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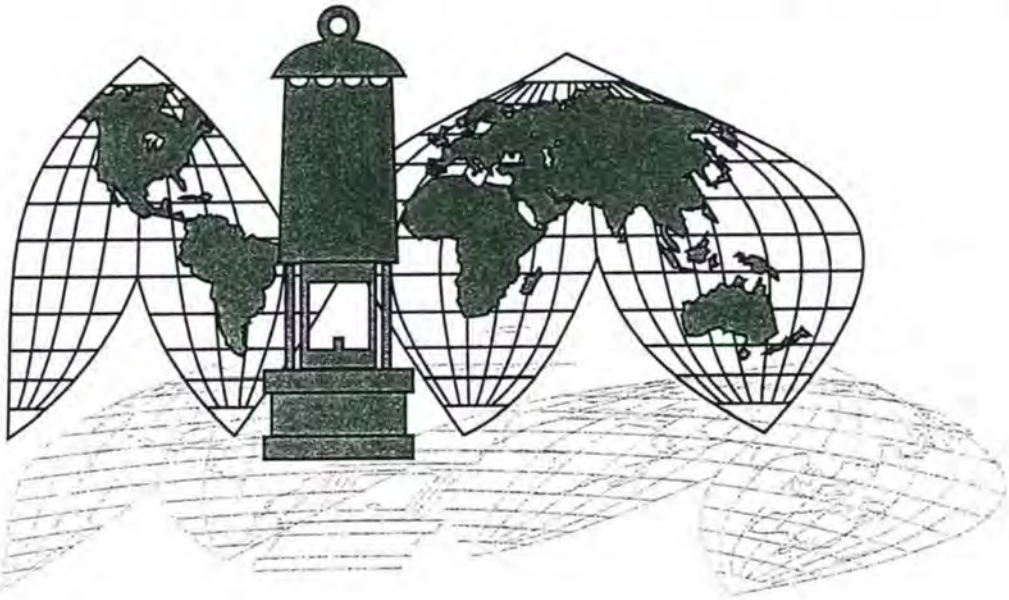

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OVERVIEW OF FIRE DETECTION TECHNOLOGY FOR UNDERGROUND MINES

by

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ABSTRACT

When methods to prevent the occurrence of fire in underground mines fail, the next line of defense in order to protect life and minimize the consequences of fire is to rapidly and reliably detect the developing fire so that subsequent evacuation and control procedures can be safely and successfully implemented. To provide this capability requires an understanding of the operational principles of different types of fire sensors, their merits as well as their limitations, and performance characteristics of the monitoring systems that control and process sensor data, an understanding of how fires develop and the different types of fires that can occur along with their characteristics and the hazards they present, an understanding of the impact of the mine environment and routine mining activities, not only in terms of these effects on fire sensors but also in terms of the impact of mine ventilation and mine geometry on fire growth, fire characteristics and the detection process. All of these factors are components of the technology of fire detection, and when insufficient knowledge of any of these components exists, the ability to implement adequate mine fire detection systems is diminished.

Within the last decade, significant advances have been made in fire detection technology applicable to underground mines. These advances include not only the development of improved sensors and better monitoring systems but also an expanded understanding of how to deploy sensors, set sensor alert/alarm levels, account for ventilation effects, etc. In addition, there has been an increase in our knowledge of the types of fires that occur, the types of combustibles involved, characteristic times for fire growth and development, the levels of heat, smoke and gas that are produced and the hazards that result. It is the intent of this paper to provide not only an overview of current mine fire detection technology, but also to describe a framework for the implementation and optimization of this technology. This paper will discuss the data, information, and resources that are currently available and seek to identify those areas most in need of further research and development.

INTRODUCTION

Fires represent one of the most hazardous accidents that can occur in underground mines for a variety of reasons. In coal mines, the solid coal roof and rib

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represent an essentially continuous source of fuel, so that fires that develop beyond their incipient stages have unlimited potential to spread and grow in intensity provided that sufficient oxygen is available. Even in non-coal mines wood is used so extensively that an essentially continuous source of fuel is still present for subsequent flame spread and fire growth. In addition, significant quantities of other combustibles, such as conveyor belting, diesel fuel, brattice cloth, electrical cables, etc., are often used and/or stored underground, presenting an increased risk for fire growth and spread. Ventilation airflow provides a continuous source of oxygen to sustain the fire, while at the same time serving to transport the smoke and toxic gases to locations within a mine that may be far-removed from the source of the fire. In typical underground workings, the routes for escape are often limited and the times necessary for evacuation can be long, increasing the probability that miners may be exposed to a spreading fire and its resultant hazards. In addition to fuel and oxygen, some source of heat must be available to ignite the fuel and sustain the initial stages of fire growth. When fire prevention methods are inadequate or have failed, and all three elements (heat, fuel, and oxygen) exist at some point in time and location, then there also exists a partial recipe for disaster. If the subsequent growth and development of the fire go unheeded, then the recipe for disaster is complete. In order to provide protection against these disastrous consequences, early-warning fire detection systems should be used.

Typical early-warning fire detection systems consist of three major components, or sub-systems. First, there is the array of sensors distributed throughout a mine or portions of a mine; second, there are underground stations that provide power to the sensors, receive signals from the sensors, and relay these signals to the third component, a central monitoring and control station, usually located above-ground in a secure location. This third component inspects the sensor outputs, issues alerts/alarms should they occur, identifies malfunctioning sensors, and in general, continuously monitors the system to ensure its functionality. Clearly, each of these components is necessary and critical in order for the system to achieve its intended function. There is also a fourth component to the system, just as crucial to the success of the system as the first three, that consists of a knowledge base used to determine the relationships that exist between the fire, the mining environment, the sensor characteristics, and the levels of protection that can result. This knowledge base is, of necessity, a continuously evolving process that must adapt to changes in mining methods, new developments in sensor technology, and a broad range of possible fire scenarios that can occur. It is the intent of this paper to focus on both the first and fourth components of fire detection systems in terms of the current status of our knowledge about the different types of fires that can and do occur, the major characteristics of the different fires, the interaction of the ventilation airflow with the developing fire, and the types of sensors that are available and their characteristics. It will be shown how all of this information can be used to define the type of sensor, the sensor alert/alarm level, and the optimum sensor locations that should be used in typical underground mining configurations in order for fire detection systems to achieve their intended purpose of providing sufficient early-warning capability.

