have been the source of many mine explosions,[17] so it is important to understand the circumstances that led to the formation of methane roof layers and the methods used to dissipate them.

> **Creedy and Phillips [1997] have written a thorough summary of methane layering and its implications for South African mines.**

Detecting methane layers. Methane layers are largely a result of inadequate ventilation. Raine [1960] asserted that a measurement of ventilation velocity is of most practical importance. He found that under conditions of "normal firedamp emission,"[18] an air velocity of 100 ft/min measured at the roof was enough to prevent layering.[19] Most current-day estimates of the necessary velocity are close to this value.[20]

An alternative approach to estimating the air velocity required to prevent layering is to use a "layering number," devised by Bakke and Leach [1962]. The layering number is a dimensionless number expressed as—

$$L = \frac{U}{37 \cdot \sqrt[3]{\frac{V}{W}}}$$

where L is the layering number, U is the air velocity in feet per minute, V is the methane release rate in cubic feet per minute, and W is the entry width in feet. In layering experiments conducted by Bakke and Leach, methane was released at a single point at the mine roof, and the air velocity necessary to dilute the layer was measured. They found that mixing by turbulence began at layering numbers larger than 2, but that a layering number of 5 was necessary for adequate dilution.[21] Compared to the 100-ft/min criterion, the layering number concept is more difficult to apply because the methane release rate V is usually not known.

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[17]For example, the 1993 Middelbult coal mine explosion in Secunda, South Africa, was attributed to a methane layer [Davies et al. 2000].

[18]The phrase "normal firedamp emission" was not further defined. However, it is clear that at abnormally high gas feeds, higher velocities are required. In a laboratory study, Bakke and Leach [1962] found that 230 ft/min air velocity was required to disperse a layer generated by a release of 12 ft^3/min of methane.

[19]The 100 ft/min applies only to horizontal entries. Higher velocities are suggested for inclined entries [Bakke and Leach 1965].

[20]For example, McPherson [2002] suggests 0.4 m/sec, or about 80 ft/min.

[21]At high methane emission rates, the layering number suggests that velocities higher than 100 ft/min are necessary to prevent layering. For example, for a methane emission rate of 16 ft/min in a 16-ft-wide entry, the velocity required to prevent layering is 185 ft/min.

Aside from inadequate ventilation, there are other circumstances under which methane layers are probable. Airways next to gobs are an example. Many of the concerns about layers were sharpened by experience in the 1960s with advancing longwalls in the United Kingdom. At these longwalls, frequently traveled gate roads were directly adjacent to fresh longwall gob, where broken overburden provided a ready pathway for roof gas emissions.

Thorough gas monitoring is a key to dealing safely with methane layers. Care in monitoring is particularly important if—

- The air velocity measured at the roof level is 100 ft/min or less.
- The airway is next to a gob[22] or intersects a geologic anomaly, such as a fault, that can serve as a conduit for gas.
- The mine roof (or tunnel crown) is not within easy reach, so measurements at roof level are less apt to be carried out regularly.
- The airway has cavities [Titman et al. 1965; Vinson et al. 1978] or roof-level obstructions to air movement.
- The airway is inclined more than 5° [Bakke and Leach 1962].

Workers who test for methane layers should be aware that the gas concentrations in these layers may fall outside of the accurate operating range of catalytic heat of combustion sensors. For accurate operation of these sensors, the concentration of methane must be below 8% *and* the concentration of oxygen must be above 10%. Also, when measuring methane concentrations above 8%, instruments with catalytic heat of combustion sensors can act in a way that is misleading, responding with a rapid upscale reading followed by a declining or erratic reading[23] [CSA 1984]. Such instrument behavior is a tipoff to the possible presence of high, possibly explosive methane concentrations.

When the roof is high and beyond convenient reach, measurements may be made in two ways. First, the methane detector can be equipped with a remote "sample-draw" capability. Sample-draw systems use a small pump or a hand-squeezed bulb to pull the sample through an extension probe and pass it through the detector. Some methane detectors have an accessory sampling pump that attaches to the detector; others have a built-in pump.

