MINE FIRE DETECTION SYSTEMS: A PRIMER

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ABSTRACT

This Bureau of Mines paper discusses a simple approach to the design and implementation of mine fire detection systems. Topics include state-of-the-art technology in fire sensors and systems, a discussion of the hazards that different types of fires can produce, and some simple guidelines for determining the level of protection required for different mining areas and types of combustibles used or stored.

INTRODUCTION

The successful performance of a fire detection system depends upon its ability to detect the presence of a fire rapidly and reliably. It should be sufficiently rapid so that there remains enough time to either safely evacuate a mine or successfully extinguish and control the fire, or both. It should be reliable so that false alarms are minimized without sacrificing sensitivity or time response. Systems should also be durable enough to withstand the mine environment over long periods of time while maintaining a high degree of reliability. Maintenance and calibration of the system should be simple and not require the expenditure of excessive time and labor to keep it operational.

Many factors influence the design of a fire detection system, such as the potential sources and modes of ignition, the types of combustibles involved, and the quantities of combustibles available for fire growth and flame spread. Mine air ventilation influences the growth and spread of a fire and also serves to transport the products of combustion to other areas of a mine remote from the fire. Fire sensor alarm thresholds place limits on the sizes of fires that can be detected. The time to respond to a detected fire, either in terms of evacuation or control and extinguishment, place additional time constraints on the design of fire detection systems.

These factors interact with each other, often in complex ways, and it is the definition and understanding of these factors and their interactions

that hold the key to the design of adequate and reliable fire detection systems. The level of understanding of the problem has increased dramatically within recent years and it is the intent of this paper to discuss the progress that has been made and how the information can best be used to implement fire detection systems in underground mines.

To address the potential for fire detection systems, a framework must be created with which the design of these systems can evolve. This framework should address not only the detection of fires, but also the levels of detection that may be required for different areas of mines. The different levels of detection are based upon the types of fires that may be expected, and their potential hazards. To begin to understand the problem, it is necessary to have knowledge about the fires that are most likely to occur and the sensors and systems available for their detection.

MINE FIRE SENSORS AND SYSTEMS

Most mine operators and mine safety personnel are familiar with mine-wide monitoring systems that are available from a number of different manufacturers. Mine fire detection is a major component of these systems, which now use CO fire sensors. Currently, the Bureau-developed submicrometer particle smoke detector is being developed commercially for use in such systems and should be available in the near future. Both CO and smoke detectors are product-of-combustion fire sensors. These sensors are designed primarily to detect the CO and smoke liberated from either a smoldering or flaming fire into the mine ventilation airflow where their concentrations are diluted and carried along with the airflow. The diluted concentrations of CO and smoke that are present within the ventilation airflow depend upon the rates at which they are produced relative to the quantity of air that mixes with these combustion products.

For fixed sensor alarm thresholds, it becomes apparent that very small fires may be detectable at low ventilation airflows, while at higher airflows larger fires are needed to reach the same alarm level. Sensor sensitivity, then, is an important parameter, but setting of alarm thresholds most often depends upon the mine background level of either CO or submicrometer particles. Alarm thresholds should be significantly higher than these background levels to protect against false alarms of the sensors. High false alarm rates can destroy confidence in a fire detection system, rendering the system useless. At the other extreme are sensors that are too insensitive, with high alarm thresholds incapable of detecting fires in their earlier stages of development. Figure 1 provides some insight into this type of phenomena. At low values of the alarm threshold level to background level ratio, false alarms significantly reduce the confidence in the system. As this ratio increases, so does confidence in the system, until, at some point, the sensor becomes much less sensitive to small fires and confidence in the system again decreases.

For CO fire sensors, confidence greater than 90 pct is usually achieved when this ratio is in the range of about 3 to 15, assuming that the background CO levels typically are 1 to 5 ppm and an alarm threshold level of 15 ppm is used. Assuming a minimum background level of 1 ppm, increasing the alarm threshold to greater than 15 ppm decreases the sensitivity of the system and, at much larger values, the system becomes incapable of achieving its desired function. A similar analysis can be made for smoke particles.