SIMPLE ANALYSIS

The basic principles of fire detection can be summarized conveniently in figure 1, where the level of fire intensity is plotted as a function of time. The scale of the y-axis indicates the level of hazard that exists and as the fire intensity increases the level of hazard also increases. There are no units on either of the axes because for different types of fires these scales can change dramatically, although the basic trends remain the same. At some point in time, usually referenced to zero time, heat is supplied to a combustible. This heat may come from some external source, such as an overheating idler along a conveyor haulage system or a shorted electrical cable, or the heat may be internal due to spontaneous combustion or self-heating of a mass of coal or rotted wood. Regardless of the source, if the level of heat supplied to the combustible is sufficient to initiate exo-thermic reactions within the combustible or at the combustible surface, then the initial stages of a fire have begun. What often follows is a period of time where the level of fire intensity and the associated hazard are very low. This stage of fire development is usually associated with the smoldering stages of a fire, but the duration of this time period can vary significantly depending upon the type of fire. For instance, if sufficient heat is supplied to a pool of liquid fuel, such as diesel fuel, flames result almost instantaneously and there is no smoldering. If the source of heat is an overheated idler and is in contact with loose coal, then the duration of this smoldering stage is usually on the order of a few to several minutes. At the other extreme are self-heating fires, or fires of spontaneous origin, where the duration of this stage may be days to weeks.

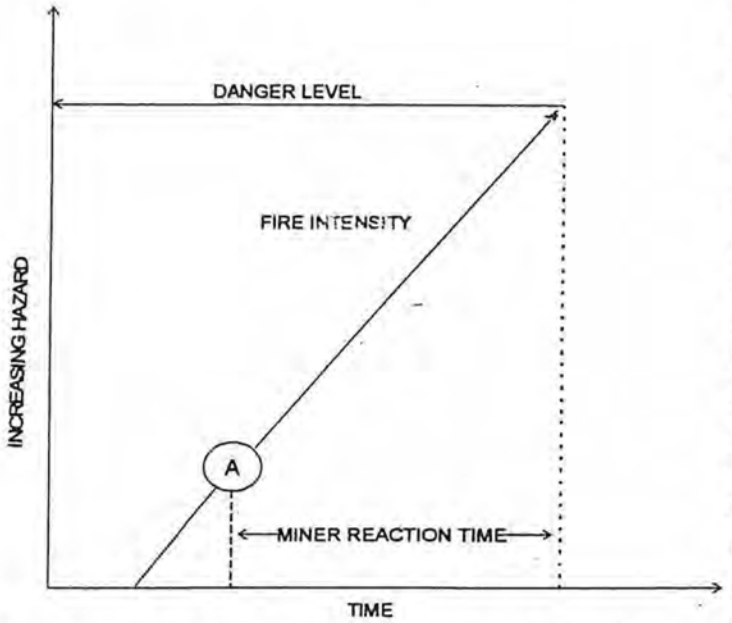

Figure 1.--Generalized schematic illustrating significant events relevant to early warning fire detection.

Regardless of the duration of this stage of fire development, at some point the fire undergoes a transition to flaming, and the fire intensity, along with the resultant fire hazards, begins to increase. In the absence of any efforts to control or extinguish the fire, and provided that there is sufficient combustible and oxygen available, the fire will continue to spread and increase in intensity. Eventually, the fire hazards that result will reach a danger level that can seriously impede the miner's ability to escape or to control and extinguish the fire. This danger level can be defined in many ways. It could be the

point at which the fire begins to produce large quantities of smoke and toxic gases, such as carbon monoxide (CO), that can severely reduce a miner's survivability. Or it could be the point at which the fire intensity is sufficient to spread to other combustibles and result in an accelerated rate of fire growth.

The times to reach this level of hazard can also vary dramatically, depending upon the type of fire and the combustibles involved. For liquid fuel fires, the time for flames to spread across the fuel surface are typically less than a minute, independent of the total surface involved, resulting in extremely intense fires and high levels of hazard. Fires that develop in conveyor belt entries usually involve loose coal initially, but can spread to the conveyor belting, where rapid flame spread and fire growth can occur. For these types of fires, the danger level can be defined in terms of the fire intensity sufficient to result in flame spread along the surfaces of the conveyor belt, with fire growth times to achieve this level of intensity typically in the range of 30 to 50 minutes. Once a conveyor belt is ignited and even before the onset of rapid flame spread, the levels of smoke and toxic gases that are produced increase substantially, resulting in hazards that severely reduce a miners' ability to escape.

At some point during this period from the onset of flaming to the fire's danger level, the fire sensor detects the fire and the detection system issues an alarm. This event is denoted by the "A" in figure 1. The time that remains from the system alarm until the danger level is reached is called the "miner reaction time," and represents the expected time available for miners to initiate the evacuation procedures and successfully escape the fire-affected area. The expected time available is an extremely important concept to understand in order to maximize the miners' chances of escape and survival and is worthy of a brief discussion.

Depending upon the type of sensor that results in an alarm and its location within the mine, there is an associated worst-case fire scenario that can occur, which, in turn, defines the minimum expected amount of time that may be available for evacuation and escape. Mine safety personnel and miners should not be lulled into a false sense of security by assuming that early-warning fire detection systems provide them with ample time to safely execute the evacuation process and escape. Conversely, mine personnel should prepare for the worst-case scenario, and, in the event that the worst-case scenario does not develop, their chances for escape and survival are dramatically improved. The reverse is not true, and the results potentially disastrous.

