PREVENTING SPONTANEOUS COMBUSTION IN GOB AREAS OF RETREATING LONGWALL PANELS BY VENTILATING WITHOUT BLEEDERS

by

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(ABSTRACT)

Spontaneous combustion occurring in inaccessible areas of underground coal mines is often intractable. Even though routine inspection and/or continuous monitoring help detect the incubation of spontaneous heatings, they may not be able to identify the locations with accuracy. Moreover, implementation of remedial measures is difficult. A new approach to ventilation system design to overcome the problem is investigated in this dissertation. Ventilation layouts are analyzed to identify potential problem areas and nullify the probability of fire occurrence. The focus is directed to longwall gobs. The changing gob characteristics, especially the varying degree of consolidation at different parts of a gob as the face moves, is considered. Analytical studies and computer modeling show that bleederless ventilation in retreating panels is promising. The W-system of ventilation is most suitable. However, there may be difficulties in maintaining the middle entry in a W-system.
On the basis of an actual case study, a new layout is described that allows pressure balancing to be applied behind the face shield supports in a U-system. This minimizes airflow through the critical areas of the gob. Multiple entries and air pressure balancing are used in implementing the method, without affecting the normal airflow rate at the working face. In addition to such measures, a methane drainage system may be implemented in gassy mines. This can be accomplished by using a proposed gob gas drainage model compatible with the proposed ventilation system.
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I. INTRODUCTION

This research project is been focused on identification, prevention and control of spontaneous combustion, and methane hazards in underground coal mines. Longwall mining is considered as the basis of the research because of its increasing application for a high rate of production. The increased rate of coal excavation is associated with a higher rate of methane liberation and greater risk of occurrence of self-heating. At a faster rate of excavation using heavy mining machinery, coal is fragmented to smaller pieces exposing a greater surface area. Smaller fragments can hold a lesser amount of methane in them, and a greater exposed surface leads to increased levels of interaction of oxygen with coal. This interaction is mainly a surface phenomenon and most active on the freshly exposed surface. This phenomenon results in generation of heat.

The essential factors in any combustion process are oxygen, fuel, and heat or source of ignition. If any one of the factors is absent, combustion cannot occur. Control on the presence of fuel such as coal, wood, or other combustible minerals, oils or gases, may be difficult in the real mining environment, especially in the inaccessible areas, such as the gob, where the major problems have been encountered. The goal is to prevent or control spontaneous combustion by regulating the airflow that carries oxygen.

Methane dilution efficiency is considered an important part of a ventilation system design in coal mines. Since the airflow has to be reduced to avoid self-heating, then the methane concentration in the gob areas increases. Though the high methane concentration lowers the oxygen concentration in the gob areas and hence the possibilities of spontaneous heating to some extent, it creates potentially explosive fringes around the periphery of the gob.

The control of self-heating and the abatement of methane hazard are two challenging tasks in a coal mining environment. Mine layouts have significant impact on initiating and sustaining the spontaneous heating process, and also on reducing methane hazards. Ventilating air distribution in a mine, particularly in a panel, is governed by its layout. On realizing the importance of mine and panel layouts, airflow patterns in the gob areas have been analyzed thoroughly for different longwall panel layouts practiced all over the world. However, similar analyses are valid for other types of coal mining systems, such as room...
and pillar operations. The objective of this research is to establish mine ventilation layouts which will control both the self-heating and methane hazard in underground coal mines.

More specifically, it is to conduct
- analytical studies of coal mine ventilation layouts for longwall panels that experience both spontaneous combustion and heavy emissions of methane
- research for preventing the access of air to zones that are susceptible to spontaneous combustion.

The content of this dissertation is broadly divided into seven chapters. The focus of Chapters 2 and 3 is the perspective of research work significant to the coal mining industry in the United States and other countries. These two chapters are based mainly on an extensive literature survey in the areas of spontaneous combustion and methane drainage. The objective is to lay the foundation for the present research work, and to avoid any inadvertent repetition of the research on the same topic using the same approach.

Chapter 2 sheds light on various aspects of spontaneous combustion such as what is spontaneous combustion, what are the various factors that govern the phenomena, how the susceptibility of coal to self-heating can be verified, and how it can be controlled. The significance and contributions of these factors have been described in detail. This chapter also describes different laboratory tests for identifying the spontaneous combustion characteristics of coal. These tests are critical for selecting appropriate panel design parameters so that the problem can be avoided by taking precautions in the planning and development stage of a mine. Various available methods to detect and monitor spontaneous combustion in an active mine are also discussed. Even though a mine is planned with regard to the results of tests for spontaneous combustion, laboratory studies are often restricted in their use. With the interaction of several factors, especially mining, geological and environmental, spontaneous combustion might take place vigorously even in a coal seam where laboratory tests indicated the least probability of spontaneous combustion.

Chapter 3 can be considered as the background of the research findings described in Chapter 5. In the first half of this chapter, widely used methods of preventing spontaneous combustion have been discussed. The rest of the chapter is on available control measures
for the mines where preventive measures have not been implemented or are not sufficient to avoid spontaneous combustion.

Chapter 4 deals with methane emission and control methods in practice. This chapter sets the stage for methane drainage modeling as described in section 5.7 of Chapter 5.

Chapter 5 is devoted to the research work as outlined in Chapter 1. Though the preceding chapters cover the background extensively, Chapter 5 also contains additional materials essential for the research work such as the specific characteristics of gob materials. This chapter may be regarded as the center stage of the research work. Chapters 6 and 7 summarize the outcome of the research conducted and its future expansion.
II. SPONTANEOUS COMBUSTION OF COAL

Coal interacts with air at temperature as low as -80°C. Heat is liberated due to spontaneous heating caused by the interaction. When the heat accumulates in the coal matrix under certain conditions, the interaction rate becomes faster, consequently generating a greater quantity of heat. In the final stage of combustion, fires break out. Apart from coal, spontaneous combustion is also found to occur in fragmented or caved sulfide minerals and in the timber supports of mines. Each of these minerals has a critical temperature called the minimum "self-heating temperature." This is the lowest temperature that will sustain heat formation or "thermal runaway." If the self-heating temperature is attained before thermal equilibrium, the process will take place at a growing rate. The temperature will rise rapidly, leading to higher rates of heating until the material begins to burn. At this stage, smoke and gaseous products are released in the ventilating air. Among them is carbon monoxide, a deadly poisonous gas. Also, the explosive mixture of methane and air may be ignited, creating explosions and open fires.

However, heat liberation may not cause combustion unless heat is accumulated continually from the beginning of the self-heating process. The physical conditions play a significant role in the accumulation of heat. For example, a large mass of coal will store the heat due to a critical flow of ventilating air that is sufficient to sustain the spontaneous heating process, but insufficient to carry the heat away at the rate at which it is produced. Under these conditions, a part of the coal mass may heat up to the point of ignition after a time interval. The duration between the time of exposure to oxygen of air to the time of ignition is often called "incubation period."

As mentioned above, spontaneous heating occurs when fragmented coal with a large surface area is exposed to the critical flow rate of air. Hence, the problem arises in the gob areas, caved zones, crushed pillar edges, fractured coal bands in roof or floor strata, and within abandoned sections of mines. The sequence of phases which finally lead to spontaneous combustion is not fully understood. Primarily, the oxidation of carbonaceous matter in coal is recognized for initiating the process.
2.1 Background

The spontaneous combustion of coal has been the root of many underground coal fires all over the world. In the United States, 15 percent of underground coal mine fires between 1978 and 1988, were caused by spontaneous combustion (National Fire Protection Association, 1990). Fires due to spontaneous combustion take place usually in the mined-out or gob areas. These fires often go unnoticed and are difficult to extinguish because of their inaccessibility. They threaten the overall safety of the mine and the personnel on duty. Often they call for sealing large sections of the mine or the entire mine, for long periods, resulting in severe economic losses. Due to a fire from spontaneous combustion in a mine in Colorado, the mine was sealed and abandoned completely (Derick, 1993; Timko, Derick, and Thimons, 1987). In a longwall gob of another mine in Colorado, heating took place. Sealing and inert gas injection were required to suppress the heating (Smith, and Thompson, 1999). Several cases of spontaneous combustion associated with floor heave in a mine in Alabama have been encountered (Miron, Lazzara, and Smith, 1992). The number of spontaneous combustion related fires is expected to increase with the use of low rank coals, deeper mines, and the longwall mining system.

Bleeder systems are used for ventilating the mined-out areas from which coal has been wholly or partially extracted, so as to control the methane content in such areas. To dilute and displace the gob gases, a ventilation pressure differential has to be maintained between the active working area and the bleeder entries. As a consequence, air leaks slowly through the caved areas of the gob creating zones susceptible to spontaneous heating. These are called "critical zones." In the critical zones, airflow is sufficient to sustain the self-heating process, but insufficient to carry the heat away at the rate at which it is produced. There are two distinct critical zones. One exists along the panel start line of the face where partial consolidation allows air leakage from the intake to return entries of the panel. The compacted center of the gob allows almost no leakage. However, the other critical zone is present between the gob center and the moving face.

The current and past experiences with the bleederless systems of ventilation, both overseas and in the United States, point out their effectiveness in controlling spontaneous heating. The major coal-producing countries such as Great Britain, Germany, Poland, France, Australia, India, Russia, and China have reported their success in minimizing the airflow
into the gob areas in coal seams prone to spontaneous heating. An appropriate panel layout for the bleederless system of ventilation minimizes air leakage into the gob. According to the most recent Federal ventilation regulations, bleederless ventilation systems may now be proposed as a method of controlling spontaneous combustion. Regulation 75.371 (U. S. Code of Federal Regulations, 1992) states, "mine ventilation plan shall contain 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 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". In the United States, two mines that have had spontaneous combustion occurrences have been allowed to use a bleederless ventilation system (Smith, and Thompson, 1991; Koenning, 1992).

In Europe and Asia, coal is mostly produced by using room and pillar, and longwall mining methods. Both advancing and retreating longwall methods have been utilized in these countries. Advancing longwall panels are effective in removing methane from the gob area because these panels allow a part of the ventilating air to percolate through the gob under ventilation pressure differential across the gob areas. As a consequence, methane is diluted and displaced from the gob. For the coal seams susceptible to spontaneous combustion, retreating longwall panels are advantageous because air leakage into the gob can be minimized.

In the United States, coal seams are relatively horizontal. Multiple entries are used as the gateroads of the longwall panel. Multiple-entry airways reduce the panel resistance to ventilation. As a result, higher quantities of air flow through the panels and its bleeders. It is clear that these panel layouts are generally oriented towards distributing a large quantity of air in the working areas, and through the bleeders for the removal of dust, gas, and heat. The multiple-entry developments are more likely to crush under a higher load of thick and heavy overburden.

The current trend is to excavate larger longwall panels. The average time to mine a complete panel has increased. As a consequence, the areas prone to spontaneous heating are exposed to the critical airflow for a longer time, increasing the possibility of active
heating. Some of the coal seams are deeper and generally gassier than those at shallower depths. Therefore, a bleedercless ventilation system must be accompanied by an appropriate provision for gas drainage.

2.2 Factors Affecting Spontaneous Combustion

Different types of coal have different spontaneous heating characteristics. Several factors have been found to affect the rate of oxidation and hence, variations in the self-heating propensity. Therefore, it is important to consider each of the major factors. The significance of these factors is discussed below.

2.2.1 Rank

The rank of coal depends on various chemical and physical properties of the original plant debris (increase in carbon, decrease in hydrogen percentage, decrease in volatile matter, increase in calorific value, decrease in inherent moisture contents, and such related properties) at different stages of metamorphosis (or transformation) while buried under the cover of earth. It is difficult to classify coals of different ranks because of the overlap in their properties. However, several discrete ranks of coal have been identified in increasing order of rank, e.g. peat, lignite, sub-bituminous, bituminous and anthracite. An increase in carbon content and subsequent decrease in oxygen content (both being calculated for the dry and mineral-free coal) are the most commonly accepted criteria for coal of higher rank.

It has long been recognized that the higher the rank and the lower the inherent oxygen content of the coal, the lower the susceptibility of the coal to self-heating. Lignite, very low in rank, oxidizes rapidly. It is often stated that it cannot be stored after mining without ignition. Low rank bituminous coal oxidizes fairly readily. However, high rank anthracite reacts very slowly (PD-NCB Consultants Ltd., 1978).
There are many exceptions in a straight rank order. For example, a coal seam of high rank may prove more troublesome than one of lower rank, or even the same seam in different mines may react differently.

### 2.2.2 Petrologic Composition

Coal is a complex heterogeneous organic compound. Based on petrologic studies, coal can be classified into three types of "macerals" (analogous to minerals in inorganic rocks):

1. woody and cortical tissues as origin, e.g. vitrinite, fusinite, semifusinite, etc.,
2. plant materials other than woody tissues, e.g. spornite, cutinite, resinite, etc., and
3. those of origin which have not yet been traced to specific vegetable tissues, but probably derived from humic mud, e.g. micrinite, etc.

It was once held that fusinite was the most dangerous constituent in causing spontaneous heating. This is most likely due to its physical form and large surface rather than any inherent qualities. It is possible that layers of fusinite would provide easy access of air to coal in much the same way as cracks or along cleats. Relatively recent studies generally concluded that vitrinite, clarinite, and duranite (in that order) are more susceptible to oxidation than fusinite (Wolowczyk, 1960). As a matter of fact, different physical conditions such as strength, particle size, cracks, etc. and factors such as available surface may affect the propensity of coal to spontaneous heating, according to their relative importance.

The nature and properties of coal depend mainly on the distribution and properties of these petrologic constituents. Thus a count of these macerals may be useful, together with rank, in determining the susceptibility of coal to spontaneous heating. Variations in maceral content may account for some of the anomalies in oxidation characteristics of the same rank coal from different seams. Therefore, it is necessary to study the composite coal as a whole, instead of studying the reactivity of individual constituents whose avidity for oxygen depends upon their distribution. The reflectance of a coal matrix is an indirect
measure of maceral types, and it may also be a useful means of indicating the relative reactivity of different coals.

2.2.3 Particle Size

The rate of oxidation increases with decrease in particle size as more and more oxygen penetrates into the pores on the coal particles, and until a size is reached beyond which the increase in the rate of oxidation is insignificant, i.e., when the particle is completely saturated by oxygen. Though the rate of oxidation increases as the particle size decreases, it is not in direct proportion to increase in the new surface area. Therefore, it is clear that oxygen penetrates into a coal particle with a pattern, which does not quite comply with the measure of the exposed surface area (Scott, 1944; Winmill, 1916). In an experiment with coal, the maximum rate of oxidation has been observed to occur in particles of less than 0.05 mm in size.

The infrared images of a freshly exposed coal surface undergoing oxidation show that the oxidation of coal begins at active centers on the surface (NCB, 1978). If the temperature due to self-heating is not allowed to rise, these centers will gradually become inactive. A solid coal surface is less prone to spontaneous combustion due to the small surface area, and possibly to a lesser number of active centers available. It is only when coal is cracked and fragmented by mining, or by roof pressure, caving (in the gob areas), faulting, or any other types of ground movement, more of the hidden surface is revealed with fresh active centers. Moreover, increase in temperature will enhance the permeability of the coal to oxygen.

2.2.4 Temperature

The initial stage of oxidation consists of a composite reaction made up of a number of concurrent reactions influenced differently by temperature. The initial rate of oxidation of fresh coal slows down quickly if the temperature of the coal mass is held constant. However, the oxidation can continue for a long time at a pace depending upon the rank of the coal.
With a rise in temperature, the oxidation reaction shifts continuously to higher activity levels. There is a pronounced temperature coefficient of oxidation, and the average rate of oxidation approximately doubles (1.4 to 2.3 for every rise of 10°C) (PD-NCB Consultants Ltd., 1978). The oxidation of coal produces heat, and thus supplies heat from its own source that elevates its temperature. In the absence of cooling, it oxidizes at an accelerating rate. Finally, the coal reaches a certain temperature critical for the mode of the reaction, beyond which a steady rate of reaction continues (at least to about 170°C). This temperature, called "threshold temperature," seems to draw a line between a changing pattern and a stable form of reactions. The value of the threshold temperature was found to vary between 80°C and 120°C, depending upon the properties of coal, particularly its moisture content (Banerjee, 1968).

Furthermore, the consumption rate of oxygen as well as the total quantity consumed by the coal, increase rapidly with the rise in temperature. In a test, it was observed that the rate of oxygen consumption increased by a factor of about 8 and the total quantity consumed by about 15, with the increase in temperature from 30°C to 100°C (PD-NCB Consultants Ltd., 1978).

When the rate of oxygen consumption, the total oxygen consumed, and the heat produced by oxidation are all considered, it can be concluded that all coals are likely to be susceptible to self-heating.