Second, the methane detector can be attached to a cradle at the end of a long handle, which is then extended to the roof. This method permits a direct reading without aspiration if the user has

[22]Five miners were killed in a 1972 methane explosion at the Itmann No. 3 Mine in West Virginia. The explosion was in a trolley haulageway that ran adjacent to a longwall gob and was attributed to excessive pressure from the adjacent strata [Richmond et al. 1983].
[23]Some instruments will report this as an out-of-range condition. For more information, consult the operating instructions for the instrument.

good eyesight.[24] Otherwise, the audible alarm on the detector could be set to engage at a low methane level.

Mitigating methane layers. Methane layers are removed by increasing the ventilation quantity and reducing the gas flow by methane drainage. In instances where the source and layer size are limited,[25] a less satisfactory, but workable method is to use a (well-grounded) compressed air-powered venturi air mover or an auxiliary fan at each methane source to blow air at the source of the layer and disperse it [Creedy and Phillips 1997]. In either case, an aggressive sampling program is necessary to ensure safe conditions.

Keep in mind that methane mixed with air cannot unmix to form a layer.

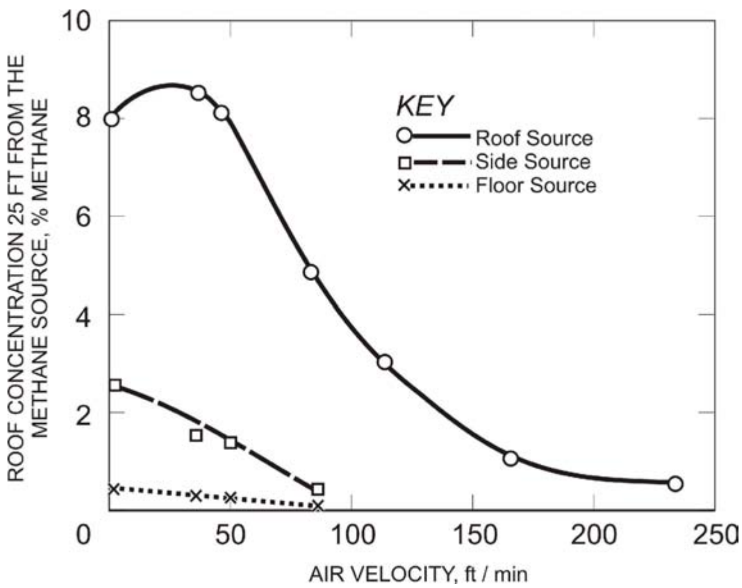

Figure 1–6.—Methane layering with roof, side, and floor sources (from Bakke and Leach [1962]).

The rib and floor as sources of methane layers. Methane layering occurs when methane is released at the mine roof. When methane is released at the mine floor or rib, this gas readily mixes into the ventilation air stream, losing its buoyancy. Figure 1–6, from Bakke and Leach [1962], compares 2-cfm methane sources at the roof, rib, and floor of the mine entry. Only the roof source produced a significant methane layer at the 2-cfm rate.[26]

WHEN RECIRCULATION OF MINE AIR CAN BE HAZARDOUS

Recirculation leads to higher methane levels only when recirculated air *replaces fresh air*.

[24]See the sampling chapter (Chapter 2) and the sections on methane detection in the continuous miner chapter (Chapter 3).
[25]For example, the immediate face area in a tunnel boring machine.
[26]The testing did not rule out the possibility of a layer at higher methane flows.

Recirculation of mine air takes place when some portion of return air is picked up by a fan and returned to the intake, potentially raising the contaminant level of the intake air. Concerns about whether recirculation is a hazard have persisted for decades. The first theory and experiments on the recirculation of mine air were reported by Bakke et al. [1964]. They concluded from a material balance[27] and from experiments that the concentration of methane leaving any region is equal to the flow of methane into the region divided by the flow of fresh air into the region. The recirculation hazard is higher only if the amount of fresh air is reduced.

An example of potentially hazardous recirculation in headings is shown in Figure 1–7. Here, the region is a heading designated *ABCD*. Within the heading is an auxiliary fan moving an air quantity Q. The fan inlet is in the wrong location, so the air entering the fan is some portion of fresh air nQ and some portion of methane-laden return air (1 - n)Q (where n varies between 0 and 1). The concentration of methane is then: $c = V/nQ$.[28] Had the fan inlet been positioned at a better location, L1, the proportion of fresh air would be greater, the value of n would be higher, and the methane concentration lower. Had the fan inlet been positioned at location L2, the proportion of fresh air would be less, the value of n would be lower, and the methane concentration higher.