For example, in a previous report [Litton et al., 1991] which describes the requirements for fire detection in conveyor belt entries, the decision was made to define characteristic times for detection relative to the onset of flaming from a pile of loose coal rather than to the onset of smoldering because the characteristic times for smoldering can vary dramatically, and, in many cases, may not exist at all. The report then proceeds to define the maximum time available for detection as the time at which belt ignition can occur. In adopting this approach, the intent was to alert mine personnel to the potential speed at which fires can develop so that they can devise their evacuation and escape plans relative to the facts that when a fire is detected within a conveyor belt entry they should assume: a) that a flaming fire has been detected; b) that the conveyor belt is in the

process of being ignited; and c) that their evacuation must be executed swiftly and efficiently before the onset of flame spread along the conveyor belt surfaces.

Clearly, the earlier a fire is detected, the better are the chances for evacuation and escape. In some instances, such as the liquid fuel fire, the fire development times are so rapid that early detection alone cannot provide sufficient time for evacuation and escape. In cases such as these, automatic fire suppression/extinguishment systems should be used. Other examples of fires which can develop rapidly and which should include automatic suppression are fires at electrical power centers, fires in underground combustible storage areas, fires originating on mining equipment, fires in underground maintenance areas, etc. All of these situations are characterized by the propensity of fires to develop rapidly and involve significant quantities of combustible. At the other extreme are fires that develop due to spontaneous combustion or self-heating of a mass of combustible. For these types of fires, the time available for detection can be long. Hours or days are not uncommon, and in some cases, weeks can elapse before these developing fires burst into flame and begin to increase in intensity at a much-accelerated rate. In between these two extremes are fires that develop in conveyor belt entries, or within other entries, where the characteristic times for growth and development of significant hazard levels is typically on the order of a few to several minutes. In each of these examples, the concept of early-warning dictates that fire detection systems must be designed and implemented relative to the potential fire scenario that may occur. This, in turn, means that the type of sensor that is used can have considerable variability in terms of the fire characteristic that must be detected in order to achieve early warning. In order to use the most appropriate sensor for a potential fire scenario, it is important to understand not only the fire characteristics, but also the different types of sensors available and their advantages and disadvantages for the various applications.

FIRE CHARACTERISTICS

Fires in their early, smoldering stages produce smoke and gases, such as CO, but very little heat or radiant energy. When flaming occurs, the smoke and CO continue to be produced, but measurable levels of heat and radiant energy also begin to be produced. Smoke, CO, and air temperature (a measure of the heat produced) are diluted by the ventilation airflow as they leave the fire source, thus reducing their levels as they move away from the fire and are convected downstream. In general, the generic equation that allows for the determination of the completely mixed, bulk average levels of these products is given by:

$$\Delta X = \beta_x \cdot Q_f / V_o A_o \qquad (1)$$

where ΔX represents the increase in gas temperature, smoke, or CO above their ambient levels in the appropriate units. For temperature, T, the units are °C; for smoke, optical density (D), the units are m^{-1}; and for CO, the units are parts per million (ppm);

Q_f is the heat release rate (HRR) of the fire, expressed in kw;
V_o is the ventilation air velocity, in m/s;
A_o is the cross-sectional area of an entry, in m^2; and,
β_x represents a parameter which relates the increase, ΔX, to the ratio of HRR to total airflow, V_oA_o.

For gas temperature, the parameter β_T is independent of the type of combustible and is equal to $1/\rho_oC_o$, where ρ_o is the density of air and C_o is the specific heat of air at constant pressure. In addition, as the hot air is convected downstream from the fire, the average gas temperature decreases due primarily to convective heat losses to the surfaces of the entry. In general, an adequate expression for the average gas temperature as a function of distance, d, in meters, downstream of the fire is given by:

$$\Delta T(d) = (\Delta T)_o \cdot \exp(-\gamma d) \tag{2}$$

where $(\Delta T)_o$ is given by equation 1, above, and the parameter, γ, is a function of the perimeter of the entry, P_o, the cross-sectional area of the entry, A_o, and the air velocity within the entry, V_o. From a previous report [Perzak et al., 1995], the expression for γ is:

$$\gamma = 4.3 \times 10^{-3}(P_o/A_o)^{1.2}V_o^{-0.20} \tag{3}$$

For smoke or CO, the respective values, β_D and β_{CO}, depend upon the ventilation air velocity in the vicinity of the fire, and, in general, decrease as the air velocity increases. In addition, these parameters are also dependent upon the type of combustible. For detection purposes, especially in conveyor belt entries, it is generally assumed that the combustible involved during the early stages of fire development is loose coal. For loose coal, when the combustion product is CO and the change in CO above ambient, ΔCO, is measured in ppm, β_{CO} has been found to vary with air velocity according to the expression [Litton et al., 1991]:

$$(\beta_{CO})_{COAL} = 4.80 \cdot \exp(-0.175 \cdot V_o) \tag{4}$$

and when the combustion product is smoke, and the change in smoke optical density above ambient, ΔD, is measured in m^{-1}, β_D varies with air velocity according to:

$$(\beta_D)_{COAL} = 0.037 \cdot \exp(-0.10 \cdot V_o) \tag{5}$$

For styrene butadiene rubber (SBR) conveyor belts as the combustible, the data show similar dependencies with air velocity [Perzak et al., 1995], with the β_{CO} and β_D values given by:

$$(\beta_{CO})_{SBR} = 9.1 \cdot \exp(-0.35 \cdot V_o) \tag{6}$$

and,

$$(\beta_D)_{SBR} = 0.07 \cdot \exp(-0.35 \cdot V_o) \quad (7)$$

both greater by about 90%, than the respective coal values.