### 2.2.5 Airflow Rate

The quantity of air in contact with coal mass controls the self-heating phenomenon. The oxidation rate is so slow in the presence of a small quantity of air that there is no appreciable rise in temperature. Again, a high rate of airflow through coal or over thin layers of coal may carry away any heat produced. Hence, the temperature does not rise and the oxidation rate is always below a certain level. However, when the quantity of available air is sufficient to sustain oxidation, but not sufficient to carry away the heat generated, the self-heating process accelerates until ignition occurs. This is called "critical flow rate." The corresponding temperature is called "critical temperature" as illustrated in Figure 2.1. The effectiveness of action taken is indicated on the vertical axis by the final
Figure 2.1 The temperature at the onset of spontaneous ignition for different quantities of airflow over a coal stock pile (after PD-NCB Consultants Ltd., 1978).
temperature rise in the coal (PD-NCB Consultants Ltd., 1978). The curve goes through
the origin when no air is allowed to pass over or into the coal and so there is no
temperature rise, i.e. natural reserve of coal in the earth. The self-heating process can be
controlled by maximizing the access of air by adequate ventilation through the coal mass.
However, clusters of coal pieces may ignite spontaneously even when ventilated
adequately, because of the presence of critical flow in the areas less accessible to the full
flow of air. The airflow through underground coal wastes, which is considered as the pivot
or center of the research work, will be discussed in the subsequent sections of this
dissertation.

2.2.6 Moisture

The effect of moisture is significant in starting self-heating. However, the relationship
between moisture content and oxidation of coal is not clear, because water can be
physically absorbed, chemically bound, or simply mixed with the coal. The moisture
content of coal depends on the properties of the coal as well as the humidity of the
environment. Based on those two factors, an equilibrium moisture content will be reached
within a span of time. The lower the rank of the coal, the shorter the time may be, possibly
an interval of only hours (PD-NCB Consultants Ltd., 1978).

Heat of absorption of water vapor is much higher, by a factor of 10, than the heat of
wetting by liquid water, because the latent heat of condensation is included in the heat of
adsorption. Moreover, a greater extent of internal surface is available in lower rank coals.
For initiating the self-heating process, this is probably most critical. Coal contains inherent
moisture, and if the vapor pressure in the air is higher than that present on the coal
surface, water is absorbed producing heat. A sensible rise in temperature and an increased
rate of oxidation can occur under unfavorable conditions (Guney et al., 1969; Mukherjee,
and Lahiri, 1957; Scott, 1956). In a number of cases, fires have been reported for open
coal stacks after heavy rains. Also after fighting a mine fire with water, spontaneous
heating may be found to occur in the mine. These incidents may be explained either by the
creation of channels (in the coal matrix with the percolation of water as well as with the
vaporization of absorbed water), or by the formation of cracks and fissures in the seam
during flooding of the mine, opening up new surfaces to air (McPherson, 1993).
In addition to those physical conditions, some researchers found that the role of moisture goes far beyond initiating the self-heating process. They observed that, to some extent, the moisture content of coal influences the formation of peroxo-complex (sometimes called "coal-oxygen-water complex"), apart from the catalytic action of moisture (Jones, and Townend, 1946; 1949).

A research group in Russia observed that wide and abrupt variations in atmospheric humidity give rise to self-heating, mostly in surface stacks of coal (Egorov, and Stankevich, 1971). A research group in India has found that there is an optimum moisture level (around 5%) in coal showing the greatest liability to spontaneous combustion (Nandy et al., 1967).

In the beginning of the self-heating process, an endothermic reaction takes place. Vapor is released from coal during this stage. The latent heat of evaporation is taken away from the coal mass resulting in cooling. The degree of cooling, which in turn depends on the extent of the exposed surface area, is found directly proportional to the inherent moisture content in the coal (as shown in Figure 2.2). As oxidation of coal continues, exothermic reactions set in and more of the moisture is released. It is found that evaporation of moisture makes the coal more susceptible to oxidation. In the initial stage, oxidation occurs on the surface macropores. After evaporation of moisture, micropores covering a large surface area are revealed and hence, open up more of the active centers on the surface. As a consequence, the extent of oxidation increases. A group of researchers in China found that if evaporation of moisture from coal is decelerated, the spontaneous heating process may be suppressed (Peng et al., 1983).

Relatively recent work carried out in France on coal and air of differing humidity values is represented by a series of curves showing that the wider the difference between the humidity of air and moisture in coal, the greater the temperature rise (Figure 2.3).

### 2.2.7 Sulfur and Other Minerals

Pyrites are the sulfur-containing minerals commonly found in coal. They play a secondary role in degrading and self-heating coal. Pyrrhotite (FeS$_2$) occurring with pyrites (FeS)
Figure 2.2 The dependence of the degree of cooling, measured in the term of the extent of the area cooled, on the inherent moisture content of different coal samples (after Banerjee, 1968).

oxidizes in moist conditions. The heat of oxidation raises the initial temperature and thus increases coal oxidation, partly because the mineral swells and causes micro-fractures in the coal mass, and thereby enhances oxygen diffusion (Li, and Parr, 1926; Winmill, 1916). This phenomenon would be more noticeable in coal with a high content of inorganic sulfur because organic sulfur hardly undergoes oxidation (Lukaszewski, 1969).
Figure 2.3  The trend in the temperature rise of coals with fixed humidities, undergoing spontaneous heating (after PD-NCB Consultants Ltd., 1978).
Other minerals present in coal can change the rate of oxidation in the early stage to some extent. Alkalis may promote or accelerate, whereas borates, calcium chloride and some wetting agents may retard the pace. Most of these minerals are present only in minute fractions in coal beds (PD-NCB Consultants Ltd., 1978).

2.2.8 Physical Properties

Quite a few physical properties such as porosity, hardness, thermal conductivity and specific heat, can govern the rate of oxidation of coal. Oxidation does not take place entirely on the surface. Evidently, porosity plays a role in limiting the extent of oxidation. The more porous a coal, the greater is the area accessible for oxidation. Moisture content of coal is usually considered as a measure of porosity. Porosity notably varies, even in coals of the same rank. Its value lies between 3% and 20% (King, and Wilkins, 1943).

Hardness, measured in terms of friability and grindability taken together, determines the ease with which coal can be disintegrated into smaller and more oxidizable products.

Specific heat and thermal conductivity are the thermal characteristics of coal. Specific heat, a measure of the heat capacity of coal, will estimate the degree of temperature rise for a given amount of heat intake or generated within the coal mass. Its value is about 837.36 J/kg °C, and it does not vary significantly from one rank coal to another (PD-NCB Consultants Ltd., 1978). On the other hand, thermal conductivity is a measure of the rate of transfer of heat over the unit area for unit temperature gradient, and its value is relatively low for coal. For bituminous coal in ambient temperature, it is around 0.2931J/ sec m °C (Krevelen, 1961).

2.2.9 Geologic and Mining Factors

The spontaneous combustion characteristics are generally studied on the basis of laboratory tests. They hold good for virgin coal beds. However, disturbances of a coal bed with the intrusion of complex mining strategies, sometimes lead to unexpected self-heating incidents. These may only occur after the excavation is started, as the different mining
factors begin to interact with the inherent characteristics of a coal. It is virtually impossible to explore the geologic conditions of a coal bed adequately for the purpose of identifying their impacts of various mine design alternatives on spontaneous combustion. The situations are to be dealt with as encountered during the course of mining. Nevertheless, past experience on spontaneous combustion and possible control measures provide valuable information in selecting appropriate control measures. Therefore, as they are discussed below, it is important to know the impact of each factor on self-heating.

2.2.9.1 Geologic Factors

As observed and experienced during mining different coal seams, several major and minor geologic factors affect the process of spontaneous combustion. Discussion on all those factors are not within the scope of this dissertation. However, the factors which have direct impact on spontaneous combustion are discussed below. Also, no attempt has been made to present these factors in any order of importance, because it is found that the priority in their importance changes from one coal seam to another, even within the same seam and in the same mine.

**Seam Thickness**

There are coal beds which cannot be mined in a single lift because bed thickness is greater than feasible mining height. For those beds, coal left in the mined-out areas is vulnerable to spontaneous combustion.

Moreover, certain bands of coal more liable to spontaneous combustion may be found to occur within a thick seam. The thicker the seam, the more multi-lift operations become necessary. Such a seam may require that the coal bands of lower susceptibility to self-heating be left within the gob area. As a result, better quality coal is treated as waste coal (PD-NCB Consultants Ltd., 1978).
Seam Gradient

In the mined-out areas of inclined seams, air or gas movement may take place due to the buoyancy effect created by the difference in densities of methane, carbon dioxide or nitrogen, and the effect of temperature. As a result, leakage in the gob areas may enhance oxidation leading to self-heating. The higher gradient, there may be a greater the effect of buoyancy. The rate at which heating develops, particularly in the later stages, is sometimes greater with higher gradients because of the buoyancy effect. This dictates the rapidity with which control measures against self-heating need to be applied (PD-NCB Consultants Ltd., 1978).

Caving Characteristics

In the longwall panels where coal is left in mined-out areas, the caving characteristics of the immediate roof are important. On the other hand, in the mines where pillars are left to provide long-standing support to the roof, as in the cases of some room and pillar mines, the caving characteristics are of little significance. However, any extent of crushing of the pillars opens up the fracture surfaces susceptible to spontaneous combustion.

The smaller the size of the caved material, the greater the volume of the gob it can fill. As a result, air leakage will be minimized. Weak and friable strata above the extracted section is favorable for closing up the gob.

Where the immediate roof is not friable, the caving characteristics may be improved by orienting the longwall face along the natural cleavage planes. When a strong "blocky" roof caves, it may lead to higher risk of self-heating (PD-NCB Consultants Ltd., 1978).

Geological Disturbances

The presence of geological disturbances in the coal seam may lead to self-heating. Air leaking through the joint planes and fissures may reach a critical area within the gob or the seam. When a fault slides, coal may be ground increasing the risk of spontaneous
combustion. The rate of advance may fall below the safe minimum limit for avoiding the possibility of heating because of bad roof conditions created by faults. A fault located in an undesirable location, from the stand point of the mine design, may create a zone prone to self-heating in the gob or outside the working horizon, and may add to the risk of spontaneous combustion (PD-NCB Consultants Ltd., 1978).

Coal Outbursts

If not properly taken care of, the incidents of coal outburst often lead to spontaneous combustion because of finely powdered coal formed in the process. Coal outbursts are most likely to occur in the harder formations rather than in the softer and lower rank coals (PD-NCB Consultants Ltd., 1978).

Coal Friability

Friable coal exposes a greater surface area to oxidation, increasing the liability to spontaneous combustion and heat (of oxidation) per unit area. As a consequence, the rise in temperature will be high leading to increased rate of oxidation and finally, open flame may break out (PD-NCB Consultants Ltd., 1978).

Depth of Cover

Increase in depth of a coal seam may cause a greater quantity of methane emission, higher natural strata temperature and hence, a higher base temperature of the seam. Larger ventilating pressure is required to provide sufficient airflow risking greater leakage. Under increased depth of cover, the crushing of coal pillars is a more likely occurrence, making the coal susceptible to self-heating (PD-NCB Consultants Ltd., 1978).
Geothermal Gradient

Where geothermal gradients are high, the temperature in the workings is more as compared to the places where the gradient is low, causing greater base temperature. In such case, a small rise in the temperature due to oxidation of coal may lead to critical temperature conditions (PD-NCB Consultants Ltd., 1978).

2.2.9.2 Mining Factors

As mentioned earlier in this section, mining factors may alter the self-heating characteristics of coal beyond any level of prediction. Like geologic factors, a broad range of mining factors may influence the self-heating process. However, unlike geologic factors or coal characteristics, mining factors can be adjusted according to spontaneous combustion control strategies. Therefore, the knowledge about the impact of mining factors on spontaneous combustion is crucial. Some of the important mining factors are discussed in the following sections.

Mining Method

The airflow through the gob area is a hazard. In an advancing system of mining, the ventilation pressure difference between intake and return entries of the panel induces air to leak through the gob, increasing the risk of spontaneous combustion. To minimize air leakage into the gob, a retreat system of mining is effective. However, a bleeder entry system used for diluting and displacing methane from the gob may nullify the benefits of the retreat system. Apart from longwall mining, proper consideration should be given to the mining methods, such as thick seam mining, horizon mining, and stope caving, in order to avoid spontaneous combustion in the course of mining (PD-NCB Consultants Ltd., 1978).
Rate of Advance

Air leaks into the gob area adjacent to a working face either due to the action of bleeders or ventilation pressure across the face. In some locations of this area, airflow rate may be critical for rapid self-heating of coal. In practice, when a working face is operating normally, these locations are passed through at a rate equal to the rate of advance of the face. If the face advance rate slows down for some unavoidable reason, self-heating may turn into a fire (PD-NCB Consultants Ltd., 1978).

Pillar Size

Pillars should be sized so that they are strong enough to resist crushing. A crushed pillar, even partially, enhances its liability to spontaneous combustion. Pillar size can play a significant role in controlling an active heating, particularly when a relatively large area has to be sealed off. If the preventive measures using pillars within an affected area of a district fail to confine heating, the complete district has to be isolated from the mine, incurring a large loss of minable coal (PD-NCB Consultants Ltd., 1978).

Sloughing

Sloughing develops on almost any coal surface. It promotes air to leak behind the outer coal surfaces. If not prevented in time, it can potentially lead to spontaneous combustion. It is also difficult to detect because of its inaccessibility. There is normally a gradation of sloughing from the pillar edge. The degree of sloughing depends upon the depth of cover, the coal strength, the number of planes of cleavage and their orientation relative to pillar edges, the pillar size, and the effects of mining (PD-NCB Consultants Ltd., 1978).

Roof Conditions

A weak roof increases the risk of spontaneous combustion, both at the working face and the entries. Roof falls create cavities that are to be supported and often filled with timber.
These sites are vulnerable to local heatings. It is preferable to fill roof cavities completely with a gypsum based material.

Roof falls on or near a working face may deflect ventilating air into the gob areas and this may be the immediate cause of a heating, especially near the intake end of the face. Similar situations may arise due to roof falls in the airways. Air may be channeled into the breaks in the roof and sides to a greater extent than before and subsequently, active heating may occur (PD-NCB Consultants Ltd., 1978).

Crushing

In general, pillars, rib edges, and coal left out in the gob undergo crushing to a significant extent. Where a pillar is subject to crush, air leaks through the cracks into the solid coal to affect an area, which is otherwise inaccessible. As a result of unmined roof coal and accidental loss of coal, loose coal is present in the gob areas. Such coal may be crushed by the convergence of the roof or heaving of the floor. As a consequence, coal is ground to smaller size with greater surface area prone to self-heating (PD-NCB Consultants Ltd., 1978).

Leakage

Leakage of air through and over coal surfaces plays a very significant role in the development of self-heating to a stage of active heating. Where air leaks through fissures and crevices in solid coal, shallow seated heating may occur. This situation arises in leakage paths at air crossings, rib sides, in and around regulators and doors, and other similar locations under high ventilation pressure. Air also leaks through or around the seals and/or an unconsolidated pack, in and around the gob areas for the advancing longwall, or through inadequately sealed bleeder systems, giving rise to deep seated heating.
Multi-Seam Working

Spontaneous combustion can take place in the first or subsequent seams above or below the seam being excavated using multi-seam mining operation. Air crossings, regulator sites, stoppings, and any such point of high ventilating pressure differential, are vulnerable to self-heating due to the added stress created by another working area above or below the currently worked seam and old workings (PD-NCB Consultants Ltd., 1978).

Coal Losses

The cause of many gob fires is remnant coal in the mined-out area. Hardly any form of mining can prevent coal losses in a waste area. In fact, a significant amount of coal is lost in most mining systems. The left-over coal in the gob is most likely to be crushed and finely divided leading to heat build-up in the presence of critical flow (PD-NCB Consultants Ltd., 1978).

Worked-out Areas

Spontaneous combustion takes place mostly in the worked-out areas. In these areas, roof falls and/or floor lift deteriorate rib conditions and crush coal to smaller pieces increasing the risk of self-heating. Airflow in those areas often reaches a critical level where oxygen supply is adequate, but the cooling effect is not. A hazard can also exist in the sealed-off gob areas due to leakage of air through or around stoppings. Leakage is most likely where the ventilating pressure difference across the stoppings is high, and least likely where the pressure differences across the stoppings are balanced systematically. Also, where the volume of such area is large, barometric changes can force inflow and outflow of air from the area creating self-heating (PD-NCB Consultants Ltd., 1978).
Machines

Machine heat is usually liberated in the ventilating air stream. Moreover, diesel equipment also adds airborne pollutants. To deal with those heat and gaseous emissions, additional air may have to be supplied. For a given layout of airways, the resulting higher ventilating pressure increase the risk of air leakage (McPherson).

Stowing

Stowing is an effective method of sealing mined-out areas to prevent spontaneous combustion. However, a significant danger is associated with this operation if it is not carried out properly (PD-NCB Consultants Ltd., 1978). When the stowed material contains more than the desired amount of water, after the material settles, the potential leakage paths in the material or pockets of water give rise to a high localized moisture content and may lead to spontaneous heating.

Methane Drainage

Methane drainage can create a flow of air into a fractured coal seam or mined-out area under high suction pressure. This situation may promote self-heating. The hazard is more likely where the drained mixture contains less than 40% of methane. This percentage is considered an indication of airflow through the zones where spontaneous combustion may occur. Furthermore, changes in barometric pressure have a significant impact on self-heating of coal in the confined areas of the gob or voids behind stoppings. Under this condition, breathing takes place both in and out of the waste area with a risk of self-heating in the neighborhood of pack sites or stoppings (PD-NCB Consultants Ltd., 1978).