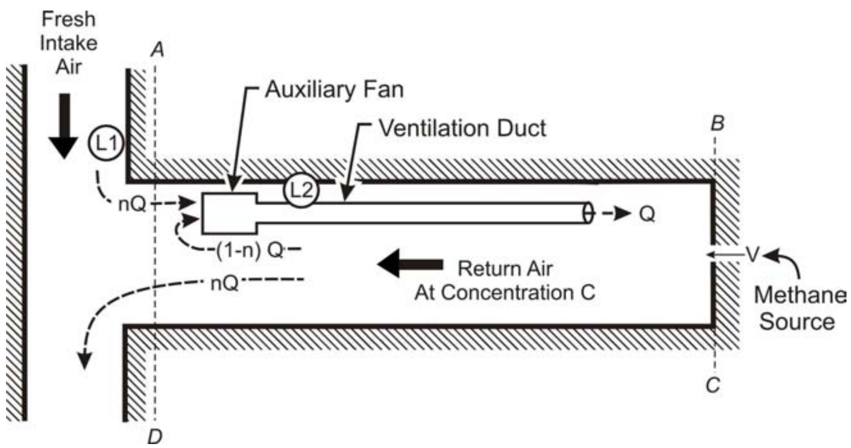

Figure 1–7.—Recirculation in a heading.

Recirculation caused by dust scrubbers on continuous miners was studied by Kissell and Bielicki [1975] (Figure 1–8). In this instance, the fresh air entering zone *ABCD* was also designated nQ. The scrubber moved air quantity R, of which a fraction mR recirculated back into the zone. A new variable Z was necessary to account for air leaving the zone without passing through the scrubber. As before,

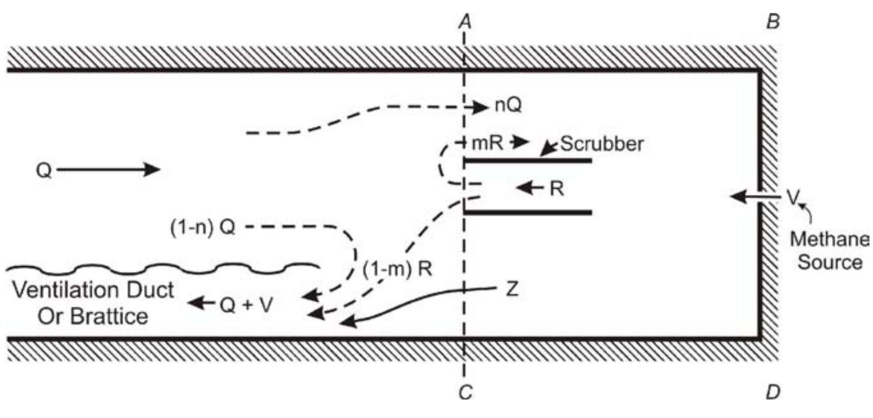

Figure 1–8.—Dust scrubber recirculation.

[27]The basic material balance equations are: air entering the zone equals air leaving the zone, and methane entering the zone equals methane leaving the zone. For more details on the material balances used, see Bakke et al. [1964] and Kissell and Bielicki [1975].

[28]Strictly speaking, it is $c = V/(nQ+V)$. However, since nQ>>V, the approximation $c = V/nQ$ is adequate.

a material balance indicated that the concentration of methane in the zone depended only on the amount of fresh air entering the zone, or nQ, and the amount of methane entering the zone, or V. However, this left open the question of what factors determine the value of n.

During experiments conducted with a full-scale model of a mine working face, Kissell and Bielicki found that n depended on whether or not the scrubber was turned on, and if turned on, where the scrubber exhaust was directed. Turning on the scrubber raised the value of n, reducing the methane concentration in the zone. Directing the scrubber exhaust into the return (in this case, behind the exhaust line curtain) was the best exhaust configuration, yielding an nQ fresh air value over four times higher and a zone methane concentration less than ¼ when compared to the test with the scrubber off.[29]

Bakke et al. and Kissell and Bielicki were primarily concerned with recirculation at coal mine working faces. Many other studies have been conducted on so-called district recirculation, i.e., recirculation of air in a major portion of a mine. District recirculation is produced by an underground fan that moves air from a return airway back into an intake airway, thus raising the total air quantity in that portion of the mine inby the underground fan. Improved dust control can be a result. Cecala et al. [1991] used SF_6 tracer gas to study recirculation in a trona mine district that contained three operating continuous miner sections. The results were consistent with a methane material balance. Pritchard [1995] has discussed his own experience and the worldwide experience with controlled district recirculation. Pritchard concluded that—

1. The initial volume of fresh air to the district should be maintained.
2. The recirculation fan should be placed far enough from the face for the dust to settle out, but close enough to the face to minimize stopping leakage.
3. District recirculation systems will increase flow and pressure losses in the mine circuit, producing a small drop in main fan flow.[30]
4. Adequate monitoring and controls must be in place.