In addition to the determination of the various β_x values, the rate at which the fire intensity increases with time is important during the early stages of fire development in order to determine the detectable levels of heat, smoke, or CO being produced. For liquid heptane fuel fires, the data available [Newman and Khan 1984] indicate that the spread of flame across the fuel surface results in a heat release rate that varies with the 1/3 power of time, according to the expression:

$$Q_f = \alpha_f \cdot t^{1/3} \quad (8)$$

where the fire growth parameter, α_f, varies with the 5/4 power of the liquid fuel surface area, S, in m^2, according to the expression:

$$\alpha_f = 1050 \cdot S^{5/4} \quad (9)$$

where α_f has units of $kw/s^{1/3}$. Since the maximum heat release rate is limited by the exposed fuel surface area, S, and for heptane is given by the expression:

$$(Q_f)_{MAX} = 4505 \cdot S \cdot (1 - \exp(-1.25 \cdot S^{1/2})) \quad (10)$$

solving for the time necessary for the flame to spread across the total fuel surface indicates that this spread time occurs within several seconds. For instance, if the fuel surface area is 1.0 m^2, then the maximum HRR of about 3200 kw is reached in about 29 s. If S is 3 m^2, then the maximum HRR of 12,000 kw is reached in about 25 s. These large heat release rates and the short time periods over which they can occur tend to re-emphasize the necessity of using automatic suppression systems in areas where these types of fires are most likely to occur.

For fires that involve loose coal, the fire growth rate is much slower and the fire growth parameter depends upon the ventilation air velocity via the expression [Litton et al., 1991]:

$$\alpha_{COAL} = 1.65 + 0.90 \cdot V_o \quad (11)$$

where the units for α_{COAL} are kw/min. Since the heat release rate for loose coal fires as a function of time is given by:

$$(Q_f)_{COAL} = \alpha_{COAL} \cdot t \quad (12)$$

where the time, t, is in minutes, it is clear that such fires could develop over long periods of time before they, themselves, represent a significant hazard. Unfortunately, the major hazard from this developing fire is that it will spread to other combustibles, and often in

relatively short periods of time. In conveyor belt entries, the data available [Litton et al., 1991; Perzak et al., 1995] indicates that, on the average, small coal fires can ignite SBR conveyor belting when the ratio of coal fire heat release rate to local air velocity, $(Q_f)_{COAL}/V_o$, exceeds a value of around 25 to 30.

This would mean, for instance, that if the air velocity were 1.5 m/s, then a coal fire with an intensity of around 45 kw would be sufficient to ignite an SBR conveyor belt, and from equations 11 and 12, the time to reach this value would be 15 minutes. Once an SBR conveyor belt is ignited, the rate of fire growth increases linearly with time (i.e., $(Q_f)_{SBR} = \alpha_{SBR} \cdot t$), and the belt fire growth parameter varies with the air velocity according to:

$$\alpha_{SBR} = 9.9 \cdot V_o^{1/2} \tag{13}$$

where, as for α_{COAL}, the units of α_{SBR} are kw/min. Once an SBR conveyor belt is ignited, then the fire intensity at which belt flame spread begins to occur is given by:

$$(Q_f)_{BFS} = 400 \cdot V_o \tag{14}$$

For instance, if the air velocity is 1.5 m/s, then belt flame spread begins when the total fire heat release rate reaches about 600 kw. This means that the fire intensity has increased by 555 kw from the value of 45 kw at ignition, and, assuming the coal fire to continue its growth, the sum of $\alpha_{SBR} = 12.1$ and $\alpha_{COAL} = 3.0$ (i.e., $\alpha_{TOTAL} = 15.1$) divided into 555 yields a time of about 37 minutes to reach this level of fire intensity once the belt is ignited. If the danger level, as previously discussed, for this scenario is the onset of belt flame spread, then a total expected time of about 52 minutes is available from the time that flames erupt from the loose coal until the onset of belt flame spread, 15 minutes for detection to occur just as the belt ignites and another 37 minutes for evacuation and escape to be successfully implemented.

For detection of this developing fire to occur within the prescribed 15 minutes, the sum of three individual time components must be ≤ 15. These components are:

1. $(t_A)_X$, the time required for the coal fire to produce a concentration of product X equal to the alarm concentration set for the fire sensor;
2. t_T, the average time necessary for the ventilation air velocity to carry the product from the fire to the sensor; and,
3. t_R, the time for the sensor to respond to the alarm concentration and issue an alarm at the central control station. Since, typically, the response time of the sensor is quite rapid and the transmission of the alarm signal to the above ground station also quite rapid, a value of $t_R = 1.0$ minute is usually sufficient. This means that 14 minutes remain for the fire to produce some alarm product level and have that product transported to the sensor. If sensor spacings are typically about 305 m apart in conveyor belt entries, and there is equal probability of a fire occurring at any point between two sensors, then the average distance the product must be transported is ½ the sensor spacing, or 152.5 m. Since the air

velocity is 1.5 m/s, the average time to travel this distance is 102 s, or 1.7 minutes. This now leaves a maximum of 12.3 minutes for the fire to produce an alarm concentration of product X. The job is now to determine the level of product X that is produced by the small coal fire within the allotted 12.3 minutes. In general, the relevant expression becomes:

$$(X)_A = [(\beta_X)_{COAL} \cdot \alpha_{COAL} \cdot (t_A)_X]/(V_o A_o) \quad (15)$$

If the entry is 2 m high and 6 m wide ($A_o = 12\ m^2$), and the product to be detected is CO, then the calculated alarm concentration for CO, for this example, is $(CO)_A = 7.5$ ppm. If the product to be detected is smoke, then the calculated alarm level is a smoke optical density of $(D)_A = 0.065\ m^{-1}$. In Title 30, Code of Federal Regulations 30CFR [30 CFR 75.1103-4 (1995)]*, smoke detectors are required to alarm at an optical density of 0.022 m^{-1}, or less. If this value of alarm concentration is used in equation 15, the time for the small coal fire to produce this level of smoke is calculated to be $(t_A)_D = 4.1$ minutes. When the values of transport time and alarm response time (1.7 and 1.0 minutes, respectively) are added to this time, it is found that the estimated time for the smoke detector to detect the fire and alarm is about 6.8 minutes. For a CO sensor to produce an alarm within 6.8 minutes, the CO alarm level would have to be 2.5 ppm, rather than the 7.5 ppm necessary for alarm within 15 minutes. Thus, this example tends to indicate that smoke detectors can provide for earlier detection, an aspect of the problem that will be discussed later in this report.