Ventilating Pressure

The pressure of ventilation can actively influence a self-heating process. With an increased rate of mining, higher quantities of methane and airborne dust are generated, which require
greater airflow in the working areas. As mining goes deeper, more air may be needed to reduce the ambient temperature at the working faces and in the return airways. The greater quantities of air can only be delivered at a higher ventilation pressure with an increased risk of spontaneous combustion.

Changes in Humidity

As mentioned earlier, when coal absorbs moisture, it heats up due to the release of the latent heat of condensation and chemisorption effects. On the other hand, when moisture evaporates out of the coal, the coal cools down. Both of the effects result from an imbalance between the moisture contents of coal and air (Guney et al., 1969; Scott, 1956).

In a complex mining environment, the balance between changing humidity in the ventilating air and moisture content of coal is difficult. Evidently, changes in the humidity in the mining condition play a significant role in self-heating of coal due to absorption, and cooling the coal during evaporation of moisture (PD-NCB Consultants Ltd., 1978).

2.3 Tests for Susceptibility of Coal to Spontaneous Heating

Any freshly exposed coal surface oxidizes and heat evolves in the process. When the heat of oxidation is more than the heat dissipated from the coal mass, self-heating takes place and finally, leading to ignition, in some cases. The rate of oxidation varies considerably and roughly depends upon the rank of the coal. In addition, several other factors affect the tendency of coal to spontaneous combustion. As a consequence, many apparently similar coals differ in their liability to spontaneous combustion.

A gob-fire can result from any kind of coal as long as it oxidizes, irrespective of its degree of oxidation. Some coals are inherently more liable to oxidation than others. However, the rate of oxidation alone is not sufficient for determining whether a gob-fire will occur or not. Several other factors are involved in the process. The tests for susceptibility must be considered as a part of an overall risk assessment, which must include all other possible
conditions, particularly mining conditions. In reality, mining parameters determine the probability of spontaneous combustion to occur. Before starting a new mine in a new seam, knowledge of the relative oxidation potential of different coals is valuable, especially in selecting mining methods, or in determining whether one part of the seam is likely to be more susceptible than any other part of the same seam. For these reasons, a number of laboratory methods have been suggested for testing the susceptibility of coal. Most of these methods are reported in national and international literature, with critical comments and recommendations for future modifications.

2.3.1 Static Isothermal Method

This is one of the oldest and yet most widely used methods, even today, for testing the susceptibility of coal to spontaneous combustion. The laboratory set-up for this experiment is using a series of bottles (usually 6), each fitted with an airtight stopper and tap. Each bottle contains
- 5 g of glass wool,
- 1 ml of distilled water, and
- 10 g of freshly ground coal.

All the bottles are placed in a thermostat at 30°C. A bottle is then removed at intervals, from 3 to 96 hours, and the gas in the bottle is analyzed for estimating the oxygen absorbed per gram of coal. According to the published experimental data, absorption is rapid in the early stage and gradually approaches zero. From the time-absorption curves for 40 British-coals, it was observed that coals not liable to spontaneous combustion absorb less than 200 ml of oxygen per 100 g of coal during 96 hours at 30°C (designated as "A96"), and those liable to spontaneous combustion absorb more than 300 ml in the same time interval (Graham, 1914, 1916; Winmill, 1913). More recent work concludes that the oxidation rate after 100 hours at 40°C was an appropriate index (Munzner, and Peters, 1969). The effect of coal particle size, temperature, and oxygen content of the oxidizing atmosphere maintained during the experiment can also be studied in this method for characterizing the spontaneous combustion tendency of coals. Over 50 coals were examined by the National Coal Board (NCB) using this method, covering almost all types of coal in the United Kingdom (Chamberlain, and Hali, 1973). The results of statistical
analysis showed no correlation of "A96" with the history of actual heatings in mines, but a highly significant correlation with rank. Although rank is an important factor in determining the level of propensity to oxidation, it alone is not sufficient to forecast liability for spontaneous combustion. The parameter "A96" appears to be a good guide to susceptibility of coal itself to spontaneous combustion in laboratory controlled conditions. On the practical side, it is now recommended that isothermal tests should be carried out at 60°C, presumably to minimize the hindering effect of smaller pore size on the rate of oxygen diffusion.

2.3.2 Adiabatic Methods

In the adiabatic method, the oxidizing coal sample is enclosed in an insulated calorimeter and hence, follows the changing temperature of the sample. This method of testing assumes actual conditions closely. The major disadvantage of this method is that it may take several weeks or even months to complete an experiment because of low starting temperature, which is normally the ambient temperature.

To speed up the process, the experiments may be started at 100°C so that an experiment, producing a temperature-time curve, could be completed in 10 to 20 hours. The main drawback of this work is that by starting the experiment well above the ambient temperature, the critical temperature range from the point of view of the initiation of spontaneous heating, between ambient and 100°F where the reactions are different from normal chemical oxidation, is not investigated (PD-NCB Consultants Ltd., 1978).

2.3.3 Paced Adiabatic Non- Isothermal Criterion

In order to shorten the time required to complete the adiabatic test, a new method, paced adiabatic non-isothermal criterion, has been introduced by the NCB. In this method a stream of air or oxygen, nitrogen, etc., is passed through a tube containing a coal sample placed in a reaction chamber. As a result, temperature is raised steadily, usually at the rate of 33°C per hour. The composition of exit gases is analyzed continuously using the techniques of chromatography. Comparing the results of adiabatic tests and paced
adiabatic non-isothermal method, no fundamental differences in the conclusions have been found in the liability to spontaneous combustion and temperature sequence pattern in gases which are formed at different phases of oxidation (Chamberlain et al., 1970).

A full range of British coals from anthracite to high volatile bituminous has been tested in this apparatus over a temperature range from $60^\circ$F ($15.5^\circ$C) to $400^\circ$F ($204.5^\circ$C). At lower temperatures there was a rather slow increase in oxygen absorption, say up to $160^\circ$F ($71^\circ$C), but as the temperature rose so did the reaction rate until it became extremely rapid and continued until an almost complete removal of oxygen from the air stream was achieved. As shown in Figure 2.4, oxygen deficiency is plotted against coal temperature between $120^\circ$F ($49^\circ$C) and $300^\circ$F ($149^\circ$C). The oxygen deficiency is the difference in the normal concentration of oxygen (i.e. 20.95% by volume composition) in the air and that of the air after oxidizing the coal. The sample of the lowest rank is the most oxidizable and the sample of the highest rank (anthracite), the least oxidizable within this temperature range. The results can be categorized into at least three groups. The group covering the high volatile, medium to non-coking coals is most reactive showing a rapid increase at about $165^\circ$F ($74^\circ$C). These types of coal gave oxygen deficiencies of 1% before $200^\circ$F ($93^\circ$C), and after about $210^\circ$F ($99^\circ$C), the oxygen deficiency increased by about 1% for each $13.5^\circ$F ($7.5^\circ$C). The high volatile, strongly coking coals (gas coals) show a similar rate of reaction although commencing at a higher temperature in the vicinity of $250^\circ$F ($121^\circ$C). The least reactive samples, anthracite to medium volatile coals, did not attain the peak reactivity until $285^\circ$F ($141^\circ$C) to $300^\circ$F ($149^\circ$C); at lower temperatures, their oxidation rates varied, sometimes fluctuated and were relatively slow, up to $250^\circ$F ($121^\circ$C). Oxygen deficiencies of 1% were not observed until at least $275^\circ$F ($135^\circ$C). Thus, as observed in other methods, there was a distinct relationship between coal rank and its susceptibility to spontaneous combustion, although a number of anomalies show that the rank is not the sole factor controlling oxidation (PD-NCB Consultants Ltd., 1978).
Figure 2.4 Oxidation of coals of different ranks in dry air and at different temperature (after PD-NCB Consultants Ltd., 1978).
2.3.4 Crossing Point Temperature

In an oxidizing environment, a coal sample (about 20 g) of certain specifications is heated in a glycerin bath at a preset rate of temperature rise (about 0.5 °C/min) with hot and humid air at the rate of 80 cc/min (Bagchi, 1965). After a duration of time, a point is reached at which the coal bed temperature curve and the furnace temperature curve cross over. This temperature is called "crossing point temperature." The liability of a coal to spontaneous combustion is considered to be associated with this temperature. Crossing point temperature would be lower for coals highly susceptible to spontaneous heating and would be higher for less susceptible coals.

A group of scientists in India found that crossing point temperature values vary with volatile matter, oxygen and moisture contents of coal (Nandy et al., 1972). They observed that the crossing point temperature normally decreases with the increase in each of these compositions of coal. However, beyond 35% volatile matter, 9% oxygen, or 4% to 6% moisture content, the crossing point temperature does not change significantly (Figures 2.5, 2.6, and 2.7). In fact, above 4% to 6% moisture content, the crossing point temperature values show a rising trend.

![Figure 2.5 Crossing point temperature attained at different contents of volatile matter of coals (Nandy et al., 1972).](image-url)
Figure 2.6 Crossing point temperature attained at different oxygen contents of coals (Nandy et al., 1972).

Figure 2.7 Crossing point temperature attained at different moisture contents of coals (Nandy et al., 1972).
On the basis of a study conducted on a number of coals mined in the U.K., a distinct relationship between rank and ignition temperature has been noticed (Sebastian and Mayers, 1937). However, it is not sufficient to draw any conclusion on the relationship between the crossing point temperature and spontaneous combustion, except that low values were more often observed for the coals liable to spontaneous combustion.

The crossing point temperature of a coal can be determined easily, not unduly subject to experimental errors and the variable can be readily controlled. The crossing point temperature method is also useful in testing the spontaneous heating tendency of coal refuses, such as washery rejects, boiler ash, even stowed materials with 90% incombustibles (Nandy et al., 1965). It undoubtedly represents a danger point in the progress of oxidation. Whether coal will reach the danger point or not, depends on other factors.

The value of crossing point temperature for a coal depends on the design of the apparatus and experimental parameters. The main drawback of this method is that the crossing point temperature values for coals with a high moisture content can be anomalous. Though the two coals, shown in Figure 2.8, indicate identical crossing point temperature, 139°C, their propensities to spontaneous combustion are different. The sample that generates a larger amount of heat at the crossing point temperature (i.e. with steeper slope) clearly has higher susceptibility (Banerjee, 1972). Therefore, the rate of temperature rise of the coal at the crossing point also has to be considered along with the values of crossing point temperature.

### 2.3.5 Ignition Temperature

To eliminate the effect of high moisture content in determining the crossing point temperature, oxygen was allowed to pass through a coal bed in a furnace till the coal ignited (Bagchi, 1973). It was observed the ignition temperature is the minimum temperature beyond which the coal temperature rises almost vertically (Figure 2.9). The higher the susceptibility of a coal to spontaneous combustion, the lower the time required to reach ignition point after attaining the crossing point temperature. It was proposed that
the time lag between crossing and ignition point temperatures is more reliable than the crossing point temperature alone.

The limitation of this method is that the transition to the ignition point is often not sharp for the poorly or even moderately susceptible coals. Hence, it becomes difficult to pinpoint the minimum temperature from which coal bed temperature starts rising rapidly and reaching ignition point. As a result, errors creep into the identified value of ignition
Figure 2.9 Crossing point temperature versus ignition point temperature for an Indian coal (after Bagchi, 1973).

temperature and thus, in distinguishing spontaneous heating susceptibility of different coals (Banerjee, 1985).
2.3.6 DTA Technique

In the differential thermal analytical (DTA) technique, a small specimen of coal is heated at a constant rate, and the temperature difference (\(\Delta T\)) between it and an identical heated inert reference material is recorded continuously as a function of the temperature (T) prevailing in the inert medium. The resultant thermogram, a plot of \(\Delta T\) versus T, depicts the intensities of physical or chemical changes of the coal sample at any particular temperature.

In a set of experiments carried out up to around 300\(^{\circ}\)C, three phases of transitions were observed in the DTA thermogram (Figure 2.10). In the initial phase of heating, phase I, the endothermic reaction mainly results from the release of moisture from coal. This is found to be followed by phase II of exothermic reaction which leads to reaction of higher exothermicity in phase III. The rise in heat evolution rate in phase II is observed to be lower for coals with lower susceptibility to spontaneous combustion. In such cases, phase II continues over a considerable range of temperature, delaying the initiation of phase III. However, once initiated, the exothermicity in phase III for the poorly susceptible coals may be as high as that of highly susceptible ones. Thus the criteria set for categorizing coals are the following:

i) the slope steepness of the thermograms in phase II, and

ii) the initiation temperature for phase III.

The limitations of the DTA technique make it difficult to obtain repeatable results. The peak sharpness may change with a change of the sample-holder, the sample cell or even if the furnace is replaced. Therefore, all experiments for comparing the propensity of coals to self-heating are to be conducted not only under similar experimental conditions but also using the same apparatus (Banerjee, 1985).

2.3.7 Infra-Red Method

In a work carried out by the NCB, fresh coal surface is exposed to an oxidizing environment, and examined under an infra-red microscope. At first, small white spots are observed in the study under the microscope, and then grow in size with time. It may be possible to assess the rate of oxidation of a coal by counting the number of spots formed
Figure 2.10 Thermograms of highly susceptible coals (of Kurasia and Bisrampur, India) and a poorly susceptible coal (of Jharia, India) (after Banerjee and Chakravorty, 1967).

or the area of white patches after a given time (PD-NCB Consultants Ltd., 1978). The advantage of this method is that no grinding or preparation or heat treatment of the coal or elaborated laboratory setup is required. Therefore, it is a rapid, reliable, and realistic
test for spontaneous combustion that need not have to be carried out under a controlled laboratory environment.

2.3.8 Chemical Methods

Most of the chemical methods are simple to conduct. It was suggested that the level of bromine absorption by coal could be used to determine in a few minutes, the liability of the coal to spontaneous combustion. It was observed that as compared to an unexposed coal, a coal exposed to air for a few hours at 130°C (265°F) absorbs much less bromine (Vaseiovskey and Orleanskaya, 1953). A similar study concludes that the level of iodine absorption instead of bromine was a measure of propensity to spontaneous combustion (Dennstedt and Bunz, R., 1908).

In other chemical methods practiced in Russia and Poland, oxidizing agents such as sodium nitrate (NaNO₂) and hydrogen peroxide (H₂O₂) are used. In one method, coal is mixed with NaNO₂ in a fixed proportion (usually 2:1) and is heated on a copper block at a temperature rise rate of 5°C per minute (Orleanskaya). The temperature at which the above mixture explodes is called "ignition temperature." In a further study, it was observed that the ignition temperature is lowered on treating coal with H₂O₂. The lowering of ignition temperature on treatment with H₂O₂ is more effective in estimating the relative susceptibility than the absolute ignition temperature. The lower ignition temperature would indicate the higher susceptibility.

In Poland, H₂O₂ alone has been used to compare the spontaneous combustion liability. A certain amount of coal (3g) is mixed with H₂O₂ (20%) and kept in a dewer flask and agitated with a magnetic stirrer (Maciejasz, 1956). The mixture is allowed to react at an elevated temperature until the maximum temperature can be reached. Also, the time required to attain 80°C can be determined. This may vary from 3 to 30 minutes, depending upon the type of coal, and categorization is accomplished from the values of those two criteria.

The major limitation of this method is that the heat is not only dependent on the oxidative characteristics of the coal but also on the heat produced due to H₂O₂ decomposition; hence, masking the results used for coal categorization. For that reason, this method is
modified. In a revised method, the quantity of carbon dioxide (CO₂) evolved during oxidation was measured along with the heat generation data (Banerjee, 1985).

2.4 Detection and Monitoring

The early detection of spontaneous heating is important to any mine. This may save the mine from considerable damage, and loss of production and equipment in some cases. When an incidence of spontaneous combustion reaches the stage of fire, it often becomes extremely difficult to control. No general criteria for determining the susceptibility of a coal seam to spontaneous heating has been found to have universal application. Therefore, it is imperative that a monitoring system be installed to follow the development of heating. In the past two decades, considerable advancement has been made in the design and development of systems for the early detection and monitoring of spontaneous heating. New techniques, especially gas chromatography and infra-red analyzers, have raised the level of sensitivity and accuracy of detection and monitoring systems compared to the traditional methods evolved during the past 100 years. This chapter outlines various methods of early detection and monitoring.

2.4.1 Methods without Using Instruments

Following the progress of heating, haze, sweating of strata, smell, sound, and smoke that develops gradually, fire may finally break out. Some of these indicators of spontaneous combustion may not be observed. For example, haze forms only when the temperature and humidity of the return air from the location of a heating zone is higher than those of the fresh air and has met a specific condition. Similarly, sweating of strata near a heating zone also depends on the temperature of the strata. Therefore, it is important to know about the occurrence of the indicators mentioned above. Under a certain circumstance, one of them may be useful in identifying a case of spontaneous combustion.
Haze and Sweating

The internal moisture is released from coal as vapor in its early stage of spontaneous heating. When water vapor comes in contact with the cooler ventilating air, haze is formed as the vapor condenses. Haze causes poor visibility in the mining environment. When moisture is liberated from the coal mass profusely, droplets start to form in the presence of cool ventilating air (Fusamura, 1967). Sweating from water droplets is usually seen on the roofs, walls and supports of the mine.