In summary, recirculation will raise the methane concentration only when recirculated air is substituted for fresh air. If the amount of fresh air entering a zone is unchanged, the methane concentration in the zone will be unchanged. At continuous miner faces, if operation of a scrubber creates an airflow pattern that enhances the amount of fresh air entering the face zone, then operation of the scrubber will lower the methane concentration (and vice versa).

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[29]Subsequent studies have confirmed the need to direct the scrubber exhaust into the return. See Figures 3–7 and 3–10.
[30]The exact amount will depend on the fan locations.

THE IMPORTANCE OF HIGHER AIR VELOCITY IN PREVENTING METHANE EXPLOSIONS

Low air velocities can lead to poor mixing between methane and air. This poor mixing in turn leads to fluctuations in the methane concentration that make an ignition more likely.

Bakke et al. [1967] first suggested that a measurement of the methane concentration alone is an incomplete means of assessing the ignition hazard and that other measurable ventilation quantities might be important.[31] A study of methane ignitions in U.K. coal mines found that the probability of an ignition is determined by both the methane concentration and the densimetric Froude number, a dimensionless quantity related to the gas-mixing process in the presence of buoyancy forces. The expression for the Froude number F is—

$$\mathrm{F} = \frac{u^2}{g\,\dfrac{\Delta\rho}{\rho}\sqrt{A}}$$

where u is the air velocity, $\dfrac{\Delta\rho}{\rho}$ is the density difference between air and methane divided by the density of air, and A is the cross-sectional area of the airway.

The data available to Bakke et al. resulted from 123 ignitions on faces and gate roads at U.K. longwalls during 1958–1965. Examination of the data indicated that the risk of an ignition was dependent on more than methane concentration alone and that it was possible to combine concentration and Froude number in one variable of the form c^2/F.

Figure 1–9 shows the normalized number of ignitions P (ignitions per year per gate road) versus c^2/F for the Bakke et al. data. The best fit to the data was $P = 0.004\,(c^2/F)^{0.9}$. A high correlation was obtained, indicating that, absent other sources of mixing, the risk of ignition P does depend on the variable c^2/F.

In most mines, the square root of A does not change much compared to changes in c^2 and u^2. Also, the factor of 0.9 is close to 1.0. It follows that ignition risk varies with the quantity $(c/u)^2$. This departs from any notion that ignition risk depends on the concentration c alone.[32]

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[31] Actually, since ignition risk also depends on human factors, there is no reason to expect that ignition risk depends only on concentration. Mines with less gas may also have a less vigilant workforce. However, Bakke et al. only sought a correlation with measurable ventilation quantities.

[32] Subsequent work at longwall shearers in the 1980s failed to confirm this finding [Creedy and Phillips 1997; CEC 1985], probably because water sprays on the shearer provided enough mixing between methane and air to overcome any velocity effect on mixing.