For thermal sensors, sensors used to detect increases in air temperature and result in alarm, the spacing required by 30CFR [30 CFR 75.1103-4 (1995)] is 38.1 m or less. For thermal sensors, it is not prudent to estimate the downstream gas temperature in terms of the average temperature, but, rather, in terms of the gas temperatures that can result in a layer of stratified hot gases that forms near the roof at distances close to the fire. These stratified roof layers are formed due to buoyant forces, with not only temperatures but also smoke and CO concentrations that can be significantly greater than the bulk average levels defined by equation 1. In order to take advantage of this stratification, which can often result in detection at much earlier times than estimated on the basis of average product levels, sensors of any type should be located as near the roof as practical. For temperatures within this layer, the experimental data [Litton et al., 1982] indicates that the following empirical expression is generally valid for a range of entry dimensions and ventilation air velocities:

$$\Delta T(d) = [Q_f/(\rho_o C_o V_o A_o)] \cdot 9 \cdot d^{-1/H} \quad (16)$$

where $\Delta T(d)$ represents the temperature increase in the roof layer (°C) at a distance d (m) from the fire; and,

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Code of Federal Regulations. See CFR in references.

H is the entry height (m).

Since the minimum alarm temperature specified in the regulations is 57.2 °C, and assuming the ambient air temperature to be 15.2 °C, then equation 16 can be used to calculate the fire intensity at which the thermal sensor will produce an alarm, assuming the fire lies equidistant from two sensors so that d is 19.05 m. Using the above example (V_o = 1.5 m/s and A_o =12 m^2), with H equal to 2 m, ρ_o equal to 1200 g/m^3 and C_o equal to 1.088 x 10^{-3} kJ/g•°C, the calculated value of the heat release rate is about 480 kw. Since the coal fire heat release rate at belt ignition was calculated to be 45 kw, it is clear that the thermal sensor does not detect the fire and produce an alarm until the belt is flaming. Using the equations for coal and SBR fire growth rates, the time at which the roof layer gas temperature reaches its alarm level is about 29 minutes after the belt has ignited, or about 44 minutes after the coal fire started flaming. Fortunately, detection has occurred prior to the onset of belt flame spread, but the remaining time of 8 minutes has significantly reduced the "miner reaction time" discussed previously.

Flames typically spread due to the transfer of heat to the surfaces of a combustible material, which may occur via either convective or radiative heating. Convective heating occurs when gases at elevated temperatures flow over the surfaces of a combustible, but, in general, the dominant mechanism of heat transfer in fires is radiative. High temperature soot particles in a flame produce continuum radiation throughout the spectrum, similar in characteristics to blackbody radiation, and responsible for the yellow color of most flaming fires. The intensity of this radiation depends not only on the flame temperature, but also on the concentrations of soot particles within the flame. The wavelength of maximum intensity is defined as the Wien peak and depends upon wavelength via the simple relationship, $\lambda_{MAX} = 2898/T$, where the maximum wavelength is in μm and the temperature in Kelvins. Since most flame temperatures of typical mine combustibles are in the range of 1,300 to 1,500 K, λ_{MAX} typically lies in the range of 1.9 to 2.2 μm.

As the concentration of soot particles and/or the volume of the flame zone increases, the emissivity, ϵ_f, of the flame increases, where the emissivity is a measure of the flame radiation to approach that of a perfect blackbody radiator. The expression defining emissivity is given by:

$$\epsilon_f = 1 - \exp(-a \cdot C_S \cdot L_B) \qquad (17)$$

where a is a constant that depends upon the flame temperature,

C_S is the soot particle concentration; and,

L_B is the mean beam length within the flame, which depends upon the flame volume and flame surface area.

For most mine combustibles and relatively moderate fire sizes, the emissivity is generally in the range of 0.6 to 0.8, and gradually approaches unity as the size of the flame increases. It is generally this type of radiation that contributes significantly to the spread of fire to other combustibles and for rapid flame spread which can occur along combustible surfaces, such as conveyor belts or ventilation ducts. As this radiation is

emitted from a flame, the resultant radiative flux at some distance, r, from the flame varies approximately inversely with the square of the distance. When this flux is incident upon the surface of a combustible material, the surface temperature begins to rise rapidly causing gaseous combustible fuels to be produced. When the combustible surface reaches some critical temperature, T_{IGN}, these gases ignite, producing flame. Depending upon the thermal properties of the combustible and its proximity to the fire, the times necessary for this to occur can be can be on the order of a few to several seconds. The equation that describes the surface temperature, T_S, as a function of incident radiant heat flux, q_i'', in kw/m^2, and time, t, is given by:

$$T_S - T_o = \eta \cdot q_i'' \cdot t^{1/2}, \tag{18}$$

where T_o is the initial, ambient surface temperature, K or °C;
η is a parameter containing the combustible's thermal properties and for wood has a value of 2.5; and,
t is the time, in seconds.