Smell

Smell is a better indicator than haze and sweating. However, only experienced mine workers can recognize with confidence the characteristic smell, called "gob stink," at an early stage of heating (Coward, 1957). The chemical composition of gob stink has not yet been identified precisely. Distillation of coal yields saturated hydrocarbons and higher hydrocarbons which carry the smell (Graham, 1929). Its recognition is purely subjective in nature. The modern techniques of detection can be more effective than smell, which does not become noticeable until coal reaches about 250°F (121°C), and is only obvious at about 300°F (149°C). However, the experienced human observation should not be discounted, particularly for the cases of shallow seated rib-side fires.

Overheating of mining equipment or an active fire in an area may be detected by stench capsules (Curzon and Eisner, 1954). In this method, a stench capsule, containing highly odorous liquid of a low boiling point and high vapor pressure (usually mercaptans, ionones, etc.), is placed at the desired point. It is fitted with necessary arrangements that would cause the capsule to burst at a certain temperature, discharging its vaporized contents into the air stream.

The stench capsules may be effective when they are placed in appropriate locations, usually in the intake side of the mine. The human nose is sensitive enough to respond to 0.001 ppm of odorant in the air. However, the warning smell would propagate only at the speed of ventilating air, which may be extremely slow in an isolated area.
When air leaks into an area prone to self-heating, injection of methyl bromide in the air into the vicinity of the area was suggested by some scientists in 1941 (PD-NCB Consultants Ltd., 1978). The chemical would undergo a marked change in odor when in contact with the heated area. The smell in the return air would then give warning of a heating.

**Sound**

At times, typical creaking sound (due to crack formation in strata or from collapse in them) may be heard behind stopping or barriers, which could be indicative of advancement of fire. Even the increased activity and chirping of roaches and crickets (possibly caused by increased temperature) inside the timber supports left out in the gob may be considered a warning of a progressive fire (Banerjee, 1985).

**Smoke**

When a "hot spot" is located near the roadway surface, its presence may first be detected through a rise in temperature of the strata surface (Howell et al., 1991). Local hot spots are also often detected by emission of smoke. Smoke is produced when fire begins in coal.

**Limitations**

The above physical symptoms, as may be noticed by experienced miners, are significant warnings. However, those indications, except smoke, cannot be relied upon. The degree of heating can neither be assessed, nor be detected in the early stages, at least not below 120°C (Fauconnier, 1981). To identify heating or fire behind a sealed off area, it is necessary to carry out certain quantitative measurement as described in the following sections.
2.4.2 Methods Using Portable Instruments

As is evident in the discussion on various methods of identifying spontaneous combustion without using instruments, the success of those methods depend on the experience to a great extent. In some cases, human perception is more informative than any accurate instrumental measurements. However, human access and presence are always limited in any mine even if a good and healthy environment is maintained underground. The use of portable instruments at the time of inspection can effectively raise the level of confidence. Some of the most widely used portable instruments are highlighted below.

Carbon Monoxide Detectors

Stain-tubes
Chemical stain-tubes are widely used portable detectors. They are relatively accurate in measuring carbon monoxide concentration, provided the appropriate range is chosen and guard tubes are used if there is a possibility of the presence of hydrogen sulfide. Stain-tubes are conveniently used to locate the emission of carbon monoxide from sealed-off areas around gobs (PD-NCB Consultants Ltd., 1978).

Hand-held Carbon Monoxide Meters
Various makes of hand-held carbon monoxide meters are available. They are based on the temperature rise of a physio-chemical cell such as the hopcalite cell or the polarographic cell. These instruments require frequent maintenance and recalibration (PD-NCB Consultants Ltd., 1978).

Temperature Survey

Well before a fire occurs due to spontaneous combustion, the local environment tends to show a rise in temperature. A temperature survey of the areas vulnerable to spontaneous heating, e.g. old workings in mines, depillared areas, crushed pillars with cracks and fissures, places where accumulation of coal is evident, or near gate roads in longwall panels, may help in the early detection of spontaneous heating (Banerjee, 1985).
In practice, two categories of temperature surveys are used - direct and indirect survey methods. Designs of instruments used for direct survey methods are based on the following principles:

- expansion of confined volume of materials, e.g. mercury-in-glass type thermometers, bi-metallic strips, etc.
- melting point of suitable materials, e.g. fire alarms operated by relays with fusible plugs (made of alloys/agents of desired melting point)
- thermo-electric effect, e.g. thermo-couple type sensors, and resistance change of the semi-conducting materials, e.g. thermistors type units (Eisner, 1953)

Appliances that can relay thermal response without wired connections are useful in detecting temperature rise indirectly.

**Infra-red Detectors**

Infra-red meters can detect a rise in temperature on a surface, over the ambient temperature. The infra-red thermometer is optical equipment. It receives the infra-red rays from any hot surface and converts them into an electrical signal. The electrical output is calibrated in terms of temperature. It is capable of measuring the temperature differential of a surface from a distance of about 100 ft with an accuracy of ±1°C. A detailed picture of temperature distribution on a surface can be taken. The equipment is provided with a telescopic sight which accurately locates the hot spots while carrying out the temperature survey. Once the hot spots are located by the scanner, variations in their temperature with the passage of time may be studied for monitoring the onset of heating in the mine (Chakravorty, and Feng, 1978; and Pursall, 1968).

Infra-red detectors are often affected by many stray effects, such as the heat generated by machines, or even by working men. As a result, false signals of heating may be detected. Furthermore, they cannot be used for detecting heating in the remote areas, such as a gob behind a working face. Although they are being used successfully for detecting hot spots on machinery, failed conveyor idlers and such, they are not yet suitable for early detection of spontaneous heating in the inaccessible areas of mines (PD-NCB Consultants Ltd., 1978). As technology improves and more underground experience is gained, their area of application will expand.
2.4.3 Continuous Monitoring

Both human judgment and measurement using portable instruments should be considered as the means of detecting self-heating on the spot. However, spontaneous combustion develops gradually under prevailing conditions. Several indicators can be identified at different stages of its development, such as carbon monoxide followed by hydrogen, ethylene, and other organic compounds (as shown in Figure 2.11). In order to take an appropriate step at the right time to prevent the development of spontaneous combustion into a catastrophic fire, it is important to monitor the potential locations continuously, especially the locations inaccessible to human inspection. Also, continuous monitoring is essential during the time when no one is present in the mine to watch for an ongoing self-heating process. Two of the different continuous monitoring systems are described below.

**Tube Bundle Method**

In this system, a series of plastic tubes are used to draw air continuously from underground locations susceptible to spontaneous heating and to analyze its carbon monoxide content at a surface station. This system is available in varying degrees of sophistication. Further developments are still taking place. Details of its design and accessory equipment are described in the reference, The Tube Bundle Technique for the Continuous Monitoring of Mine Airs, an NCB Handbook published in 1977.

The tube bundle system is simple in construction. All the controls and analyzing instruments associated with the system are installed on the surface where they can be conveniently serviced, and are not restricted by the requirement that they should be explosion proof or intrinsically safe. Furthermore, the system can operate even when the power supply underground is cut off in the wake of explosive environment, e.g. behind stoppings. Although the system was developed for continuous monitoring of carbon monoxide concentration, it can analyze mine air for other gases, e.g. oxygen, methane, hydrogen, ethylene, etc., with appropriate instrumentation.
Figure 2.11 Evolution of different gases in a dynamic oxidation test for spontaneous combustion at different temperature (PD-NCB Consultants, 1978).
A disadvantage of the tube bundle system is that the sample lines are long, resulting in delay between the occurrence of change in air composition at the sampling point and the subsequent indication on the read-out device.

**Thermistors**

Thermistors are temperature sensitive elements. They have been used in the gob to detect any temperature rise (McCrickard, 1952). However, they are rarely used in practice because it is difficult to place the thermistors in the right locations and very large numbers of them are required to cover the mine workings. Further development in the thermistor technology may increase their use.

**Manual Sampling versus Continuous Sampling**

The time needed to take samples from one portal to another is often hours. Continuous analysis of sample from the strategic points of a underground mine is invaluable for early detection of spontaneous heating as well as irregularities in the ventilation system, such as failure of an auxiliary ventilation fan or the malfunction of ventilation control doors. The need to send a team into the mine for sampling gas on weekends and holidays can be minimized with the installation of a continuous monitoring system.

**2.4.4 Conclusions**

Reliable systems are available for the detection and monitoring of self-heating. They range in complexity from human observations, through hand-held instruments and intermittent air sampling, to continuous monitoring. The selection of a system should depend on the likelihood of spontaneous combustion and the degree of risk involved. Maximum security is provided by a properly installed and maintained continuous monitoring system. Wherever the risk of spontaneous combustion prevails, a system should be adopted. However, the regular inspection of the workings should always be conducted as an integral part of a survey plan for early detection of spontaneous heating (PD-NCB Consultants Ltd., 1978).
III. PREVENTION AND CONTROL MEASURES FOR SPONTANEOUS COMBUSTION

Proper planning, both in the development and operating stages of mines, is essential for preventing and controlling occurrences of spontaneous combustion. The selection of mine layouts and mining methods is critical at the development stage. However, heatings may take place even after implementation of the best possible planning and operating procedures. At the operating stage, proper arrangements for detection and monitoring should be maintained so that preventive actions can be taken at an appropriate time.

3.1 Precautions during Mine Planning Stage

In order to minimize the risk of self-heating and implement preventive measures, they should be incorporated in the mine design and planning stage of the mine. Otherwise, control measures may become indispensable in the cases where spontaneous combustion has been detected in the later stage of mining. As described below, the experienced gained from other mines in excavating coal under similar geological settings may be valuable in framing the preventive measures.

3.1.1 Selection of Mining Method

In the mines that are susceptible to spontaneous combustion, a mining method that minimizes the probability of such incidents should be the foremost choice. For example, when mining spontaneous combustion-prone coals, methods should be adopted that

- minimize pillar crush
- require low ventilating pressures
- obviate the need for ventilating gob areas
- provide adequate pillars between working sections, and
- minimize the amount of remnant coal left in the gob.
However, in reality, the methods are selected on the basis of a balance between the objective of preventing spontaneous combustion versus the objectives of

- minimized capital investment
- maximized productivity, and
- compatibility with existing mine operations, etc.

It is essential to consider the potential consequences of spontaneous combustion. Though a method may have a high theoretical recovery rate, should spontaneous combustion take place and result in the loss of a section or sections, the actual percentage of extraction achieved could be much less than that obtained from a method of mining with lower but reliable recovery percentage (PD-NCB Consultants Ltd., 1978).

3.1.2 Strata Control

Sides of roadways are often found to be vulnerable to self-heating due to overburden stress and subsequent crush forming leakage paths, and fine particles of coal. Adequate support is necessary at the locations of high stress such as junctions, or at locations of high ventilation pressure differentials such as at overcasts, doors, and regulators sites. A mining layout or method of support that minimizes ground movement will also reduce the probability of spontaneous combustion. It is particularly important to support the roof adequately near the site of geological disturbances. In the cases where roadway enlargement is necessary, the work should be carried out in the direction opposing that of the ventilation airflow, especially if the roof, floor, or sides of airways are carbonaceous material. In the places where the ground is badly broken, pump packing is a major step forward. This system helps to minimize bed separation and provides better support by minimizing the roof convergence (PD-NCB Consultants Ltd., 1978).

3.1.3 Stability of Openings and Pillars

The load bearing capacity of pillars and ribs plays a crucial role in causing spontaneous combustion. The larger the pillars and the more stable the entries, the lower the risk of
spontaneous combustion. However, it may not be practical nor economical to design pillars that will eliminate any crush. Stable pillars must be constructed at strategic locations so that sections of the mine can be isolated effectively if necessary. In cases where relatively large entries are required for ventilation purposes, additional parallel entries of a smaller size should be considered (PD-NCB Consultants Ltd., 1978).

3.1.4 Ventilation Controls

The objective of minimizing the access of air to carbonaceous materials can only be achieved by attention to details in the planning stage and subsequently, in operating and salvage stages. A ventilation layout that minimizes pressure differences should be chosen. This normally requires the provision of a sufficient number of airways, each of adequate cross-section to carry the planned ventilation quantities. The number of doors and regulators should be minimized and sited in stone, wherever possible. Otherwise, sealing may be necessary. In the same token, the number of air crossings should also be minimized, particularly when they are constructed in proximity to the seam or gob. In such sites, surface coatings may be used or strata injection of sealants should be considered. Regulators should be designed in such a way that opening and closing of the associated doors have a minimum effect on the static pressure level within the district. Any form of sudden restrictions to airflow in the mine may cause self-heating and so should be avoided, if possible. The ventilation pressure distribution in a newly-planned district and any nearby workings close proximity requires examination. This is particularly important when pillars of coal are to be left between adjacent panels (PD-NCB Consultants Ltd., 1978).

Retreat mining should be used in the mines where risk of spontaneous combustion is high. Gob bleeders induce fresh airflow through the waste, and will inevitably contribute significantly to the spontaneous combustion risk. When possible, gob bleeders should be avoided. In a longwall panel, critical leakage flow zones inside the gob move forward with face progress. However, when the face movement slows or stops for any reason, a heating is more likely to develop. Under such circumstance, sealing the roadside will reduce leakage across the gob area. Also air leakage through the waste will be reduced in greater proportion than the airflow on the face for a given drop in the district ventilation pressure (PD-NCB Consultants Ltd., 1978).
Sealing Worked-out Areas

When a panel of coal has been worked out in a mine, it is generally advisable to seal off the area. Adequate stoppings to isolate the area from the other parts of the mine can be erected in sites that are either outside of the working seam, or situated within pillars of coal substantial enough not to crush.

Barriers or Stoppings

The type and nature of the barriers or stoppings depend on their applications. To prevent accidental access into workings, a construction of brick blocks may be sufficient. Where a stopping is required to be explosion proof, it must consist of sufficient bulk materials of adequate density. In cases where a leak-proof and explosion-proof stopping is required but there is no necessity for it to be fireproof, the most convenient method of construction is by the use of pumped plaster. If it is necessary for a stopping to be made fireproof, then it must be constructed from a sealant which is stable at high temperatures (Summers, and Lord, 1977). A selected number of stoppings should be equipped with a steel pipe (approximately 1 inches in diameter) to enable measurement of pressure and gas samples to be taken.

When it is necessary to seal off a whole mine section comprising of a number of panels, the danger of spontaneous combustion in the locality of the main stopping sites is greater than in the case of a single panel. When a section is sealed, the larger void behind the stoppings amplifies the effort of barometric changes. If these outer stoppings cannot be constructed from the working seam, then use of the following technique is suggested in two stages:

i.) The stoppings should be constructed in the normal manner, but sited in such a way that further light-weight stoppings can be constructed some distance outbye

ii.) After balancing the pressure differential between a pair of stoppings, the zone between such a pair may be filled by carbon dioxide, nitrogen and methane evolving naturally in the abandoned area, provided the zones are made large enough.
Any breathing around the inner seals will not be detrimental to an oxygen-rich atmosphere around the outer seals. The risk of heatings occurring around the outer seals does not exist as these are constructed as barriers to prevent unauthorized entry and are, therefore, not required to withstand any differential pressure except possibly during a large rise or fall of barometric pressure (PD-NCB Consultants Ltd., 1978).

3.1.5 Other Control Measures

Inhibitors

Chemical components such as borates and calcium chloride inhibit the oxidation of coal. These compounds can be sprayed either in solution or powder form into the gob, on the longwall panel start line, or onto the coal pillars. However, injection or spray of these compounds into the wastes and other locations where spontaneous combustion is likely to be active, is technically difficult. Moreover, borax powder is too expensive for general use (Lukaszewski, 1969). Calcium chloride produces highly corrosive conditions if proper precautions are not taken, and is, therefore, generally hard on electrical equipment, steel supports and machinery. It may also give rise to health problems, particularly dermatitis and ulcers (Report of the South Wales Coal Owners' Association, 1947).

Inspection

As described in sections 2.4.1 and 2.4.2, spontaneous heating, in some cases, can be detected by physical inspection. A regular inspection schedule must be formulated based on past experience and diligently pursued.

Monitoring

As mentioned in section 2.4.3, monitoring plays a significant role in providing indications of incipient heating and active fire. Comprehensive monitoring is desirable, and in many cases essential, in a mine prone to spontaneous combustion.
3.2 After Detecting Self-heating

Any measure to suppress active heating depends upon many factors such as carbon monoxide and combustible gas temperatures and concentrations, explosion risk, limited visibility due to smoke or haze, or high air temperatures due to direct heat emission. Attention must be focused on the rate of change of any of these factors. The availability of manpower and materials should be considered, because this may determine the duration of time required to carry out remedial measures. One heating incidence is rarely the same as any other heating incidence. However, combat experience is a valuable guide in any situation. The type of action is mainly governed by the circumstances. To be specific, the accessibility of the affected site and the vulnerability of the rest of the mine to the concerned heating site are critical. Whenever combat work is in progress, the rate of development of heating must be monitored closely. Generally up to six sample points may be located at strategic positions with one on the intake side as a reference. Moreover, the barometric pressure must be monitored carefully. Precautions should be taken against any rapid fall in barometric pressure and subsequent increase in emission of toxic or explosive gases from the gob.