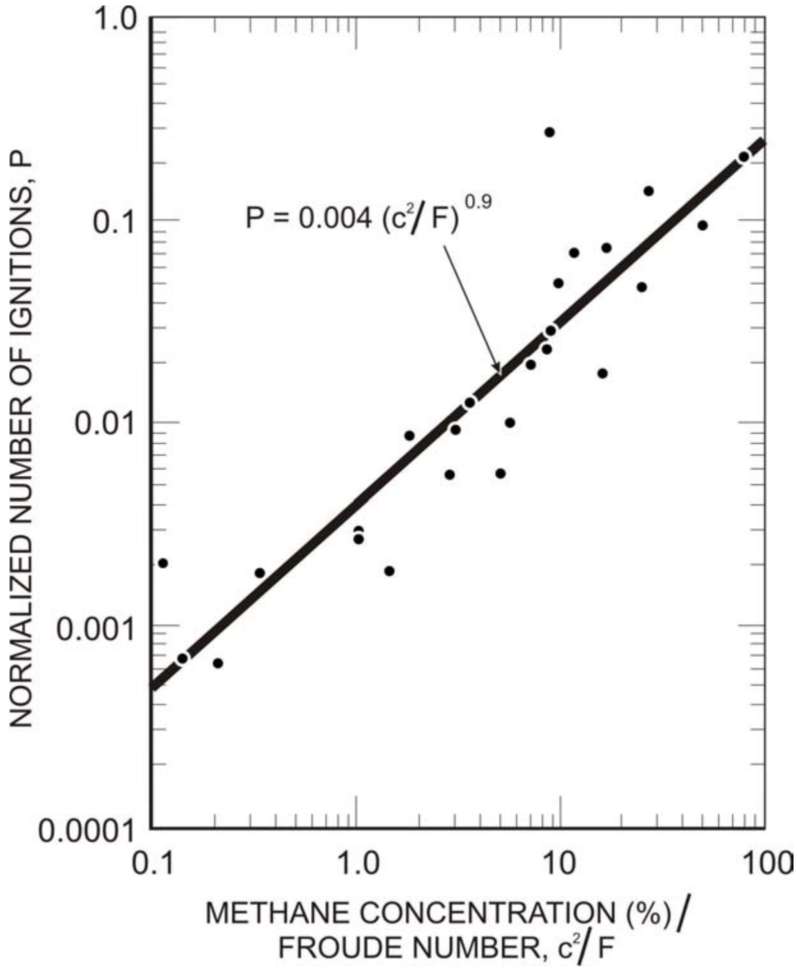

Figure 1–9.—Ignitions per year per gate road.

As an example, assume that the methane concentration is 1.0% and that the air velocity is 100 ft/min. If then the air velocity is raised to just 120 ft/min, the methane concentration becomes 0.83%. If the ignition risk is proportional to $(c/u)^2$, this modest increase in air velocity cuts the ignition risk in half.[33]

The findings of Bakke et al. have important implications for using higher air velocity to prevent methane explosions:

- In the absence of other means to promote mixing, raising air velocity is a highly effective way to reduce ignition risk. Higher air velocity promotes better mixing in addition to lowering the average concentration.

- Water sprays and auxiliary air movers (small fans or compressed-air venturis) that promote mixing can reduce ignition risk.

- At similar methane concentration levels, tunnels or mines with large cross-sectional entries and low air velocities have higher risk of ignition than those with small cross-sectional entries and higher air velocities. Both the lower velocity and higher area will work together to give a lower Froude number.

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[33]Some confirmation of the importance of air velocity in reducing ignition risk was obtained by Bielicki and Kissell [1974], who conducted a study of the methane concentration fluctuations produced by incomplete mixing of methane and air at a model coal mine working face. Poor mixing was characterized by wider concentration fluctuations and resulted from low airflow or a high methane release rate. In other studies of methane-air mixing, Kissell et al. [1974] found that good mixing was characterized by normally distributed peaks and poor mixing by log-normally distributed peaks. Schroeder and Kissell [1983] found the same effect and suggested that the term $\sigma(\log c)$, the standard deviation of the logarithms of the sampled peak concentrations c, be used as an indicator of mixing.

MINE EXPLOSIONS, BAROMETRIC PRESSURE, AND THE SEASONAL EXPLOSION TREND

Although mine explosions are far less common than in the past, this deadly hazard to miners has not disappeared. Mine operators must always be alert to the circumstances that make a mine explosion more likely. The chapter on dust explosions (Chapter 12) outlines what must be done to prevent a methane ignition from triggering a dust explosion, which is usually lethal. Two other important factors, discussed here, are barometric pressure lows and drier dust in the winter.

In South Africa, most mine explosions have followed a low in the barometric pressure; however, there is no seasonal frequency trend. In the United States, mine explosions have been more frequent in the winter because the dust is drier.

Barometric pressure lows and mine explosions. Many researchers have documented an inverse relationship between barometric pressure and the amount of methane flowing from a mine [Carter and Durst 1955; Stevenson 1968; Füssell and Hudewentz 1974; Eschenburg 1977]. A falling barometric pressure causes expansion of the methane that has accumulated in underground cavities and crevices. The methane then flows into the mine, making an ignition more likely.