For illustrative purposes, assume that there exists a spherical flame with a radius, r_o, of 0.5 m, that the flame temperature, T_f, is 1,500 K, and that the emissivity of the flame is 0.70. The radiant flux emitted at the flame surface is readily calculated from the expression:

$$q_R'' = \epsilon_f \cdot \sigma \cdot T_f^4 \tag{19}$$

where σ is the Stefan Boltzmann constant equal to 5.67×10^{-11} kw/(m^2•K^4). The radiant flux leaving the flame surface is found to be approximately 200 kw/m^2. At some distance, r, from the flame is a typical wood, with a surface ignition temperature of about 673 K, and thermal properties such that η has a value of about 2.5. First, the ignition temperature can be used to define a minimum, critical radiant flux, q_{CRIT}'', at which the wood surface will ignite using equation 19 with ϵ_f equal to about 0.9 and T_f set equal to the surface ignition temperature. The resultant value is about 10.5 kw/m^2. When the distance from the flame to the wood surface is sufficiently great that the incident radiant flux is less than this value, then ignition of the wood surface cannot occur. For values of incident radiant flux greater than this value, ignition will occur, but the time for ignition will vary, depending upon the magnitude of the flux. For the spherical flame assumed above, the incident flux at a distance r can be calculated from:

$$q_i''(r) = q_R'' \cdot (r_o/r)^2 \tag{20}$$

The value of r at which the incident flux equals the critical flux can be found to be about 2.2 m. At distances less than this value, ignition of the wood will occur. For instance, if the distance is 1.5 m, the incident flux is 22.2 kw/m^2, and from equation 18, if the ambient temperature is 293 K (20 °C), then the minimum time to ignite is about 47 seconds. If the spherical flame expands to a radius of 1 m, and the emissivity

increases to 0.9, then the critical distance for ignition increases to almost 5 m. In fact, if a constant emissivity of 0.9 is assumed and the flame temperature remains constant, the critical distance for ignition of a wood surface is approximately 5 times the flame zone radius. For this larger flame, a wood surface at a distance of 1.5 m could ignite in about 2 seconds. Even at a distance of 3 m, ignition could occur in less than 30 seconds. These examples clearly indicate the rapidity with which fires can spread to other combustibles, even for combustibles located at distances removed from the actual fire.

FIRE SENSORS

The types of sensors generally available can be divided into four broad categories:

1. thermal, or temperature, sensors;
2. optical, or radiation, sensors;
3. gas sensors; and,
4. smoke sensors.

Within each category there are diverse principles utilized in order to achieve detection of a particular fire characteristic. What follows is a brief description of some of the most widely used detection principles and techniques.

Thermal Sensors

The most universal thermal sensor is the thermocouple, a bimetallic junction that generates an emf (voltage) when heated. Another thermal sensor is the thermoresistive type, such as a thermistor, which changes in resistance as the temperature increases. A more versatile thermal sensor is the line-type heat sensor, which can form a continuous heat sensor along the roof of an entry, or other space to be protected. By connecting the sensor in an electrical circuit and monitoring some electrical characteristic, such as current or frequency, changes in the electrical characteristic indicate temperature increases in the gas temperature surrounding the sensor. A fiber optic cable is a special example of this type of sensor. At one end of the cable, monochromatic light enters and then exits at the other end, where it is detected. When the cable temperature begins to increase due to increases in the surrounding gas temperature, the refractive index of the fiber optic waveguide changes, distorting the monochromatic beam. This distorted beam is detected and an alarm given. Sophisticated versions of this type of sensor can pinpoint the location at which the distortion occurs, thus facilitating identification of the fire location.

Fixed-temperature sensors are made of temperature-sensitive materials which can expand, bend, or fuse at specified temperatures. This type of sensor is most often used in sprinkler heads to actuate the sprinkler when specified gas temperatures are reached. Heat-sensitive plastic tubes are a version of this type of sensor, where the plastic tube is pressurized with a gas. An increase in the gas temperature surrounding the tube causes the tube to melt, resulting in a loss of pressure that is detected resulting in an alarm.

Rate-of-temperature rise thermal sensors respond to changes in temperature per unit time, and are generally more sensitive to large changes in temperature, somewhat limiting their usefulness.

Most thermal senors are robust and their performance not drastically affected by harsh mine environments. Because they respond primarily to open flaming fires, they require close proximity to the fire in order to be most effective. Because of this, their use is best-suited for applications in confined spaces, such as electrical power stations, underground fuel/combustible storage areas, underground maintenance areas, on-board mining equipment, etc. In addition, they are often most effective when coupled to an automatic fire suppression system.

Optical Sensors

Optical sensors respond to electromagnetic radiation emitted from a fire. As with thermal sensors, they are most responsive to flaming fires due to the increased levels of radiation that are emitted from the flame. This radiation can be produced, selectively, within discrete wavelength regions due to high temperature gases and radicals that are formed within the flame, or as a continuum, due to emission by high temperature soot particles, as discussed previously. Selective emission occurs in the near ultraviolet and blue visible regions of the spectrum due primarily to formation of OH and CH radicals within the flame zone. In the green region of the visible spectrum, molecular C_2 exhibits strong selective emission. In the infrared regions of the spectrum, both H_2O and CO_2 are selective emitters, with intense emission bands occurring near 1.8, 2.7, and 4.3 μm wavelengths, as well as weaker emissions at other wavelengths due to combination and overtone bands.

Optical sensors are designed to detect either selective emission or continuum emission, or both. They are usually classified according to the wavelength region of the spectrum to which they are most sensitive. Ultraviolet sensors respond to energy emitted between 0.18 and 0.40 μm; visible sensors respond to energy emitted between 0.40 and 0.75 μm; and infrared sensors, to energy emitted between 0.75 and 20.0 μm. Optical sensors, with time responses that range from a few picoseconds to a few milliseconds, are generally used for fire and explosion detection in applications where rapid response is a primary consideration. In the ultraviolet and short visible wavelength regions, most detectors are of the photoemissive type (i.e., photomultiplier tubes). This type of sensor utilizes a light sensitive material that emits electrons due to incident radiation. The emitted electrons move to an electrode, producing a current proportional to the intensity of incident radiation. At longer visible wavelengths and in the infrared, most optical sensors are either photovoltaic or photoconductive. Photovoltaic sensors are semiconductors which produce a voltage that is proportional to the intensity of the incident radiation, while photoconductive sensors are semiconductors that change their conductivity in proportion to the incident radiation.