Active heating can be suppressed by applying the methods which fall in the following five broad categories:

- digging out
- ventilation techniques
- burying the fire
- sealants
- flooding with water

3.2.1 Digging Out

Before undertaking the operation, it may be necessary to determine the location by drilling for hot material. When the location is identified, the roadway surface, 10m on either side of the site, must be thoroughly dampened with water and rock dusted. The site should then be excavated about 1 m upwind of the location. The newly exposed coal surface
should be dampened and cooled with a water spray. When the incandescent material is reached, great care must be taken to cool the periphery of the hot material first, and then progressively approaching the center to avoid the risk of formation of water gas. Water gas, a mixture of carbon monoxide and hydrogen, is both toxic and potentially explosive. The excavated hot materials may burst into flame. Therefore, an adequate supply of dry non-flammable dust must be readily available (PD-NCB Consultants Ltd., 1978).

3.2.2 Ventilation Techniques

The control of ventilation at the sites of active heating is the most frequently used technique. The specifics of the action taken depend on the situation. However, the objective is to minimize air leakage into the heating areas. The ventilation techniques include controlling ventilation pressure to restrict airflow, sealing off, and flooding with nitrogen. Techniques are described as follows:

**Pressure Control**

Leakage of air into a fire zone can be minimized by reducing the pressure differential through the zone. This can be implemented by reducing the pressure on the intake side or by raising the pressure on the return side. As a result, airflow through the zone decreases. Depending on situations, the method of implementation varies. The following example illustrates an application of pressure control in air-crossings.

Air leakage may take place through an air-crossing due to the high pressure differential between the crossing airways. If the conventional seals or injection of grout are ineffective, heating takes place due to air leakage. The pressure differential between the airways may be reduced or nullified completely by a fan (Figure 3.1(a)) or bypassing the air through an adequately-sized duct (Figure 3.1(b)), before intensively injecting grout.
Figure 3.1 A schematic depiction of methods of relieving or balancing pressure across an air-crossing (after PD-NCB Consultants Ltd., 1978).
Suppression by Gob Gases

In a bleederless ventilation system for a retreating panel, high concentration of gob gases may suppress any probable heating. If properly planned at an early stage of heating, this may be an effective measure. When gob gases contain mostly methane, they are lighter than air. By controlling airflow through the face and/or minimizing its scouring effect on the gob adjacent to the face, the body of gob gas may be brought close to the gob edge for a panel retreating to the dip. On the other hand, when the gases contain a high percentage of carbon dioxide, which is heavier than air, the same technique may be used for retreat workings to the rise. In layouts with gradients along the working face line, it is sometimes possible to induce the forces causing air movement to act against each other. Heat or gases lighter than air may create a buoyancy force which may counter the force of ventilation in a panel ventilated descentionally.

Gob Pressurization

In this method, the return end of the workings is filled with air by means of a suitably sited fan and duct line. As a result, the gases evolved due to spontaneous combustion will be held in the confines of the gob. This method is effective and can be implemented easily (PD-NCB Consultants Ltd., 1978).

Control of Heating within Sealed Areas

Heating may occur in the sealed-off areas after construction of the seal. The heating zone may prevail in the abandoned area or near one of the seals. Wherever feasible, especially for locations remote from the seals, the ventilation pressure differential across the sealed area should be balanced. The pressure balancing becomes an onerous task in an area having multiple entries as compared to an area having a limited number of entries. Also, difficulty is encountered in an abandoned area bounded by a gob or damaged pillars on one or more sides.
With an objective of equalizing the pressure within the sealed-off area, a combination of chambers may not be necessary, provided the site of a chamber is chosen carefully. The other factors being the same, a chamber should be erected at a site where conventional sealants may not be effective. Heating in an abandoned area is often sensitive to changes in air pressure distribution in the surrounding roadways. Experience shows that heatings which have been dormant for periods of months, and in a few instances for years, have been reactivated by relatively minor changes in the pressure around the heating zone (PD- NCB Consultants Ltd., 1978). Under this situation, a balance should be carried out using ambient air pressure existing underground. This enables a dynamic balance, self-adjusting to some degree, against ventilation changes. This also ensures a long life of a pressure chamber, independent of power supply failure or equipment breakdown. Such pressure chamber should be placed on the low pressure side of the district, if possible. Carbon monoxide is normally detected on the return side. An immediate control of the emission can be exercised from the return end.

Two categories of the most widely used pressure chamber are:

- static
- flow through

A static pressure chamber is normally setup in an underground roadway using two stoppings, usually one is explosion-proof, and the other may be a light-weight timber barricade with suitable treatment for minimizing air leakage through it (as shown in Figure 3.2). In all probability, the shorter the length of the chamber, the higher is the pressure requirement. The chamber pressure may be controlled by the mine ventilation system or by means of an auxiliary fan. A flow through balancing chamber is used when a normal ventilating current of air is to be maintained in an airway (as shown in Figure 3.3A and 3.3B).
Figure 3.2 A schematic depiction of a typical static balancing chamber for pressure differential across the chamber (after PD-NCB Consultants Ltd., 1979).
Ventilation pressure in \( \frac{\text{b} \text{l}}{\text{ft}^2} \)........... 0.04

Air quantity in \( \frac{\text{ft}^3}{\text{min}} \)...................... 9000

**Figure 3.3A** A schematic diagram of pressure distribution in a longwall mining district before installation of any pressure chamber (after PD-NCB Consultants Ltd., 1978).
Figure 3.3B A schematic diagram of pressure distribution in the longwall mining district after installation of a flow-through pressure chamber (after PD-NCB Consultants Ltd., 1978).
3.2.3 Burying the Fire

Leakage airflow into the gob area adjacent to the face line is often critical to self heating. When a heating is detected in that area, it is advisable to increase the rate of advance as much as practicable. This may reduce the access time of air into the heated materials by burying the materials in the waste (PD-NCB Consultants Ltd., 1978).

Access of air in a heating zone may be reduced by burying it under a heap of broken rock mass. Leakage through a roadside pack can be reduced by bringing the roof down in the airway with the help of localized shot firing, if necessary, removing only a portion of the debris and compacting the remainder over the area to be sealed (McPherson, 1993).

3.2.4 Sealants

Heating zones are often inaccessible and develop due to high ventilation pressure difference across leakage paths at stoppings, air-crossings, doors, regulators, roadside packs, and airway surfaces. Sealants can close the leakage flowpaths and thus reduce the risk of heating. Different types of sealants are available. Resins or gel-type sealants can give a very tight filling. Concrete and gypsum plasters can be sprayed quickly and effectively onto an airway and also can be used as fillings between stoppings. Slurries containing mill tailings or other waste materials have also been used as grouts or for injecting into heating prone areas. Any leakage path leading to a fire zone from a roadside should be sealed. It is particularly advantageous to seal on the inlet or high pressure side (McPherson, 1993).

3.2.5 Flooding with Water

Under suitable conditions, hot spots can be flooded and steeped under water to prevent the access of oxygen to the site. Generally, the following two methods may be practiced:

(i) slowly submerging the heated materials under water, and
(ii) using local gradients to hold the water in one place and to cover the hot spot.
The first method may be effective under a favorable gradient, especially for a working that is located entirely to the dip. It may be necessary to construct new dams or to convert existing seals into dams if the hot spots are located above the water level. However, heating may recur when water is removed (PD-NCB Consultants Ltd., 1978).

The second method does not have this disadvantage and provides an air-tight seal that is easily removable. However, it can only be applied when gradient is suitable for a hot spot at a low point in an airway.
IV. METHANE EMISSION AND CONTROL

4.0 Introduction

The objective of this research is to analyze and modify existing bleederless ventilation systems. Bleeders are used to draw the gob gas out of a panel without contaminating air at the face workings. When bleeders are removed, the gas-laden air from the gob is bound to come in contact and mix with the face air. However, the impact can be minimized by draining the gas out of the gob. Methane is the major gob gas. In general, the deeper the seam, the higher is its methane content. Therefore, the drainage of the gob gas does essentially mean the drainage of methane. In order to formulate a control strategy, it is important to know the methane emission pattern in the gob.

Coal contains methane gas within its pores and interstices both in the free and adsorbed form. With the fracturing and crushing of coal in mining, methane is liberated. A mixture of methane in air is explosive in the range of 5% to 15%. There are several sources of ignition in an active mine. Therefore, maintaining methane concentration below the explosive limit is crucial. To attain this objective, methane must be either drained or diluted. In mines with low emission, dilution is economical. On the other hand, in case of high emission, the gas has to be drained out of the mine. The rate of emission is governed by the following factors:

(i) the shape and size of the gas-emitting zones surrounding a mine working, which includes the number and thickness of seams and of gas-bearing strata in the zones
(ii) the gas contents of these seams and strata
(iii) the natural permeability of the strata and in particular, the dynamic variations in permeability caused by mining
(iv) the degree of gas emission from the gas-bearing beds in relation to place and time
(v) method of mining
(vi) operational conditions
(vii) mining sequences
(viii) the rate of coal extraction
(ix) degree of coal being ground during excavation
(x)  gob conditions
(xi) the variation in the atmospheric and ventilation pressure
(xii) degree of dip of the zone

4.1  Methane Emission Sources and Patterns

In room and pillar mines, gas is liberated from the pillar under extraction and the rib-sides. Exposed surfaces of the pillars may release gas rapidly as compared to prolonged gas emission from the ribs. Maximum gas is produced in the working face where coal is broken to pieces in the process of mining. In longwall mines, the gob is a significant source of methane due to emission from source beds in the roof and floor strata, in addition to the coal left in the gob (Noack, and Janas, 1984). The details of the parameters that control gob gas follow:

(i)  the upper and lower limits of the gas-emitting zone that are not fixed but depend on the original gas pressure and on the composition of strata
(ii) the pattern of residual gas pressure distribution in the roof that is influenced by the thickness of the worked seam
(iii) the adsorbed and free gas of the seams, as well as for the strata between the seams are considered.

Methane is also liberated into the ventilating air from the excavated coal during transfer from the mine to the surface.

In a gob area, methane emits from various sources. The major sources of gob methane are the following:

4.1.1  Coal left in the gob

Some amount of coal is always left in the roof and/or floor of an excavated area because that coal could not be mined economically. Under the increasing load of the caved materials, coal crushes to finer fragments, exposing greater surface area. As a consequence, much of the methane entrapped in the coal is liberated into the gob.
Figure 4.1 Methane emission pattern of roof and floor sources towards the gob and the working horizon (after McPherson, 1993).

4.1.2 Roof

The roof stores methane migrated from the seam under excavation or from superincumbent coal bed(s) on top of it (as shown in Figure 4.1). Any coal seams or carbonaceous bands within a range of some 200 m above the working horizon are liable to release methane that will migrate through the relaxed strata on the gob area (McPherson, 1993). Roof strata works as a reservoir consisting of layers of rock. In some cases, the rock layers, like carbonaceous matter, have the potential of forming methane. As the roof rock layer breaks off, methane stored at high pressure is released in the void of the excavated areas.
4.1.3 Floor

The floor strata also stores methane under similar conditions as those for the roof. However, due to the weight of the coal seam and overburden, scarcely any gas could release from the floor reservoir of gas. However, as soon as the loading of the seam and overburden is removed from the floor with the excavation of the seam, methane is liberated in the gob. Any coal seams or carbonaceous bands within a range of some 100 m below the working horizon are liable to release methane from the relaxed strata in the gob (McPherson, 1993).

4.2 Methane Layering

The concentration of methane released from strata near their exposed surfaces is often very high, in excess of 90% (McPherson, 1993). Moreover, methane is lighter than air and so experiences a buoyancy effect. As a result, concentrated gas tends to accumulate in the roof cavities and to layer along the roofs. Scientists of the Safety in Mines Research Establishment in England quantified an important parameter, called layering number (Bakke and Leach, 1962). Through a combination of analytical and experimental evaluations, they found that the characteristic behavior of the gas layer was proportional to the dimensionless group

\[
\frac{u}{\left( g \frac{\Delta \rho}{\rho} \frac{q}{w} \right)^{\frac{1}{3}}}
\]

where

- \( u \) = velocity of ventilating air stream [m/s]
- \( g \) = gravitational acceleration [m/s^2]
- \( \rho \) = relative density of air
- \( \Delta \rho \) = difference of relative densities of air and methane
- \( q \) = rate of gas emission [m^3/s]
- \( w \) = width of airway [m].
The layering number, $L$, is a fundamental parameter in characterizing the behavior of methane layers. The air velocity is the most sensitive parameter in Equ. 4.1 for the layering number. As a result, mixing characteristics and the length of the layer depends on air velocity. Although $u$ is the air velocity in contact with the layer, the mean value in the upper third of an air passage may be used. For non-rectangular air passages, $w$ may be taken as three-quarters of the roadway width.

Using the following values

$g = 9.81 \text{ m/s}^2$

$\rho = 1$

$\Delta \rho = 1 - 0.554 = 0.446$

the dimensionless number for methane layers in airways is found to be

$$L = \frac{u}{\left(9.81 \times 0.446 \times \left(\frac{q}{w}\right) \right)^{\frac{1}{3}}}$$

$$L = \frac{u}{1.64 \left(\frac{w}{q}\right)^{\frac{1}{3}}} \quad (4.1)$$

For any given gas emission rate and roadway width, the layering number is proportional to air velocity ($u$) on a level roadway. As shown in Figure 4.2, at low velocity, the layer is not affected significantly by small additional increases in velocity. Mixing is caused primarily by turbulent eddies. With the increase in the relative velocity, methane mixes into the air at a faster rate. When the layering number rises above 1.5, the layer shortens rapidly.
Figure 4.2 The relationship between the layering number and the length of methane layer on the roof of a level airway, based on experimental data from Bakke and Leach, 1962 (after McPherson, 1993).

4.3 Methane Control Measures

In most of the coal mines, ventilating airflow is sufficient to maintain methane concentration below the lower limit specified by the mining law. The explosive range of methane concentration air is roughly 5% to 15% with the most explosive mixture occurring at the concentration of 9.8%. However, mining law does not permit methane concentration above a fraction (usually about 20%) of the lower limit. For example, electricity must be discontinued when the concentration exceeds 1% to 1.25%. In gassy mines, ventilating air is often not sufficient to maintain concentration within the permissible limit. Methane drainage is essential for such mines. Different methods are
applied for methane drainage. The selection of the method depends upon the following (McPherson, 1993):

i. the natural or induced permeability of the source seam(s) and adjacent strata
ii. the purpose of drainage of the gas
iii. the method of mining (if any)
iv. depth of workings
v. gas content of the seam(s)

Four major methods of methane drainage used in mines are currently in practice. They are:

- in-seam drainage
- gob drainage by surface boreholes
- cross-measures drainage
- drainage from worked-out areas

4.3.1 In-seam Drainage

As the name implies, drainage holes are confined within the coal seam. The success of this method depends heavily on the permeability of the seam. The higher the permeability, either natural or induced, the greater the volume of gas yielded. In addition, improved drilling technology enhances the potential of in-seam gas drainage. Up to 50% of free methane of a seam (i.e. methane that can be drained and normally emits into ventilating air) can be extracted from the seam before carrying out any mining operations (McPherson, 1993).

Gas from a coal seam can also be drained by sinking a small diameter shaft that intercepts the seam (U.S. Bureau of Mines, 1980). Long multiple boreholes are drilled radially outwards from the shaft into the seam and piped to a surface station. The same shaft may be used as a service or ventilation access in the future. Using this method, gas from an area can be drained well ahead of mining.
4.3.2 Gob Drainage by Surface Boreholes

In this method, several vertical bore holes are drilled into the gob from the surface. The gases from the gob are generally drawn out using vacuum pumps. If these gases are not drained, then they will move towards the working areas and increase the gas load on the ventilating air. In addition to longwall panels, this method also applies to pillar extraction areas to reduce emissions of methane into mine workings (McPherson, 1993).

4.3.3 Cross-measures Drainage

In this method, drainage holes are usually drilled underground from the entries adjacent to the panel. The holes are drilled at an angle into the roof over the gob areas and if necessary, into the floor strata. This method can also be used for draining methane from the zones of longwall panels relieved of overburden stress during excavation. Though the technique is particularly applicable to advancing longwall panels, it is equally practicable for multiple entry retreat system (Smith et al., 1994). Often suction pressure is needed to control both the flow rate and direction. The optimum suction pressure should be maintained to ensure that the interface between the air and the strata remains above the level of the airway (McPherson, 1993).

4.3.4 Drainage from Worked-out Areas

In the void space of worked-out or sealed gob areas, gas is emitted mainly from the caved strata and the "destressed" zones. Gas emission may continue for several years in the abandoned areas where overlying or underlying coal beds are fractured or multiple-seam workings are present in the vicinity of those areas. To draw the gas out before it mixes into the main stream of ventilating air, drainage pipes can be inserted through stoppings. The pipes should be extended to a place unaffected by air penetration during a period of rising pressure. The purpose is to remove methane approximately at the same rate it is produced (McPherson, 1993).
V. ANALYSIS OF LONGWALL VENTILATION SYSTEMS

5.0 Introduction

The purpose of choosing a particular ventilation layout under certain mining and geologic conditions is to create a safe and healthy mine environment. By selecting an appropriate ventilation system, it is possible to minimize the adverse physiological effects of dust, gas, heat, humidity, and ground control problems. However, the investigation of the layouts have been made from a completely different standpoint in this research. The goal is to select a layout which can effectively minimize air leakage in a gob of a panel. It is somehow related to safety aspect of mine because spontaneous combustion problem in the mine can be avoided. However, in a gassy mine, a panel ventilation layout that minimizes air infiltration into the gob can potentially build an explosive environment inside the gob. Therefore, such a layout should be coupled with an effective gob degassification system. For this reason, a methane drainage system compatible with the suggested ventilation layout has been proposed as an integral part of a mine. Finally, a detailed case study on a mine is carried out to demonstrate the application of the research findings.