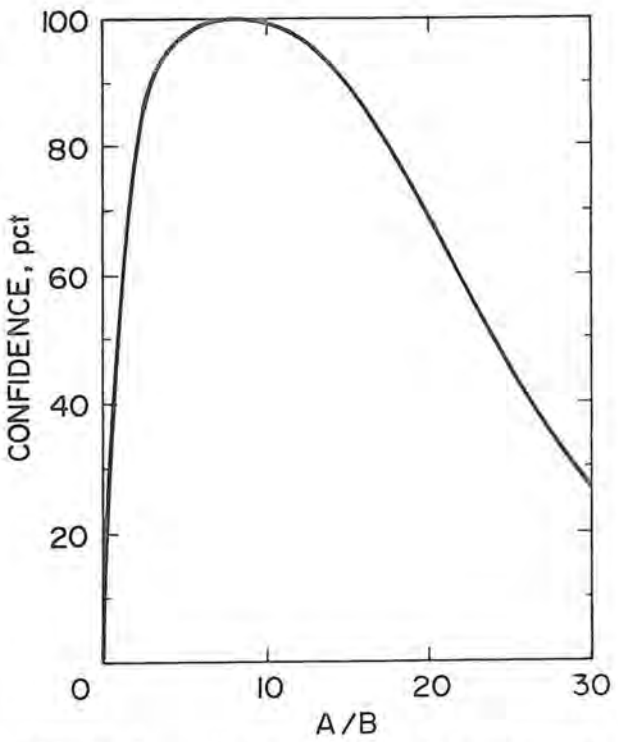


FIGURE 1. - Variation in the percent confidence in a mine fire detection system as a function of the ratio of alarm threshold level to background level (A/B) for product-of-combustion fire sensors.

The electrical and electronic components necessary for the system to operate must also exhibit a high degree of reliability. Their function is to provide power to the sensor, accept sensor signals, supervise the sensors to assure proper operation, and record and display information and alarms. This is usually done in two stages. Outstations, to which a number of fire sensors and other transducers (such as velocimeters) are electrically connected are installed underground. Sensor power is supplied by these outstations and sensor signals accepted. This information is then transmitted to a central processing unit, usually located aboveground at a permanently staffed location. The central station accepts the data from underground, records it, and if desired, displays it on a video screen. Many levels of sophistication are possible for the total system. What level is used depends upon the particular mine and its needs, as well as the cost of the system.

At the outstation level, most commercial systems are designed to accept signals from a variety of transducers. This is important from a fire detection standpoint when sensors, other than CO or smoke, such as optical sensors are used. Optical sensors, such as ultraviolet or infrared sensors, are fast responding detectors (approximately milliseconds or faster) that sense the radiant energy emitted by a fire. They are recommended for use in applications where instantaneous response is critical, such as fuel storage areas and power centers. Such sensors may not be available from the manufacturer of the monitoring system, but can be purchased separately and are easily interfaced with most monitoring systems. It is usually wise to determine in advance if a monitoring system can use a variety of transducers, or if interfacing them to the system is a simple procedure which is relatively inexpensive.

Mine monitoring systems and, in particular, those systems used primarily for fire detection have shown tremendous growth in use within the past 2 to 3 years. At the same time users of such systems are beginning to express some dissatisfaction with the calibration and maintenance requirements of the sensors. This is particularly true for systems installed in large mines where the number of sensors required can be quite high. Past research by the Bureau has shown that an alternative approach to that of fixed-point fire sensors is a pneumatic monitoring system.

For this type of system, individual tubes extend from a central pumping and detection station to the desired monitoring locations, as indicated in figure 2. This central station may be