In general, optical sensors are line-of-sight devices and find their greatest utility for fire detection in localized areas, such as those previously discussed for thermal

sensors, but for applications where rapid response is critical. Optical sensors can be used for the detection of hot and cold spots within mines and for detecting overheating equipment and machinery. Optical sensors are often used for the early detection of gas and dust explosions where time response is critical in order to effect suppression and extinguishment of such explosions.

Gas Sensors

By far, the most common type of sensor used for fire detection in underground mines is the gas sensor, most notably for CO, because CO is produced in measurable quantities from both smoldering and flaming fires involving essentially any type of mine combustible. The most common type of CO sensor is the electrochemical type operated in a diffusion mode. In an electrochemical cell, a special electrode, such as platinized platnium, is placed within an electrolyte. When CO is present in the air passing over the electrolyte, a chemical reaction takes place at the electrode, resulting in a current that is proportional to the level of CO in the air. This current is then amplified and converted to a voltage that is proportional to the CO present in the air. Operation in the diffusion mode means that the air containing the CO diffuses to the electrolyte rather than being forced to flow to the electrolyte via a small pump. CO sensors are typically sensitive and reliable at concentrations of 1 ppm and higher, with uncertainties in the actual concentration of about ±0.5 ppm or lower. Because these sensors are a measure of the partial pressure of CO, some care should be taken during their calibration to insure that the sensor is not over-pressurized, a condition that results in de-sensitizing the sensor when in actual operation.

Other types of sensors, such as metal oxide semiconductors (MOS), are also sensitive to CO, but MOS type sensors also have much greater sensitivity to other oxidizable gases that may be present, some of these that may be produced during routine mining operations. Hence, this type of sensor can be less reliable and more prone to false alarms than electrochemical CO sensors. However, sensitivity to other gases may enhance detection during the early, smoldering stages of fire development, should such smoldering stages be of sufficient duration. This enhanced sensitivity is due to the formation of aldehydes and other aromatic hydrocarbons that are often produced at lower, smoldering temperatures. CO is also detectable using infrared absorption techniques, usually measuring the absorption at a wavelength of 4.6 μm, one of the primary CO absorption bands. But instruments based upon this approach are generally much more expensive than either electrochemical or MOS type sensors.

Another typical gaseous combustion product is CO_2, which is produced primarily during flaming and at much lower levels during smoldering. The methods available to detect CO_2 are based primarily on infrared absorption, and as for CO, can be somewhat expensive. However, if both CO and CO_2 were measured simultaneously, then the ratio of their concentrations can be used to determine whether the fire is smoldering or flaming. Smoldering fires result in CO/CO_2 ratios that are generally about 0.40 and higher, while flaming fires result in ratios that are about 0.15 and lower.

Smoke Sensors

Smoke sensors are sensors that detect concentrations of smoke particles that are produced from fires. An individual smoke particle is usually made of chains of much smaller primary particles and form many irregular shapes and patterns with each individual aggregate smoke particle containing a few to several hundred of these smaller, primary particles. Because of this, fractal theory can be used to more accurately describe the properties of aggregate smoke particles [Litton 1997]. Aggregate smoke particles produced during smoldering differ markedly from aggregates produced during flaming. First, the primary particle diameter of the smoldering aggregates is typically in the range of 0.070 to 0.075 μm, while flaming aggregates have a primary particle diameter in the range of 0.025 to 0.040 μm. Secondly, the radius of gyration, R_g, which is a measure of the size of an aggregate particle, is in the range of 0.20 μm for smoldering aggregates, while for flaming aggregates, R_g has a value of around 0.40 μm. Also, the number of primary particles that initially form a smoldering aggregate is typically on the order of a hundred or so, while flaming aggregates may contain, initially, around a thousand primary particles. The fractal dimension, D_f, which is a measure of the shape of the aggregate particle, is about 2.2 for smoldering smoke aggregates and about 1.8 for smoke aggregates produced from flaming fires. Aggregates that are more spherical in shape have larger values of D_f, while more elongated aggregates have smaller values. In addition to these differences in physical characteristics, smoldering aggregates contain a significant fraction of volatile components while flaming aggregates are mostly carbon, with negligible fractions of volatile components. Both physical and chemical differences result in different optical properties for the two types of smoke and can be important in the selection of the type of smoke sensor best-suited for particular applications.

There are two basic types of smoke sensors, namely, ionization-type and photo-electric type. In the most common photoelectric-type, the light from a small light source, such as a light-emitting diode (LED), is projected across an open cell and a light detector, located off-axis, used to measure the light that is scattered when smoke particle aggregates enter the cell. Typically, the light detector is positioned so that it measures the light scattered at angles between 45 and 90° as measured from the forward direction. In this type of detector, the intensity measured by the light detector is directly proportional to the optical density of the smoke. Because the intensity at the light detector is zero when no smoke is present, this type of detector generally exhibits good signal-to-noise characteristics and is quite sensitive. The characteristic equation that describes the relative scattered-light intensity as a function of scattering angle, θ, as measured from the forward direction, is given by:

$$I(q)/I(0) = [1 + (2q^2R_g^2/3D_f)]^{-D_f/2} \qquad (21)$$

where q is the modulus of the scattering vector and given as a function of wavelength and scattering angle by the expression:

$$q = (4\pi/\lambda)\cdot\sin(\theta/2) \quad (22)$$

If the wavelength of the light source is 0.63 μm, typical of a red LED, and the scattering angle is 45°, then for smoldering smoke aggregates, using the above-defined values of R_g and D_f, the relative intensity at this angle is 0.556. For flaming smoke aggregates, the relative intensity is 0.261. These two relative values, assuming equal smoldering and flaming smoke concentrations, indicate that the scattering type of photoelectric smoke sensor is more sensitive to smoke produced from smoldering fires than to smoke produced from flaming fires, a result generally verified experimentally.