5.1 Longwall Ventilation Layouts

Several types of ventilation systems are practiced all over the world for longwall mining operations. These system layouts are designated by "U," "Y," "Z," "double-Z," "W," "E," etc. due to their close resemblance to those letters. All of these systems can be applied to both advancing and retreating longwall panels, with single entry or multiple entries (Fuller, 1989). Each of these systems has its merits and demerits, and applications under specific mining conditions.
5.1.1 U-type Ventilation System

Under this ventilation system, the movement of ventilating air through major airways assumes the configuration of the letter "U" (Figure 5.1A). It has several variations with different methods applied to drainage of methane from the gob and retreating panels. One of these variations is the back return system, where return air is brought into the gob by diverting it from the return end of the face in order to avoid inflow of methane at high concentration into the face workings. These systems reportedly can be used to control methane emission hazards from the longwall gob (Matuszewski and Lunarzewski, 1980).

Merits:
- In retreating longwalls, no gob sealing is required to prevent contamination of the panel return air or to create an oxygen deficient environment in the gob.
- As the longwall face retreats, the gob enlarges and panel gassiness increases. However, the resistance of the ventilation circuit decreases. Consequently, panel airflow increases, maintaining a reasonably constant methane concentration in the return.
- The spontaneous combustion problem is minimized in the gob as a whole, except the area immediately behind the operating face.
- Methane emission on the face workings is less in the advancing panels. However, it may be a significant problem if the face retreats.

Demerits:
- For any given face length, depth and geological conditions, the same amount of ventilating air may have less cooling power in this system as compared to some other ventilation systems, such as the E- or W- system.
- A significant amount of face air is often diverted into the gob of a gassy mine by means of an extended chain pillar and an outbye cross-cut on the tailgate of the panel using a regulator. The control of the regulator is critical. Failure of these regulators leads to dramatically reduced face airflow and diverted airflow into the gob. Consequently, methane concentration may increase in the panel return.
Figure 5.1A  Schematic diagram of the U-type ventilation system implemented in longwall panels.

5.1.2  Y-type Ventilation System

In this ventilation system, both the headgate and tailgate entries are used as the intake airways. The airway maintained alongside the gob serves as the main return, giving the overall ventilation layout of the panel the shape of "Y" (Figure 5.1B).

Merits:
- In the advancing panels, ventilation pressure can be controlled on the intake airways in both sides of the gob by means of a regulator in the tailgate. As a result, air leakage into the gob can be minimized and so the risk of spontaneous combustion. However, the leakage of air into the gob on the tailgate end of a retreating face may give rise to the self-heating problem.
- Tailgate intake dilutes the gas concentration on the return airways. The likelihood of methane contamination of the tailgate area is minimized even in the event of malfunction of the system, as the effect of the pressure distribution is to pull the gas in the gob away from the tailgate.
Figure 5.1B Schematic diagram of the Y-type ventilation system implemented in longwall panels.

Demerits:
- Seals between the gob and panel return are essential to prevent unacceptable contamination of return air, as well as to prevent an excessive leakage of air into the gob.
- The main heading, especially as the return airway, has to be maintained in good condition over the complete life of the panel.
- Total airflow in the panel decreases and at the same time, gassiness increases with the enlargement of the gob area. As a result, more gas is diluted with less airflow, increasing gas concentration in the return airway. Therefore, face airflow has to be carefully adjusted by regulator.

5.1.3 Z-type Ventilation System

As shown in Figure 5.1C, the Z-type ventilation system evolves out of the Y-type ventilation system when the intake airway, in line with panel return, is maintained at minimal airflow to handle rib-side gas.
Figure 5.1C Schematic diagram of the Z-type ventilation system implemented in longwall panels.

**Merits:**
- Methane can be controlled more efficiently than with the U-type ventilation system.
- Less gob sealing is required than the Y-type ventilation system in an advancing longwall panel. Only one side of the panel has to be sealed.
- Compared to the Y-type ventilation system, ground control problems are reduced for panel intakes and returns, because one intake instead of two (as in the Y-type ventilation system) has to be maintained.

**Demerits:**
- A bleeder return has to be maintained for gas dilution and has to be supported adequately.
- A spontaneous combustion problem may arise in areas around the gob center following the leakage flow from the intake to the return.
Figure 5.1D  Schematic diagram of the double Z-type ventilation system implemented in longwall panels.

5.1.4 Double Z-type Ventilation System

The double Z-type ventilation system results from the Y-type ventilation system when the main return is maintained through the center line of the panel (Figure 5.1D).

Merits:
- Good pressure equalization can be achieved across the gob of a longwall panel.
- Longwall face length is effectively halved by the middle return. Consequently, the cooling requirement, methane and dust control problems, either on tailgate or headgate, are reduced.

Demerits:
- A ground control problem is encountered in maintaining the main panel airways. For a retreating longwall, the maintenance of a central return may be difficult, depending upon the geology of the overlying as well as the underlying strata, because it passes through the gob.
- The sealing requirement is as high as in the Y-type ventilation system.
5.1.5 W-type Ventilation System

The W-type ventilation system is analogous to the double-Z type ventilation system, except the central return airway is maintained parallel to the panel intakes (Figure 5.1E).

Merits:
- Many of the advantages associated with the double-Z type ventilation system are also available in the W-type ventilation system.
- This system is the most effective in reducing the face cooling loads on the retreating longwalls (Uchino and Higara, 1984).
- Dust and methane generated on the face are carried to the middle return, reducing their concentrations on the ends of the face.

Demerits:
- In advancing panels, considerable air leakage due to the pressure differential acting across a shorter gob width, may give rise to the spontaneous combustion problem within the gob, since the middle return effectively cuts through the gob in two halves.
Figure 5.1F Schematic diagram of the E-type ventilation system implemented in longwall panels.

- To maintain the middle return entry, often an insurmountable ground control problem is encountered, especially in advancing longwalls.

5.1.6 E-type Ventilation System

The E-type ventilation system has the same configuration or layout as that of the W-type ventilation system. However, the middle entry is used as one of its two panel intakes (Figure 5.1F).

Merit:
- Additional dilution and cooling capacity can be achieved at the mid-face by the middle intake.

Demerits:
- In retreating panels, the middle intake tends to increase air leakage into the gob.
- In advancing panels, if necessary, pressure can be adjusted across the half of the gob between intake airways in order to reduce leakage through the waste. However,
leakage may take place on the other half because of pressure differential between intake and return.
- Air velocity is considerably greater on one half of the face than on the other half which may hamper the dust control measures.

5.2 Gob Structure Characterization

The gob is the center stage of this research on self-heating in the inaccessible locations of the gob is of primary concern. Therefore, the characterization of the gob, especially sinuous cracks, crevices and flow paths that carry leakage air into gob giving rise to self-heating, is most important. In this section, considerations have been given to the factors that are involved in the gob characterization and the approach used to characterize the gob in this work.

5.2.1 Consolidation of the Gob

The degree of the gob material consolidation, in the absence of geological disturbances, is governed by:
- load on the gob
- sizes and shapes of the fragmented rock mass

Load on the gob:
depends upon the type of the caved rock mass, depth of overburden, and intensity of caving.

A typical gob loading curve is derived from the correlation between field and laboratory data. As shown in Figure 5.2, loading is parabolic in the lateral direction from the collapsed headgate to tailgate. However, a gradual increase in load from the face line to the panel start line is observed.
Figure 5.2  Load curve based on field and laboratory data put together by Pappas, 1993.
Figure 5.3 Diagram showing classification of different shapes and associated parameters (after Krumbein and Sloss, 1963).

Sizes and Shapes of the Fragmented Rock Mass:
Due to the uncertainty about the factors affecting sizes of the particles and blocks in the confines of the gob, the particle size is predicted to be proportional to the intensity of loading at any point of concern. Shape depends mainly on rock type. The width-to-length and thickness-to-width ratios are considered to be the two major parameters defining the shape of a particle. As shown in Figure 5.3, relative to thickness-to-width ratio, width-to-length ratio does not change significantly with fragmentation to smaller sizes as the loading increases. However, the parameters governing shape such as thickness-to-width and width-to-length ratios are considered to be proportional to the intensity of loading.
5.3 **Estimation of Gob Resistance**

The resistance pattern in the gob space is estimated on the basis of permeability of the fractured rock mass, and dimensions of the gob area.

In the model of the porous medium used in our research for the analysis of the leakage airflow through the gob, shale is chosen as the gob material because it is one of the frequently occurring rock in the roof of coal mines. Extensive studies relating bulking factor to a strength parameter (tangent modulus) and shape factor such as thickness-to-width ratio have been conducted on shale (Pappas and Mark, 1993). The bulking factor is defined as the ratio of the volume of the broken rock mass to the volume of the intact rock mass. It can be given as

\[ \phi = \frac{V_b}{V_i} \]  \hspace{1cm} (5.1)

where
\( V_b = \) volume of the broken rock mass, \( m^3 \)
\( V_i = \) volume of the intact rock mass, \( m^3 \).

Different mechanical properties of shale and other coal measure rocks are listed in Table 5.1. Under various loading condition, a set of equations have been developed (Equs. 5.2A, 5.2B, 5.2C, 5.2D, 5.2E, 5.2F, and 5.2G). The trends of these equations are plotted in Figure 5.4.

At stress level, \( \sigma = 400 \) psi

\[ \phi = 0.0000184E_t + 0.267\eta + 1.16 \] \hspace{1cm} (5.2A)

At stress level, \( \sigma = 600 \) psi

\[ \phi = 0.0000203E_t + 0.274\eta + 1.06 \] \hspace{1cm} (5.2B)
Table 5.1 List of properties (average values) for different rock types (after Pappas and Mark, 1993)

<table>
<thead>
<tr>
<th></th>
<th>Shale</th>
<th>Weak Sandstone</th>
<th>Strong Sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Void Ratio</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>0.7950</td>
<td>0.7426</td>
<td>0.8667</td>
</tr>
<tr>
<td>@ 800 psi</td>
<td>0.2958</td>
<td>0.3232</td>
<td>0.4877</td>
</tr>
<tr>
<td>Final</td>
<td>0.1522</td>
<td>0.1536</td>
<td>0.2524</td>
</tr>
<tr>
<td><strong>Shape Ratio (initial):</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness-to-width</td>
<td>0.4355</td>
<td>0.6302</td>
<td>0.5420</td>
</tr>
<tr>
<td>Width-to-length</td>
<td>0.7022</td>
<td>0.7356</td>
<td>0.6730</td>
</tr>
<tr>
<td><strong>Shape Ratio (final):</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness-to-width</td>
<td>0.5295</td>
<td>0.6688</td>
<td>0.6740</td>
</tr>
<tr>
<td>Width-to-length</td>
<td>0.7183</td>
<td>0.7336</td>
<td>0.7053</td>
</tr>
<tr>
<td><strong>Tangent Modulus, (psi)</strong></td>
<td>8363</td>
<td>7588</td>
<td>7335</td>
</tr>
<tr>
<td><strong>Secant Modulus, (psi)</strong></td>
<td>3011</td>
<td>3154</td>
<td>3808</td>
</tr>
</tbody>
</table>

At stress level, $\sigma = 800$ psi

$$\phi = 0.0000187E_t + 0.262\eta + 1.04 \quad (5.2C)$$

At stress level, $\sigma = 1000$ psi

$$\phi = 0.0000185E_t + 0.269\eta + 0.992 \quad (5.2D)$$

At stress level, $\sigma = 1500$ psi

$$\phi = 0.0000160E_t + 0.209\eta + 1.00 \quad (5.2E)$$

At stress level, $\sigma = 2000$ psi

$$\phi = 0.0000150E_t + 0.221\eta + 0.963 \quad (5.2F)$$

At stress level, $\sigma = 2500$ psi

$$\phi = 0.0000136E_t + 0.247\eta + 0.931 \quad (5.2G)$$
Figure 5.4 Multiple regression curves - rocks strength versus bulking factor for various thickness-to-width shape ratios (after Pappas and Mark, 1993).
where
\( \phi = \) bulking factor
\( E_t = \) tangent modulus [psi]
\( \eta = \) thickness-to-width shape ratio.

Porosity (or void ratio) of broken rock mass is defined as the volume of void space present in the broken rock mass to its total volume. It can be given as

\[
\varepsilon = \frac{V_v}{V_b}
\]

(5.3)

where
\( V_v = \) volume of void space in the broken rock mass, m\(^3\)
\( V_b = \) volume of the broken rock mass, m\(^3\)

Now

\[
V_v = V_b - V_i
\]

\[
\varepsilon = \frac{(V_b - V_i)}{V_b} = 1 - \frac{V_i}{V_b} = 1 - \phi
\]

\( \Rightarrow \quad \phi = \varepsilon + 1 \)

(5.4)

The coefficient of permeability is computed using the Kozeny-Carman equation (Equ. 5.5) that relates the coefficient of permeability to porosity under laminar flow condition (Carman, 1963). The coefficient of permeability is defined in terms of the flow rate (in m\(^3/s\)) through 1 m thickness and 1 m width of a given medium under a pressure gradient of 1 Pa per meter.
Kozeny-Carman equation:

\[ B = \frac{d_m^2 \varepsilon^3}{36k (1 - \varepsilon)^2} \]  

(5.5)

where

- \( B \) = the coefficient of permeability for viscous flow \([m^2]\)
- \( d_m \) = surface mean diameter of broken rock pieces \([m]\)
- \( k \) = Kozeny constant.

Surface mean diameter is estimated on the basis of the measured surface area of a non-spherical particle. The diameter of a sphere of surface area equal to that of the particle is defined as surface mean diameter.

The complete gob area has been considered to consist of rectangular blocks of broken rock mass (Figure 5.5). The objective is to incorporate the effect of varying rock mass characteristics and overburden loading on the leakage flowpaths through different parts of the gob matrix. For any direction (either X- or Y-), permeability values for three planes at an equal spacing from one end of the block to the other end have been estimated (i.e. three parallel planes IX, IIX, and IIIx in the direction of X-axis) and their average value are considered for estimating the flow resistance in the direction of Y-axis for the block (as shown in Figure 5.6). A similar approach is used to estimate the resistance of the same block in the direction of X-axis. While calculating resistance, permeability is considered to be constant all over a plane.

As mentioned earlier, the size of the particles at any point of the block is assumed to be proportional to the overburden load on that point, because specific sizes of particles and their distribution in a block are not known in detail.
Figure 5.5 Schematic diagram of the planes (depicted by the dotted lines) which divide the gob into blocks.

Figure 5.6 Schematic diagram of the planes chosen for permeability estimation of a block.
Since a gob is inaccessible, the relative size distribution of the broken pieces inside the gob is based on a crude estimation made from the image analysis of a photograph taken on the exposed part of the gob (Figure 5.7). For the purpose of modeling, the complete gob area is divided into blocks of sizes as indicated in Table 5.2. The leakage flow through the gob matrix is mostly laminar in nature, and so the permeability values of each block, in two orthogonal directions along the gob floor, are estimated by using Equ. 5.5. The dimensions of the block, its aggregate permeability and air viscosity are used to determine the laminar flow resistance in the two directions according to the following equation:

\[ R = \frac{\mu L}{BA} \]  
(5.6)

where

- \( R \) = flowpath resistance [Ns/m^5]
- \( \mu \) = dynamic viscosity [Ns/m^2]
- \( L \) = length of bed in the flow direction [m]
- \( B \) = the coefficient of permeability for viscous flow [m^2]
- \( A \) = area of flow cross-section [m^2].

Resistance values computed using Equ. 5.6 are for laminar flow condition. Laminar flow resistance is converted to turbulent flow resistance. The following criterion used for the conversion of flowrate at the initial stage of the network analysis. When the flowrate is higher than 0.5 m^3/s, the flow condition is assumed to be turbulent. Otherwise, the flow is considered to be laminar. The network analysis software, VNETPC (McPherson, 1993), has been modified according to the Reynolds number criterion (as given below). This modification was necessary because VNETPC was developed for the ventilation network carrying turbulent flow. In the context of mixed flow analysis, the Reynolds number is considered as the decisive parameter.
**Figure 5.7** A vertical cross-section of a gob showing the arrangement of particles and blocks. A digitized cross-section of a gob photograph taken in a Virginia coal mine (after Pappas and Mark, 1993)

**Table 5.2** Typical length, width and height of a block chosen arbitrarily for the purpose of characterizing leakage flowpaths through a complete gob.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>21 m</td>
</tr>
<tr>
<td>Width</td>
<td>6 - 24 m</td>
</tr>
<tr>
<td>Height</td>
<td>5 m</td>
</tr>
</tbody>
</table>

For the flow through the porous medium of fragmented rock mass in the gob,

\[ \text{Re} = \frac{\rho \nu d}{\mu} \]  
(5.7)
Figure 5.8 Flow cross-section \(A\) for the flow \(Q\) through a porous medium.

\[
v = \frac{Q}{A}
\]  
(5.8)

where

\(\text{Re} = \text{Reynolds number}\)

\(v = \text{fluid velocity around a rock particle or block [m/s]}\)

\(A = \text{Area of flow cross-section [m}^2\text{]}\)

\(Q = \text{fluid flow rate through the cross-section(A) [m}^3\text{/s]}\)

\(d = \text{diameter of the particle or block [m]}\)

\(\rho = \text{density of the fluid [kg/m}^3\text{]}\)

\(\mu = \text{viscosity of the fluid [Ns/m}^2\text{]}\).