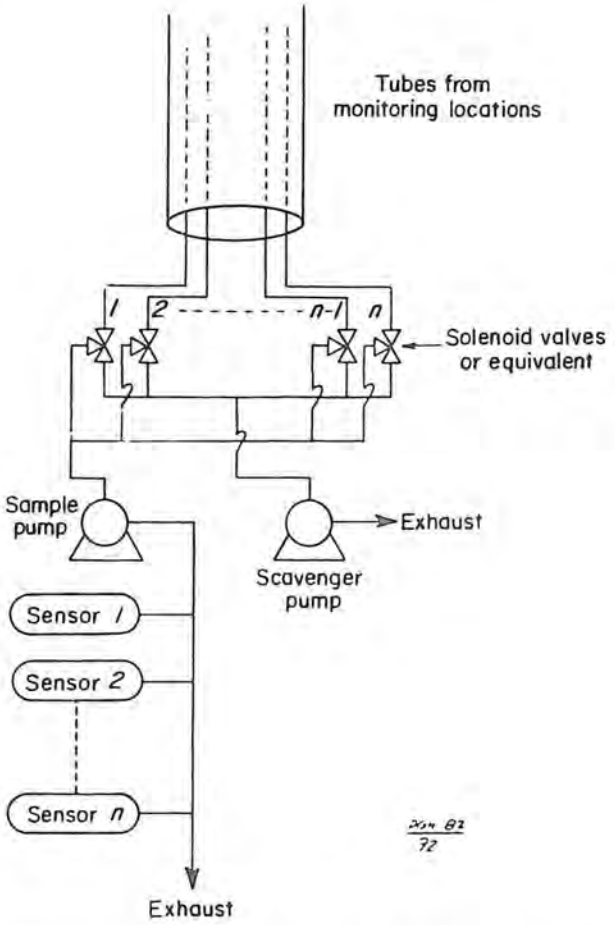


FIGURE 2. - Schematic of central detection and pumping station for use with a pneumatic fire detection system.

located aboveground or at some convenient location underground. When located underground, this central station is analogous to the outstation of the fixed-point mine monitoring system. At the central station, (fig. 2) all tubes except for the one being sampled are continuously purged by a scavenger pump. Each tube has its flow diverted through a three-way solenoid valve at fixed time intervals to a smaller sample pump, which presents the tube contents to one or more sensors for measurement of CO, smoke, or other gases of importance.

This type of system is attractive for a number of reasons. First, the cost of the system is less than that of a fixed-point monitoring system. Second, because all components, including sensors, are located at the same place, calibration and maintenance requirements are significantly less. Third, measurement of any additional gas at all locations is easily accomplished by adding a single gas analyzer to the system. This system is ideally suited for continuous monitoring of gobs, mined-out areas, return airways, etc. Through proper choice of tube diameters and pump capacities, the system can be designed for rapid response.

The use of this system suffers from the fact that it is not commercially available as a system. However, all components necessary are readily available, off-the-shelf items and design of these systems is easily accomplished.

FIRE CHARACTERISTICS

Fires produce heat, light, and combustion products (gases and smoke). These represent measurable quantities that, when detected at low levels, signal the presence of a developing fire. Fires develop through three distinct stages. The first stage is the preflaming, smoldering stage where fuel is pyrolyzed and produces products of incomplete combustion and fuel vapors that are eventually ignited, resulting in open, flaming combustion. Smoldering fires produce little heat or light, but copious amounts of smoke, CO, and often other gases. Further, the smoldering stage of combustion may last for prolonged periods of time, hours or days, or it may be of much shorter duration depending upon the source of ignition.

The transition to open, flaming combustion signals the beginning of the second fire stage. During this stage, detectable levels of heat, light, and products of combustion are produced as the fire grows in intensity. The rate of growth may also vary dramatically.

Liquid pool fires reach a stage of steady-state burning in a matter of several seconds, while fires of coal rubble or other solid combustibles grow in size at a much reduced rate. In general, this stage of the fire remains localized, consuming the combustibles present in the general vicinity until, at some point, the fire intensity is sufficient to produce propagation or rapid flame spread down an entry.

The propagating fire represents the final stage of a developing fire and represents the most severe hazard. Once this stage is reached, entire mines can be devastated. Little, if any, opportunity exists for either escape or control of the fire.

FIRE HAZARDS

Smoldering fires, or fires that develop to the point of smoldering due to spontaneous combustion or other modes of self-heating, produce little heat or light, but are more appropriately characterized by the liberation of smoke, CO, and other potentially toxic gases. External sources, such as overheated equipment or electrical shorts, may produce smoldering periods that last for minutes or hours, while smoldering fires of spontaneous origin may have much longer periods of prolonged smoldering before flaming combustion is reached.

The primary hazard associated with smoldering combustion is the toxicity of the smoke and gases that are produced. Knowledge of this toxicity is lacking and represents an area of intensive research. However, both CO and smoke are major products of smoldering fires and either CO or smoke detectors are capable of providing for early warning of this stage of fire development. Research into the relative toxicities of smoldering fires will provide the information necessary to evaluate the response of CO and smoke sensors relative to the potential toxic hazard. It is sufficient to say, for the moment, that CO and smoke sensors provide for early warning of most smoldering, incipient fires, but the relationships between their alarm level thresholds and the potential toxic hazard are not well understood.