Some photoelectric-type smoke sensors are based on the principle of light extinction where the light detector measures the intensity of light across the cell produced by the light source. When smoke enters the cell, this light is attenuated, reducing the intensity measured by the light detector and resulting in alarm. Because the light path across the cell is not very large, the resultant light extinction can be quite small. At smoke concentrations necessary for alarm, the percent of light attenuated by the smoke can typically be on the order of 1% or less of the total intensity, and to measure this level of attenuation reliably can be difficult. For this reason, the extinction method is more commonly used as an open path smoke sensor, where, for example, the light source is situated along one rib of an entry with its beam projected across the entry to the light detector located on the opposite rib. In this mode of operation, the increased path length enhances the sensitivity, resulting in smoke attenuation across the path that is a significant fraction of the total intensity and increasing its reliability.

For example, the transmission of light along some path, L, in m, containing smoke is given by the expression:

$$T = 10^{-D\cdot L} \quad (22)$$

where D is the smoke optical density in m^{-1}. The smoke optical density is related to the mass concentration, m_o (mg/m^3), of smoke particle aggregates by the expression:

$$D = (1000\cdot\sigma_{EXT}\cdot m_o)/2.303 \quad (23)$$

where the parameter σ_{EXT} is the specific extinction (m^2/g), and for flaming coal smoke, has a value of 9.6 [Litton 1997] at a wavelength of 0.63 μm, the wavelength of a typical red LED. As discussed previously, smoke sensors must detect a fire and produce an alarm at smoke optical densities of 0.022 m^{-1}, or less. For a small smoke sensor, the path length, L, across the sensing chamber is typically about 0.025 m, and from equation 22, the transmission at the maximum allowable smoke optical density can be calculated to be 0.9987. If instead, the light source and light detector measure the transmission across the width of an entry, where L may typically be about 6 m, then the transmission becomes 0.7379. This change in intensity, about 26%, can be measured more easily and reliably than the much smaller change, 0.13%, that would occur if light source/detector were within the sensor.

In the ionization-type, a small quantity of radioactive material is used to generate ions in the air space between two electrodes. In the most common ionization-type, a third, collector electrode is placed between the two primary electrodes and the potential on this electrode measured. When the ions are produced, the potential between the primary electrodes is distorted due to space charge effects, resulting in a reduced potential at the collector. When smoke particle aggregates enter the air space between the electrodes, the ions attach to the aggregates, depleting the ions, reducing the distortion of the potential due to space charge, and causing the potential at the collector electrode to increase. The increase in collector potential is detected resulting in an alarm. In some versions of the ionization-type smoke sensor, the current at one of the primary electrodes is measured and no collector electrode used. Again, when smoke is present, the ion concentrations are depleted, producing a reduced electrode current and resulting in alarm. The expression that defines the reduction in current is given by [Litton 1979]:

$$I/I_o = (1/2\kappa_o R_g n_o)\cdot(1 - \exp(-2\kappa_o R_g n_o)) \qquad (24)$$

where κ_o is a constant that depends upon the geometry of the ionization chamber with a typical value of about 0.03 cm^2;
n_o is the number concentration of aggregate smoke particles, expressed as particles/cm^3; and,
R_g is the radius of gyration, expressed in cm.

This expression can be used compare the response of the ionization-type smoke detector to aggregate smoke particles produced from both smoldering and flaming fires. If the number concentration of smoke particles is 10^5, and using the previously-defined values of R_g, converted to cm, it is found that the current ratio for smoldering particles is 0.942, and for flaming aggregates, 0.889, indicating, in general, that ionization-type smoke sensors are more sensitive to smoke produced from flaming fires, a result typically verified by experiments. Unfortunately, no convenient analytic expression exists for determining the change in a collector electrode voltage, because this parameter depends strongly upon the geometry of the ionization chamber in order to distort the potential at this electrode. However, the relative change in voltage should remain about the same as the relative change in electrode current discussed above.

Although there are other techniques that can be used to measure smoke concentrations, such as condensation nuclei counters, direct mass measurements via tapered element oscillating micro-balances or via piezoelectric techniques, instruments based upon these principles are generally expensive and more suited for laboratory measurements than for underground smoke detection.

CONCLUSIONS

The data, equations, examples and discussion presented above provide a general summary of the level of fire detection technology currently available for under-ground

mines. In recent years, there have been significant advances in the knowledge and understanding of the different types of fires that can occur, the times associated with their development, the hazards that result from fires, the types of sensors generally available, and, perhaps, most importantly, how to integrate all of these factors into the design of a rapid and reliable early warning fire detection systems. There is, however, much room for improvement and further research. More sensitive and reliable fire sensors, especially for smoke, need to be developed and evaluated. Specific problem areas, such as the use of CO and smoke sensors in mines contaminated by the exhausts from diesel engines, improved sensors and techniques for the detection of spontaneous combustion, the impact of new mining methods and technology, and the integration of fire detection and automatic fire suppression systems in high hazard areas, need further research and development. Fires involving new and different combustibles used in underground mines, the potential fire hazards they may present, and the types of associated fire scenarios that result are continually in need of testing and evaluation. All of these areas, and others, are subjects of continuing research with the ultimate goal of providing life-saving, reliable mine-wide fire detection systems that can be applied with confidence to the many diverse fires that can occur in underground mines.

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