When \(\text{Re} < 1 \sim \text{flow is laminar.}\)

When \(\text{Re} > 1 \sim \text{flow is turbulent.}\)

On the other hand, when the fluid is flowing through the open airways,

\[
d = \frac{4A}{S}
\]  
(5.9)
where
\[ d = \text{mean hydraulic diameter of an airway [m]} \]
\[ A = \text{cross-sectional area of the airway [m}^2\text{]} \]
\[ S = \text{wetted perimeter of the airway [m]} \].

When \( Re < 2300 \) \sim \text{flow is laminar.} \)
When \( Re > 2300 \) \sim \text{flow is turbulent.} \)
However, \( Re \) could be as high as 100,000 for turbulent flow through a smooth airway.

### 5.4 Structure of Resistance for Network Analysis

As a continuation of the previous section on gob characterization and assigning resistance to each block of leakage flow paths, in this section each element of resistance is integrated into the complete body of a gob, more broadly into a panel as a whole in the form of a network. The purpose of framing such a network is to make a model of a ventilation system adaptable to available ventilation network analysis tools, such as VNETPC software (McPherson, 1993).

#### 5.4.1 Linear Resistance Paths

In order to form the basis for the flow analysis, the resistance of each relevant part of a mine where air is flowing is built into a network of resistances representing the whole mine. Two major categories of resistance used for the analysis follow:

- resistance of all the major and minor airways of a mine, especially the panel entries (such as headgate, tailgate and belt entries) and face areas
- gob interior - the resistance of the sinuous leakage flowpaths spreading through the gob, mostly laminar.

The typical aerodynamic characteristics and dimensions of mine airways (Table 5.3) are incorporated into the ventilation network.
Table 5.3 Typical dimensions of mine airways and their aerodynamic characteristics.

<table>
<thead>
<tr>
<th>Type of Airway</th>
<th>Width (m)</th>
<th>Height (m)</th>
<th>Friction Factor (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Intake or Return</td>
<td>6</td>
<td>2</td>
<td>0.012</td>
</tr>
<tr>
<td>Panel Intake or Headgate</td>
<td>6</td>
<td>1.8</td>
<td>0.012</td>
</tr>
<tr>
<td>Panel Return or Tailgate</td>
<td>5</td>
<td>1.7</td>
<td>0.012</td>
</tr>
<tr>
<td>Bleeder Return</td>
<td>2.5</td>
<td>1.5</td>
<td>0.012</td>
</tr>
<tr>
<td>Belt Entry</td>
<td>6</td>
<td>1.8</td>
<td>0.015</td>
</tr>
<tr>
<td>Airways along panel to bleeder</td>
<td>4</td>
<td>1.5</td>
<td>0.015</td>
</tr>
<tr>
<td>Face Line</td>
<td>4.3</td>
<td>2</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Figure 5.9 Configuration of a block in relation to the flow network inside the gob and schematic diagram of interconnection of the orthogonal gob resistance elements in the grid-like network. The solid lines are for resistance elements and the dotted lines are for the blocks into which the gob is divided.

5.4.2 Variation of Gob Resistance in Orthogonal Directions

The center of each block is taken as a connecting node to the adjacent blocks or around it as shown in Figure 5.9. For each block constituting the gob, resistance in two orthogonal
Figure 5.10A  Gob resistance distribution in the direction parallel to the main entries of a retreating longwall panel with the U-system layout. The numbers on the contours have the unit of $Ns^2/m^3$ and those on the rectangular boundary have the unit of $m$.

directions (along the length and width) are estimated for simplicity. The magnitudes of flow resistances are different in two orthogonal directions because the level of compaction is different in the two directions (as indicated in the load curve, Figure 5.2). The contour maps of resistance for the same gob space are drawn separately to demonstrate the difference in their resistance patterns (Figures 5.10A and 5.10B).
Figure 5.10B Gob resistance distribution in the direction parallel to the face of the same panel as shown in Figure 5.10A. The numbers on the contours have the unit of Ns²/m⁸ and those on the rectangular boundary have the unit of m.
5.4.3 Network Model for the U-type Ventilation System

As an illustration for the method of establishing ventilation network for a longwall panel, the U-type ventilation system is depicted in Figure 5.11. Similarly, ventilation networks for the other panel ventilation layouts, as mentioned in section 5.1.1, can be constructed.

5.5 Airflow Distribution Analysis

The purpose of gob characterization and network formation is to set a groundwork for analyzing the flow through ramifications of leakage paths inside a gob. The distribution of airflow, obtained as an outcome of network analysis at its final stage, has been taken here and processed further for flow visualization and its graphical presentation. The objective is to draw conclusions on the self-heating potential of the gob. More importantly, the locations susceptible to spontaneous combustion can be identified.

5.5.1 Direction of General Body of Air Movement

The results of the network analysis have been processed further to derive the overall direction and magnitude of the airflow through each block. In this stage of analysis, magnitude and direction of the resultant airflow have been computed for each of the blocks forming the gob (Equs. 5.10A and 5.10B). Airflow (vectors) in two directions of a block are obtained from the leakage flow distribution analysis and used for the computation of magnitude and direction of the resultant flow (Figure 5.12).

\[ Q_r = \sqrt{Q_x^2 + Q_y^2} \quad (5.10A) \]

\[ \theta_r = \tan^{-1}\left(\frac{Q_x}{Q_r}\right) \quad (5.10B) \]
Figure 5.11 Illustration of the resistance diagram for each of the flowpath segments in the ventilation network for the U-type ventilation system as shown in Figure 5.1A. The numbers on the network have the unit of \( \text{Ns}^2/\text{m}^8 \).
Figure 5.12 Vector diagram illustrating direction and magnitude of the resultant airflow.

where
\( Q_r = \) resultant airflow rate \([m^3/s]\)
\( Q_x = \) airflow rate in the X-direction \([m^3/s]\)
\( Q_y = \) airflow rate in the Y-direction \([m^3/s]\)
\( \theta_r = \) inclination of \( Q_r \) relative to the X-direction [degree].

For all the blocks, \( Q_r \) values are mapped in the form of contours and also in the form of the arrows (vectors) using \( \theta_r \) to depict the direction of airflow. The length of each arrow is proportional to the magnitude of airflow at that location. The direction of the general body of leakage flow through the gob (as shown in Figures 5.13A, 5.13B, 5.13C, 5.13D, 5.13E and 5.13F) has been traced from the direction of flow as observed in each block and for each type of ventilation system (such as E, H, U, W, Y, and Z-systems).
Figure 5.13A  Direction of general body of air leaking through the gob of a retreating longwall panel under the E-system of ventilation.
Figure 5.13B Direction of general body of air leaking through the gob of a retreating longwall panel under the H-system of ventilation.
Figure 5.13C  Direction of general body of air leaking through the gob of a retreating longwall panel under the U-system of ventilation.
Figure 5.13D  Direction of general body of air leaking through the gob of a retreating longwall panel under the W-system of ventilation.
Figure 5.13E  Direction of general body of air leaking through the gob of a retreating longwall panel under the Y-system of ventilation.
Figure 5.13F  Direction of general body of air leaking through the gob of a retreating longwall panel under the Z-system of ventilation.
5.5.2 Distribution of Leakage Airflow in the Gob

The magnitude of airflow in each of the blocks has been mapped in the contours (as shown in Figures 5.14A, 5.14B, 5.14C, 5.14D, 5.14E and 5.14F). The purpose of drawing the contours is to identify the areas critical for self-heating and their extent for each ventilation system.

It should be noted that H-, Y-, and Z-systems are designed to implement the bleeder system as compared to the bleederless systems such as E-, U-, and W-. The bleeder system is used to dilute the gas emitted into the gob. As shown in Figures 5.14B, critical airflow zones (40 - 48 mm/s, range of leakage velocity chosen arbitrarily for the purpose of illustration) are confined to locations close to the panel start line, the working face, and the short sections of the tailgate adjacent to the start line and face under the H-system. However, under the Y- and Z-systems, the critical flow zones surround the highly compacted gob center, except the headgate side of the panel (Figures 5.14E, and 5.15F). Moreover, the zone penetrates deeper into the gob under the Y-system as compared to the Z-system. As a sharp contrast to the leakage airflow distributions inside the gob under the ventilation systems with bleeders, the critical airflow zones are all shrunk close to the face under the bleederless systems of ventilation (Figure 5.14A, 5.14C, and 5.14D). The critical airflow zones for the E- and U-systems occupy nearly the same space location in the gob, with the zone relatively close to the face under the E-system. On the other hand, the zone under the W-system of ventilation is almost non-existent. Therefore, it can be concluded that the E-, U- and W- systems are appropriate for the control of spontaneous combustion in the gob areas of retreating longwall panels. The W-system is most suitable for the mines without major ground control problems. However, the U-system is desirable for the mines withstanding a huge overburden pressure.
Figure 5.14A Contour map of air leakage rate through the gob of a retreating longwall panel under the E-system of ventilation. The numbers on the contours have the unit of \( \text{mm/s} \), and those on the rectangular boundary have the unit of \( \text{m} \).
Figure 5.14B  Contour map of air leakage rate through the gob of a retreating longwall panel under the H-system of ventilation. The numbers on the contours have the unit of mm/s, and those on the rectangular boundary have the unit of m.
Figure 5.14C  Contour map of air leakage rate through the gob of a retreating longwall panel under the U-system of ventilation. The numbers on the contours have the unit of m/min, and those on the rectangular boundary have the unit of m.
Figure 5.14D Contour map of air leakage rate through the gob of a retreating longwall panel under the W-system of ventilation. The numbers on the contours have the unit of mm/s, and those on the rectangular boundary have the unit of m.
Figure 5.14E  Contour map of air leakage rate through the gob of a retreating longwall panel under the Y-system of ventilation. The numbers on the contours have the unit of mm/s, and those on the rectangular boundary have the unit of m.
Figure 5.14F  Contour map of air leakage rate through the gob of a retreating longwall panel under the Z-system of ventilation. The numbers on the contours have the unit of mm/s, and those on the rectangular boundary have the unit of m.
An arbitrary range is chosen as the critical airflow for the purpose of illustration. This range varies depending upon:

- properties of coal left inside the gob
- degree of comminution of coal
- temperature and humidity of air leaking through the critical areas.

For any coal type, field and laboratory studies are recommended for determining the range of airflow critical for self-heating as described in detail in the sections 2.2 and 2.3 of Chapter 2.

5.6 Implications of Face Movement

With the movement of the longwall face in a panel, the leakage airflow distribution pattern alters. Consequently, the locations of those areas, prone to self-heating, change. In order to implement effective and timely control measures, it is important to know the changing phases of leakage airflow in the gob. The causes of variation in the airflow requirement for a panel are the following:

- overall resistance of the panel changes as the face advances
- leakage airflow inside the gob changes (with the enhanced gob caving) as its size enlarges.

Assuming resistance along a face line remains the same, only the resistances of the intake, return, belt line and any other airway alongside them change. Differential changes in the resistance of the leakage flowpaths within the overall body of the gob can be estimated from the airflow distribution analysis. For that purpose, the ventilation survey data of airflow and pressure drop across the face and in the panel should be recorded at a regular intervals of face movement (as shown in Figures 5.15A and 5.15B).
Figure 5.15A  Schematic diagram of different locations of a retreating longwall face of a panel.

Figure 5.15B  Varying load curves at different locations of the face line (Mozumder, 1974).
Figure 5.16A Contour map of air leakage rate inside the gob at the initial phase of the face movement in a retreating longwall panel, as shown in Figure 5.15A, under the U-system of ventilation.

Moreover, assuming the aerodynamic resistance pattern and leakage airflow characteristics of gob materials adjacent to the panel start line and the face line remain unaltered for the most part, the change in resistance pattern beyond that section can be estimated. The trend in variation of the gob characteristics with the movement of the face can be established for a longwall panel. As a result, the prediction of gob mass characteristics based on the studies carried out in other mines may not be necessary. In fact, the study may not be applicable to another mine in the strict sense of the gob characterization.

5.6.1 Changing Leakage Airflow Pattern

With the movement of the face, the leakage airflow distribution inside the gob changes (Figures 5.16A, 5.16B, 5.16C, 5.16D, 5.16E, 5.16F, 5.16G, and 5.16H). This is a direct reflection of the changing aerodynamic resistance pattern of the gob. The critical airflow zone moves with the face. As mentioned earlier, when the rate of the face movement is faster than the rate of development of spontaneous combustion in the critical zone, the risk of fire is minimum. This is because the self-heating prone gob material gets buried under newly caved rock mass as the face moves. Consequently, access of air in the critical areas virtually ceases.
Figure 5.16B  Contour map of air leakage rate inside the gob at the second phase of the face movement in the same retreating longwall panel, as shown in Figure 5.15A, under the U-system of ventilation. The numbers on the contours have the unit of mm/s.
Figure 5.16C  Contour map of air leakage rate inside the gob at the third phase of the face movement in the same retreating longwall panel, as shown in Figure 5.15A, under the U-system of ventilation. The numbers on the contours have the unit of mm/s.
Figure 5.16D Contour map of air leakage rate inside the gob at the fourth phase of the face movement in the same retreating longwall panel, as shown in Figure 5.15A, under the U-system of ventilation. The numbers on the contours have the unit of mm/s.
Figure 5.16E  Contour map of air leakage rate inside the gob at the fifth phase of the face movement in the same retreating longwall panel, as shown in Figure 5.15A, under the U-system of ventilation. The numbers on the contours have the unit of mm/s.
Figure 5.16F Contour map of air leakage rate inside the gob at the sixth phase of the face movement in the same retreating longwall panel, as shown in Figure 5.15A, under the U-system of ventilation. The numbers on the contours have the unit of mm/s.
Figure 5.16G Contour map of air leakage rate inside the gob at the seventh phase of the face movement in the same retreating longwall panel, as shown in Figure 5.15A, under the U-system of ventilation. The numbers on the contours have the unit of mm/s.
Figure 5.16H Contour map of air leakage rate inside the gob at the final phase of the face movement in the same retreating longwall panel, as shown in Figure 5.15A, under the U-system of ventilation. The numbers on the contours have the unit of mm/s.
5.6.2 Analysis of a Changing Gob Resistance Pattern

A detailed work on correlating the gob resistance pattern and the airflow pattern in the face area has been carried out in one panel. From the analysis, it has been confirmed that with the enlargement of the gob size as the face moves, the broken rock mass in the gob undergoes consolidation with the increasing overburden pressure. Consequently, the overall resistance of the gob decreases (Figure 5.17A). Within a short distance from the panel start line as compared to the total length of the panel, the resistance of the gob reaches the minimal. However, the resistance increases by a small amount from the lowest value before it becomes roughly constant. At this stage, the gob resistance is essentially comprised of the resistances of gob materials adjacent to the panel start line and the face line, the most part remaining outside of the influence of the gob loading. Figure 5.17B shows that with the increase of the gob resistance as the face moves, the leakage flow into the gob decreases. This analysis not only can help in finding the critical airflow zone in the gob area of the panel, but also serve as a guideline for the new panels to be opened in the same mine. This approach is discussed further in the following page.
For each phase of face movement (as shown in Figure 5.15A), a detail network of the gob has been established based on the gob loading curves (Figure 5.15B). The airflow contours represent the flow condition inside the gob under each phase of face movement (as shown in Figures 5.16A, 5.16B, 5.16C, 5.16D, 5.16E, 5.16F, 5.16G, and 5.16H). To determine the resistance of the gob including the face line, the pressure difference between one end of the face to the other has been estimated (as shown in Figure 5.18A). Total airflow in the panel is known from the network analysis (as shown in Figure 5.18B). Therefore, the resistance is computed with the help of Square Law (Equ. 5.11). The same method is applied to each phase of the face movement.

\[ P = RQ^2 \]  \hspace{1cm} (5.11)

where

- \( P \) = frictional pressure drop across face [Pa]
- \( R \) = overall resistance of the gob and face line [Ns²/m⁸]
- \( Q \) = airflow in the panel [m³/s].
Figure 5.18A Illustration of the pressure distribution diagram for each of the flowpath segments in the network for a panel under the U-system of ventilation as shown in Figure 5.11. The numbers on the network have the unit of Pa.
Figure 5.18B  Illustration of the airflow distribution diagram for each of the flowpath segments in the same network as shown in Figure 5.18A. The numbers on the network have the unit of m$^3$/s.
5.7 Methane Gas Drainage Modeling

As observed in the leakage airflow analysis, the bleederless ventilation system effectively minimizes air leakage into the gob. However, the gob gas concentration increases under this system. Methane is a predominant gob gas and it is explosive when its concentration ranges from 5% to 15% with its peak explosive concentration of 9.8%. Therefore, to implement a bleederless ventilation system, a provision for an appropriate methane drainage system should be made. In this section, a drainage system adaptable to the suggested ventilation system has been developed, analyzed, and proposed for the gassy coal mines.