The hazards that result from flaming fires are functions of the ratio of the fire size to the ventilation rate, expressed as Q_f/v_fA, where Q_f is the heat release rate of the fire (kW), v_f is the ventilation velocity (m/s), and A is the average entry cross-sectional area (m^2). Three major hazards result from fires:

1. Toxicity associated with the gases and smoke products of combustion

2. Reduced visibility (smoke obscuration) from the smoke particles

3. Fire propagation or rapid flame spread along the combustible surfaces of an entry.

The relative toxicities of products produced from a variety of mine combustibles is an area of research currently being addressed. It is known that CO is a major toxic gas component of the combustion products. Others have been found, such as HCl from materials containing chlorine. For purposes of this paper, it will be assumed that CO represents the primary toxic hazard reaching an incapacitating stage at a concentration of approximately 1,500 ppm (0.15 pct) or greater. The fire size necessary to produce this concentration is given by

$$\dot{(Q_f/v_fA)}_T \geq 300.04 \qquad (1)$$

where the subscript T denotes the toxic hazard.

The production of copious amounts of smoke severely reduces mine visibility

and can significantly reduce the potential for escape. It is generally recognized that when the smoke level reaches a concentration sufficient to reduce visibility by approximately 84 pct over a 12-ft path, an extreme hazard exists. To produce this reduced visibility, a smoke particle concentration of approximately 225 mg/m^3 is required. The fire size necessary to produce this concentration is given by

$$(\dot{Q}_f/v_f A)_S \geq 150.0, \qquad (2)$$

where the subscript S denotes the smoke hazard.

Fully developed, sustained fire propagation occurs when the hot gas temperatures from a fire are sufficient to ignite exposed surfaces of combustible materials along an entry. Both theory and data indicate that this condition is reached when the fire size is defined by

$$(\dot{Q}_f/v_f A)_P \geq 450.0, \qquad (3)$$

where the subscript P denotes the propagation hazard.

The times that are required for fires to reach these critical, hazardous levels can vary dramatically with the type of fuel involved, the amount of fuel available, and its distribution. Fires that involve spills of flammable liquids or liquid pools develop within seconds to these levels. For instance, a spill of liquid heptane, if ignited, will reach the critical smoke hazard level in 5 to 10 s, and the critical propagation hazard in approximately 40 s. Fire detection systems for these cases should also contain means for automatic suppression and extinguishment.

At the other extreme are fires that are preceded by prolonged periods of smoldering. Such fires generally occur in areas of the mine that are free from sources of external heat and energy, and are due to spontaneous, self-heating. The detection of these fires need not be so rapid. Several minutes or hours will generally suffice, but if left undetected, the consequences can be just as dramatic as those of the liquid pool fire.

Between these two extremes lie fires, usually of solid combustibles, which are ignited by external sources of heat and energy. Periods of smoldering may be of short duration or nonexistent. Once flaming occurs, the fire intensity begins to increase, although generally at a much slower rate than for a liquid pool fire. Clearly, once flaming occurs, there exists only a finite amount of time available to detect the fire, evacuate personnel, and extinguish the fire before the situation becomes critical, lives are lost, and property devastated.

Figure 3 illustrates the times that are involved during the growth stages of a fire involving solid combustibles (solid line). At the origin of the fire, alarm levels of smoke or CO are produced within a minute or so, perhaps even before flaming if there is enough smoldering combustion. Once these alarm levels are produced, the ventilation airflow carries them away from the fire to a fire sensor that must respond and issue an alarm. All of this must occur in approximately 15 min, or less. This leaves about 50 min before the fire reaches a stage where smoke obscuration becomes critical. In about another 60 to 70 min, the CO becomes life threatening, and within another 60 min the fire is spreading rapidly throughout the mine.

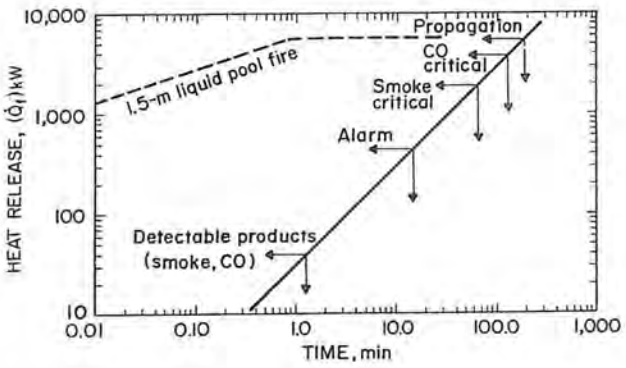


FIGURE 3. - Graphical representation of the sequence of events common to the development of many underground mine fires.