Fauconnier [1992] has examined the role of barometric pressure changes in South African mine explosions. Using barometric data corresponding to 59 methane explosions (26 in coal, 33 in gold mines) for the period 1970–1989, he concluded that most of the explosions were associated with medium-term (longer than 1 day) downward trends in barometric pressure. He also concluded that explosions occur randomly during the year, in contrast with U.S. coal mines, which are known to have a seasonal trend.

The seasonal trend in U.S. coal mine explosions. Historically, U.S. coal mine explosions have been more frequent in the winter than the summer [Boyer 1964]. Although barometric pressure might be a cause because changes in barometric pressure are more abrupt and intense in the winter months, it is also true that mines are drier in the winter because of the low moisture content of the air [Williams 1914; Pappas et al. 2002]. This means that coal dust is drier and more easily dispersed and ignited during the cold months.

According to a study by Kissell et al. [1973], the second factor—drier coal dust—is the most influential in making winter explosions in U.S. coal mines more frequent. In this study, coal mine accident reports from 1911 to 1970 were examined to see whether winter explosions were more likely to occur in regions of the mine more susceptible to barometric pressure fluctuations (e.g., gobs). No such tendency was found. Next, based on the accident reports, explosions were divided into five different categories:

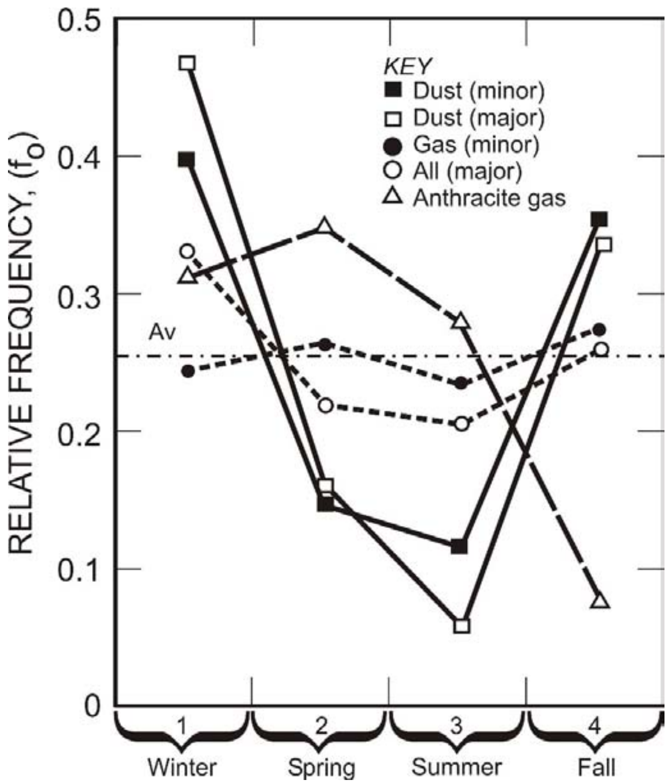

Figure 1–10.—Relative frequency of occurrence of major and minor gas and dust explosions.

- *All major explosions* (where five or more miners were killed). Most major explosions involved both gas and dust.
- *Major dust explosions*. Dust explosions are those where the accident investigators concluded that dust was directly ignited, without gas participating as an intermediate stage. Typically, these took place in mines known to be relatively free of methane and where the dust was ignited by a blown-out shot.
- *Minor dust explosions* (fewer than five miners killed).
- *Minor gas explosions*. Accident investigators concluded that dust was not involved.
- *Explosions in anthracite mine*s. These were known to be "gas only" because anthracite dust is not explosive under the conditions prevailing in mining.

Figure 1–10 shows the relative frequency of each of these types of explosions for the period 1911 to 1970. When all major explosions are considered, the higher frequency in winter months is clearly evident. However, this trend is far more pronounced for the dust explosions. No trend favoring the winter months is evident in the anthracite mine explosions or those categorized as "gas only." This provides strong evidence that it is dust, not gas, that accounts for the seasonal trend in U.S. coal mine explosions.[34]

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[34]The results of Kissell et al. do not contradict the conclusions by Fauconnier. The seasonal trend for coal mine explosions in the United States might be due to colder winter months or the fact that a different timeframe was examined. Also, Fauconnier combined explosions at both coal and gold mines.

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