5.7.1 Double Layer Model of Gob Resistance

As observed from the photograph on the sizes of particles and blocks, and their distribution (Figure 5.7), the small particles are close to the floor of the gob the large ones are on the top of the pile. The small size particles towards the bottom are considered as one layer, and the large blocks towards the roof are depicted as the second layer. In reality, several layers can be designated for the finer analysis of the flow through the gob. However, all the layers are roughly categorized into two major layers for simplicity of the analysis. The average size of the blocks in the upper layer is arbitrarily chosen as 5 times to that of the lower layer, and the height of each layer is assumed to be 5 meters for the purpose of illustration. The network model of two layers inside the gob (as shown in Figure 5.19) has been developed based on the approach used for the single layer of flow network (Figure 5.9).

Methane is nearly half as dense as air, and it has the tendency to accumulate near the roof.
Density of air = 1.2 kg/m$^3$ at S.T.P. (Standard Temperature and Pressure)
Density of methane = 0.665 kg/m$^3$ at S.T.P.
Figure 5.19 Network model of the double layer inside the gob for the leakage airflow and gas distribution analyses.
The method used to control spontaneous combustion is to minimize airflow leakage inside the gob. Even if air is flowing through the gob, its movement should be maintained as low as possible. When the air flow is sluggish through the gob, methane accumulation in the roof areas is enhanced, as opposed to its emission into the general body of panel airflow. As a result, a layer of relatively stagnant methane accumulates near the roof of the gob (Figure 5.20). On the other hand, air which is depicted as another layer moves slowly near the floor (Figure 5.21A and 5.21B). This is the major reason for developing the double layer model of the gob, apart from the layering of the particles of increasing size upward from the floor (as mentioned above). Of course, mixing of methane in the body of airflow through the gob always continues at the interface of these layers. In the bottom layer, methane comes from the fragments of coal and accumulations in the floor itself. Methane mixed with air inside the gob is finally carried into the main course of panel airflow. When the leakage of air into the gob is minimized, methane addition from the gob may be low as compared to the volume of methane released in the face area due to combustion of coal.

5.7.2 Preparatory Steps towards Methane Drainage

As observed in the preceding sections, the minimization of air leakage into the gob is the most effective measure of controlling self-heating in the gob areas. For the mines undergoing spontaneous combustion along with high methane emissions in the gob, a significant volume of methane accumulates in the gob due to the lack of sufficient air to dilute the gas. Under this circumstance, the effective means of controlling methane from liberating into the general body of a panel or mine is gob drainage.

Developing a methane drainage system is not the focus of this research. The focus is to identify the area of maximum methane accumulation under a proposed scheme of self-heating control measures. Knowing the rate and the extent of methane accumulation in the gob, an appropriate methane drainage system can be designed.
Figure 5.20 Contour map of methane layering numbers for the upper layer of the double layer model of the gob. The numbers on the contours are dimensionless, and those on the rectangular boundary have the unit of m.
Figure 5.21A Contour map of leakage air velocity in the upper layer of the double layer model of the gob. The numbers on the contours have the unit of **mm/s**, and those on the rectangular boundary have the unit of **m**.
Figure 5.21B Contour map of leakage airflow rate in the lower layer of the double layer model of the gob. The numbers on the contours have the unit of $\text{m}^3/\text{s}$, and those on the rectangular boundary have the unit of m.
5.8 Pressure Balancing in Multiple-Entry Panels

Multiple entries are developed for a panel to reduce its aerodynamic resistance and improve safety. As a consequence, a greater quantity of air can flow into the panel at a lower pressure. A high rate of airflow is often necessary for deep mines with a high rate of methane emission and increased temperature in the working areas. However, air leaks at a greater rate into the gob and its surrounding areas, through the stoppings and the gaps between face supports.

Pressure differentials across the face can be balanced by a new method. In this method, the primary and secondary intakes and returns of the panel have been used to balance the pressure behind the face support line without reducing airflow through the face. As demonstrated in the application for a mine given in the following section of this paper, leakage into the gob and its surrounding areas is minimized significantly.

5.8.1 Application: Case Study

Ventilation survey data have been collected from a longwall mine of Jim Walter Resources, Inc. in Alabama, specifically for one of its multiple-entry panels. This mine is highly gassy. A large quantity of air is required to dilute methane to the lower allowed concentration. Methane emission rates in the face and the gob areas are so high that bleeder and methane drainage are used in addition to high airflow rate through the face. The panel entries near mined-out areas are maintained for bleeding the methane from the gob. A high pressure differential along these bleeder entries is necessary to sustain the required airflow because of their high resistance. The presence of bleeder entries near the high stress zone of the gob area degrades their condition and hence their resistance increases. Deterioration of the entries is further aggravated by the floor heaves, particularly in this mine. In some areas, the floor heave is so severe that it leads to almost complete closure of the bleeder entries. These constricted airways pose high resistance to airflow. In order to maintain the desired airflow through these entries, a higher pressure differential is called for. In turn, a higher pressure differential forces air to leak through the cracks and crevices of the heaving floor. The leakage flow through the cracks is slow because of their high resistance. Moreover, coal and carbonaceous material with
traces of sulfide minerals in the floor is of poor quality, as shown in Figure 5.22, and is highly susceptible to self-heating. As the floor material receives oxygen from the air leaking into those areas through the cracks on the heaves, the self-heating process is sustained. In some of the cases, leakage air is not sufficient to carry away the heat at the rate it is produced. As a consequence, heat builds up in those hidden areas of floor heave with time and results in a spontaneous heating. These areas often go unnoticed till the point of active combustion because they are remotely located and traveled infrequently except for mandatory inspections. At this point, it should be mentioned that the spontaneous combustion problems are mostly encountered in the degraded panel entries or entries receiving airflow critical to self-heating. Spontaneous combustion is not observed inside the gob of this panel. The reason may be that the broad expanse of the gob floor area is free of floor heaves.
Some of the major parameters and conditions for the mine are given below (Howell, McNider, and Stevenson, 1991).

- depth: 396 - 640m (1300 - 2100 ft)
- face length: 198 - 259 m
- approximately 118 m$^3$/s (250,000 cfm) of air courses through a longwall panel to the bleeder entries for methane dilution
- the face volumes can vary from 24-47 m$^3$/s (50,000 - 100,000 cfm) depending upon methane liberation
- pressure differential across the gob from the headgate of the face to the tailgate of the bleeder can vary from 0.74 to 2.22 kPa (3 - 9 inches w.g.)
- the retreating longwall faces are ventilated from headgate to tailgate (antitropal), as shown in Figure 5.23.
- the primary intake is coursed through the headgate entries with a secondary intake coursed through the tailgate entry.

Exhaustive research and analyses have been conducted on the basis of the ventilation survey data collected for the mine and one of its panels under spontaneous combustion problems. In order to control spontaneous combustion in the remote locations of the bleeder airways on the side of the gob, the following modifications of the existing ventilation layouts are proposed. The bleeders could be sealed off. Consequently, the original H-system of ventilation would then be converted to the U-system of bleederless ventilation. As shown in Figure 5.24A, the U-system alone cannot reduce air leakage in the gob areas significantly. The W-system would have been more appropriate for this panel. However, a W-system is not considered because of great depth (600 m) of this panel. As a solution to these problems, the secondary airways of the panel are used effectively to balance pressure behind the face support line. The ventilation network model of the proposed scheme of balancing pressure is shown in Figure 5.23. Airflow through the secondary intake and return has been balanced actively in order to achieve desired balance of pressure behind the face line. Airflow regulators would be appropriately adjusted to control the flow through those secondary entries. The permissible airflow required to achieve the balance can be established through an iterative procedure of
Figure 5.23 The ventilation network for a mine of Jim Walter Resources, Inc. This shows the pressure balancing zone technique behind the face support line implemented in a multiple-entry panel under the U-system of ventilation.
Figure 5.24A Contour maps of air leakage rate through the gob under the original H-system and later the converted U-system of ventilation for the panel. However, the pressure balancing scheme is not implemented. The numbers on the contours have the unit of m³/s, and those on the rectangular boundary have the unit of m.
Figure 5.24B  Contour map of air leakage rate through the gob under the U-system of ventilation for the panel depicted in Figure 5.23. The pressure balancing scheme is active. The numbers on the contours have the unit of m³/s, and those on the rectangular boundary have the unit of m.
ventilation network analysis. The result of the pressure balance has been reported here for a fixed size of the gob, i.e. one stationary position of the face. However, the same exercise can be carried out for each position of the face indicated in Figures 5.16A, 5.16B, 5.16C, 5.16D, 5.16E, 5.16F, 5.16G, and 5.16H. The similar analysis can be applied to determine an interval of face movement within which the prevailing pressure balance can keep air leakage into the gob in within a tolerable limit. Airflow through the face areas before and after the implementation of the proposed scheme was not allowed to change significantly. However, airflow inside the gob area decreased drastically (as shown in Figure 5.24B). Also, the advantage of this system is that it contains the critical airflow zone close to the face at any of its position. As a result, no critical airflow zone is allowed to stagnate in the remote areas of the gob under the modified U-system. On the other hand, the presence of critical airflow zone in and around the return airways (i.e. tailgate in this case) close to the bleeder entries (and panel start line) give rise to severe spontaneous combustion in those locations under the existing system or a simple U-system (Figure 5.24A).
VI. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The objectives of this research are (i) to prevent and control spontaneous combustion by minimizing air leakage into a gob of a coal mine, and (ii) to alleviate the hazards of methane emissions in the gob. Based on this research, the following conclusions may be drawn.

The detail analysis of various ventilation layouts shows that the bleederless system with an appropriate gas drainage measure is efficient for controlling self-heating. Among various ventilation layouts, the W-system of ventilation is most effective in reducing the quantity of air leaking into the gob, without resorting to an additional pressure balancing system. However, the U-system of ventilation can be considered as an alternative to the mines and their longwall panels under severe overburden loading. For the multiple-entry retreatting panels, pressure balancing at the back of the face support line is found to reduce air leakage into the gob to a significant extent. With the proposed modified U-system, high airflow requirement at the face can be met, especially for the mines where high methane emission at the face is to be diluted.

Multiple entries of a longwall panel are utilized in the proposed behind-the-face-shield-line pressure balancing system. The use of multiple-entry is not otherwise recommended in the coal seams where spontaneous heating is a crucial problem, because with the increase in the number entries the number of cross-cuts and stoppings and sealed sites increases. Multiple entries reduce the overall panel resistance, and hence, the ventilation pressure requirement, which in turn reflects on the overall fan duty for the mine.

In retreat panels, the bleederless ventilation system does not require heavy sealing or stoppings during its active period, and hence, the cost of mining is reduced. Also the risk of self-heating in or around the seals due to leakage is minimized. In addition, the bleederless systems have the following advantages:

i.) The cost of maintaining bleeder entries can be eliminated. Also, panels require less air and hence, less capacity of the main fan and power.
ii.) The bleederless ventilation system helps in recovering commercial grade methane from the gob because this system minimizes the dilution of the gob gas.

iii.) Airflow at the face need not have to be increased in order to keep methane concentration within a permissible limit, when a methane drainage system is used efficiently. Therefore, the deeper penetration of the critical zone with the increased leakage into the gob can be avoided.

Without using a monitoring system, it is possible to keep track of the changing environment inside the gob at any point of time, which would otherwise have required extensive installation and reliance on a sophisticated and expensive monitoring system. However, a monitoring system may be useful as a safety precaution, and also in verifying and validating the results of simulation.

For the longwall system of mining, retreating panels are preferable to advancing panels for minimizing air leakage in the gob areas and so the possibilities of self-heating.

6.2 Recommendations for Future Work

Within the boundary of the available resources and time, the depth and breadth of the foundation for the present research work has been laid. Limitations have been encountered in several areas. Also, extension of the work has been envisioned for future in those and other areas for fine tuning in the framework of the research findings. Some of those salient areas have been enlisted below and discussed.

The gob can be characterized based on the results of study on (1) the caving behavior of overlying strata loading on the gob, and (2) by using the changing ventilation parameters, such as airflow through a panel and the pressure drop across it, with the movement of the longwall face.
All of the flow analysis conducted in this study approaches closer to the reality if the gob is modeled properly. The porous medium of the gob is the basis of forming the flow network. Detailed characteristics of the caved rock mass, especially the size and shape variations within each of the blocks, in which gob is subdivided, are to be included in the estimation of flow resistance of the block. The geological disturbances in the gob areas should be considered appropriately for gob modeling.

Load distribution due to caving may be measured by using point load measuring devices spread out all over the gob floor. Based on load distribution, the different areas where load is only due to a heap of broken rock mass, and where the weight of the caved overburden is added onto the broken rock mass on the floor, may be identified for modifying the proposed gob model.

The effects of first loading and periodic loading in the areas adjacent to the face line are to be considered in gob modeling, especially for identifying the impact on the critical airflow zones close to the face line. Any probable correlation between the frequency of periodic loading and the extent of increase in the gob loading, especially at the center while face is moving, may be sought through future research. For the shallow mines, subsidence characteristics may be used for estimating the gob loading characteristics because they have a direct correlation with the gob caving behavior.

Ventilation survey data collected at a regular interval of face movement can be used for gob characterization. A careful analysis of the data will lead to a detailed resistance structure of the gob, appropriate for identifying the locations of "hot spots" where spontaneous combustion is active. In this approach, the characterization of the knowledge about physical parameters of the gob materials is not necessary. A detailed evaluation of the gob characteristics for one panel, starting from the face start line to the finish line, would be considered as a guideline for subsequent panels of mines, provided no major geological disturbances are encountered.

A gob characterized on the basis of ventilation data will lead to a comparative evaluation of degree of compaction in different parts of the gob. This result will directly correspond to the caving characteristics of the strata over the panel, especially its movement with the advance or retreat of the face.
Based on load and/or materials characteristics, porosity variation spatially or vertically at any point may be determined for the gob model. However, the gob characteristics on the basis of the ventilation survey data may be used for estimating gob loading at different points inside gob, as an inverse solution to the gob material characterization problem.

In the initial stage of the gob resistance network formation, a coarse grid (i.e. large blocks) should be chosen and then, if necessary, gradually the grid size may be reduced. In the process, the areas of high variability in airflow resistance can be identified. Focus should be centered on those areas through selection of an appropriate grid size. A more coarse grid should be considered for the other parts of the gob.

For a refined model of the gob, each block of the gob should be further subdivided and a row of parallel resistance elements should be assigned. Then the equivalent resistance should be estimated by combining the elements, as compared to assigning a single value of resistance in one flow direction for the whole block.

The relationship between permeability and porosity used for the gob modeling should be reevaluated, because the relationship is valid for a laminar flow condition only.

A method of differentiating laminar, transitional and turbulent flow zones, and if possible, their interfaces, and the use of the method in modeling the gob, should be considered. A mathematical analysis of leakage flow through the gob in three dimensions may be analyzed by using the finite element approach to the theory of non-linear infiltration field in the porous medium of the gob under large Reynolds numbers as suggested by a group of Chinese researchers (Xiang, Qiang, and Qian, 1993).

Quantity of air leaking into the gob is considered the governing parameter for self-heating. However, the physical factors, such as temperature, humidity, and oxygen concentration in different parts of the body of the gob, especially in the self-heating prone areas, play a vital role. The present model can be refined in order to incorporate the effects of these factors on self-heating. Spontaneous combustion characteristics of the coal under different particle size, airflow rate, humidity, temperature conditions are to be tested on a laboratory scale before deciding mine design parameters, specifically panel design parameters. Effects of all the factors mentioned in the last two paragraphs, including
airflow rate, are to be considered while delineating the critical zone for spontaneous combustion.

The concentration of carbon monoxide is a strong indicator of an ongoing self-heating process. In order to map the carbon monoxide distribution inside the gob area, a detailed method of analysis is needed. In this method, airflow distribution contour maps can be superimposed onto the carbon monoxide concentrations measured around the periphery of the gob. Based on the knowledge of airflow distribution on a grid-like network, the locations of maximum concentrations can be identified. These are the most likely sources of carbon monoxide or in other words, the actively self-heating spots.

In this dissertation, the focus is directed towards control of self-heating in retreating longwall panels because of their effectiveness. However, ventilation controls of self-heating in the advancing and room and pillar panels are yet to be worked out.

In the areas of active self-heating, localized inertization can be very effective. A partial recirculation of an inert gas around the point of injection is efficient and economical from the viewpoint of conserving the gas. In order to ensure the injection of an inert gas in the appropriate locations, a detailed interpretation of leakage airflow distribution is essential. That will lead to a good compliance between a leakage airflow distribution and an inert gas injection plan.

Apart from the inert gas injection, other alternatives to prevent or suppress the self-heating process of a gob may be investigated. For the remote areas of a gob, where ventilation control is not effective, supplementary control measures, such as back filling and others, can be considered. Use of incombustible or nearly incombustible and nontoxic materials, such as foam with high expansion and spongy characteristics to fill the void in the gob tightly and adhere to the surface of broken rock mass completely, can be considered for sealing the gob matrix. With this arrangement, methane from the roof and floor can be drained off efficiently.
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