For comparison, the dashed line shows the growth rate of a liquid pool fire with a surface area of 1.5 m^2. In less than a minute, the fire is large enough to begin propagating.

From this discussion, it is apparent that fires of differing origins require different levels (or times) of detection. For smoldering fires, detection times of a few to several hours will suffice. For fires of solid combustibles driven by external sources of heat and energy, detection times of a few minutes are required. And for fires of flammable liquids or fires in areas where significant combustible materials (solid, liquid, or gas) are stored or used, detection must be within a few seconds and often must contain a means for automatic suppression of the fire. This analysis points to a need for defining those areas of a mine applicable to the three levels of detection.

It is proposed that a mine be divided into three distinct classes when considering the design of minewide fire detection systems. The first class (class I) areas are those areas where the risk of fire is high and also where the consequences are most dramatic. Typical class I areas would include fuel storage areas, fuel transfer areas, maintenance areas, and other areas where significant quantities of combustibles or flammable materials are stored or used.

The second class (class II) areas are those areas where the risk of fire and its consequences are not so great, but where there exist sufficient external ignition sources. Examples of class II areas would include conveyor belt entries, track entries, or other entries within which potential external sources of ignition exist and on which routine mining operations depend.

The third class (class III) areas are those areas where the risk of fire is the least. In general, these areas do not contain sources of external ignition, but rather, fires develop via spontaneous heatings or self-heatings independent of external sources. Examples would include return airways, mined-out areas which are feebly ventilated, and other areas that in general are remote and not crucial to the routine operation of the mine.

Class I Areas

In general, these areas are relatively small, localized areas where the risk of fire and its consequences are greatest. Rapid detection, often coupled with automatic suppression capability, within seconds is generally warranted. To achieve this level of detection, optical sensors, or a well-defined array of thermal sensors, should be used as the primary detection system.

While these areas may be well-defined, localized areas, they are also under the influence of some degree of ventilating airflow. Consequently, the possibility exists that these fires may contaminate the ventilating airstream before detection and suppression can be achieved. To provide some degree of protection against this possibility, it is also recommended that one or more product-of-combustion sensors be

located downstream of these areas in the primary ventilating airflow to detect any leakage of combustion products. Further, fires within these areas may, in some instances, be preceded by a prolonged smoldering stage for which no heat or light is produced. To provide protection for this possibility, a secondary product-of-combustion sensing system should be used in conjunction with the primary optical or thermal sensing system.

If the ventilation flow within a class I area is well defined, then the product-of-combustion sensor should be located within the area and immediately upstream of the point at which the ventilation flow from this area and the primary ventilating air mix. If the ventilation pattern within the area is poorly defined, then a system of two or more sensors spaced according to National Fire Protection Association standards (or equivalent standards) should be used.

To summarize, class I areas represent extremely high risk areas for which the potential consequences of fire are the most severe. Rapid detection of the initial flaming stages dictates the use of an optical or thermal sensing system. In many areas, the system should also contain automatic fire suppression capabilities. An additional secondary product-of-combustion fire sensing system should be used in parallel with the primary system to protect against the possibility of smoldering fires. One or more additional product-of-combustion sensors should be installed within the primary ventilating air immediately (approximately 50 to 100 ft) downstream of a class I area to protect against potential contamination of the primary air.

Class III Areas

At the other extreme lie the class III areas for which the risk of fire is the least. However, if these areas are left unprotected, then the consequences of fire can be just as dramatic. In general, these areas are characterized by the absence of external ignition sources. As a result, fires that develop in these areas can be expected to develop over longer periods of time, most probably because of spontaneous combustion or self-heating resulting from other causes.

Since no heat or light is produced during smoldering, the fire sensor of choice is a product-of-combustion sensor. The choice of which product-of-combustion sensor to use (CO or smoke sensor) depends upon the most probable fire scenario. If a mine has a history of spontaneous combustion or if the area to be protected consists of caved-in areas or gobs, then a CO sensor is the logical choice. This arises from the fact that CO is the best indicator of spontaneous combustion fires. Smoke is usually generated at a later point in time relative to CO. If smoldering fires other than those of spontaneous origin can be expected within a class III area, then smoke sensors are the obvious choice to provide an earlier warning. For smoldering fires of unknown origin, a combination of CO and smoke sensors may be warranted.

But where are the sensors to be located? Excluding for the moment return entries as class III areas, the bulk of class III areas can be expected to be remote areas, normally weakly ventilated and for which ventilation patterns may be ill defined. However, it is generally known that ventilating air goes into an area and comes out. To determine if combustion products are produced within this area, it is prudent to make a differential measurement. This means that a sensor should be located within the airstream entering a class III area and one outby the area to measure what comes out. The difference is what is produced within that area.

For primary return airways, sensors should be located immediately upstream of each junction of airways where flows mix. If, for instance, three splits of return air mix or merge at some point, then a sensor should be located within each split entry just prior to that point. An alternative to this approach would be to locate a single sensor immediately downstream of the mixing point. However, the concentration of CO or smoke measured at that point will be reduced because of dilution by clean air from the unaffected splits. This implies that a more sensitive detector may be warranted if only one is used. The single sensor approach also does not provide the information of which split entry contains the fire, and significant time may be lost in locating the fire.

Optimum location of mine fire sensors for the protection of class III areas is an area of research that needs to be addressed more explicitly. For these areas, the primary concern is the detection of fires in their spontaneous or smoldering stages for which function either CO or smoke sensors are the primary sensors to be considered. These products are carried from point to point by the ventilating airflow. As a result, the optimum placement of sensors depends critically upon accurate definition of the airflow patterns within these areas.

A tool that is ideally suited for this application is the Michigan Technological University mine (fire) ventilation code. Other ventilation codes exist, but this code is designed to provide information that is more relevant during a mine fire emergency. First, the code is capable of predicting ventilation patterns from a minimum of information. Second, the code is capable of predicting the rates of contamination of all areas of the mine by fire combustion products. The first capability can provide the information necessary to optimize fire sensor locations. The second capability can provide information relevant to the most prudent escape route to be followed during a fire emergency.

The code is available for use by the mining industry. Its potential for use as a tool in the design of fire detection systems is a subject of current research.

Class II Areas

Firmly entrenched between the class I and class III areas of a mine are the class II areas. For these areas, there exist many potential sources of ignition-overheated equipment, electrical arcs and shorts to name two of the most common. These areas are characterized by the presence of equipment necessary to the normal mining activity-conveyor belt haulage systems, electrical trolley entries, track haulage entries, etc. They are also entries, some of which may be long or short, that are frequently used and which are critical to the mine operation. Class II areas may contain class I areas, but these are separately protected.

The times that are available before critical hazards are reached in class II areas were previously discussed. Unlike class I or class III areas, the time to respond to a fire within a class II area is a significant factor, which must be addressed during the design stages of the system. Ventilation is usually well defined in class II areas, and it is the ventilation which transports the combustion products from a fire to a fire sensor. A good estimate of the spacing requirements between sensors can be made by multiplying the desired maximum response time by the velocity of the air within an entry. For instance, if a response time of 15 min or less is desired in an entry where the velocity is 100 ft/min, then the sensor spacing should be no more than 1,500 ft.

The detection of fires based on product-of-combustion sensors is one approach where the number of required sensors is relatively low. The sensors also provide a capability for the detection of any smoldering combustion, which would precede the onset of flaming. Thermal or optical sensors may also be used, but their numbers increase dramatically in order to provide the same level of detection. Such sensors would also be insensitive to any smoldering combustion that might occur.

DISCUSSION

There exist many areas of mine fire detection research that need to be addressed. The toxicity associated with products of combustion is not well understood. Advances in detector technology need to be made, especially for applications in diesel-operated mines where the diesel combustion products often overwhelm the fire products and render detection systems to a low level of reliability. The effects of ventilation patterns on developing fires and the converse effects of a fire on the ventilation system need further study in order to quantify these effects. Mine ventilation codes offer significant potential for use as tools in defining optimum sensor locations and in the preplanning of evacuation and escapeways.

Much remains to be done before the understanding of mine fire problems and detection systems is complete. Yet, the level of information and resources available at the current time indicate that there exists the potential for significant improvement in mine fire detection systems. As the level of understanding of these problems increases, so will the levels of detection that can be provided increase.

The design and implementation of fire detection systems need not be overwhelming. It can begin by identifying those areas of mines that are most in need of protection and building from there. The framework presented here serves as a guide to what is practical and possible with the present level of technology.

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