Ranking factors impacting survival during coal mine fires

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Abstract — *This study ranks the factors impacting survival during a coal mine fire. It has already been established that reducing time delays is the most important factor in saving lives. Consequently, every event during a fire is measured in terms of its duration, and the effectiveness of any action taken to improve survival is measured in terms of the time it saves.*

By ranking actions according to time saved, these authors found that a combination of actions was most effective. This combination was:

- *installing lifelines,*
- *moderately decreasing air leakage and*
- *decreasing the fire growth rate.*

Changing ventilation leakage alone was much less effective, as was altering the CO (carbon monoxide), sensor alarm threshold.

These results confirm an earlier fault-tree study on escape from mine fires. The fault-tree study had shown that, with the exception of delays, single-factor changes have minimal impact. Significant reductions in fire fatalities only take place with multiple-factor changes.

Introduction

When a fire occurs in a coal mine, it triggers a chain of events that may involve instrument performance, decision-making under uncertain conditions and knowledge of safety procedures. To reduce the hazard from fires, this event chain must be treated as a system of related events. By relating these events mathematically, the tradeoffs necessary for system optimization can be calculated.

Roberts (1987) has devised a simple, yet very effective, way to relate the various events taking place during a mine fire. He viewed the system as resulting from a competition between the creation and circulation of toxic fumes and the withdrawal of workers. This competition is represented symbolically by:

$$I = (T_1 + T_2) - (T_3 + T_4 + T_5) \qquad (1)$$

where:

I = a survival index (min) for a specified fire situation and a specified miner.

T_1 = time (min) for a fire to grow in size to produce a toxic concentration of fumes in the ventilation.

T_2 = time (min) for fumes from the fire to circulate in the ventilation to the point of escape from the contaminated airway.

T_3 = time (min) for fire detection.

T_4 = time interval (min) between fire detection and the beginning of worker withdrawal.

T_5 = time (min) for a worker to travel from his original location to a point of escape from the contaminated airway.

Increasingly positive values of I represent safer conditions. The essence of the Roberts' approach is that every event is measured in terms of the time it takes. Implicit in this simple analysis is the important notion that timely action is the essential element to saving lives during a mine fire. This notion is supported in a recent fault-tree analysis conducted by Goodman and Kissell (1989), who found that reducing time delays during a mine fire was by far the most important factor in saving lives. Using this approach, the effectiveness of any action taken to improve survival is measured in terms of the time it saves.

Objective

The objective of this study is to examine each of these time factors for fire conditions in underground US coal mines, and if possible, determine where gains in fire survival are most achievable.

Modification of Roberts' equation

US coal mines always have multiple entries. Thus miners will generally have the opportunity to escape through an entry adjacent to the one on fire rather than the one containing the fire. The important survival factors are how much air leaks from the fire entry and how long it takes the fire to grow to a size such that the concentration of leakage smoke and fumes makes the escape entry[1] unusable. To indicate that it is the escape entry concentration that is being used, T_e will replace T_1.

Also, when the fire takes place at a location outby the working face, it is very probable that workers must move toward and around the fire to reach fresh air. Since this involves passing close by the fire, then $T_2 = 0$. With these changes, the modified equation is:

$$I = (T_e) - (T_3 + T_4 + T_5) \qquad (2)$$

This study's approach will be to evaluate the time saved by various actions taken to improve survival during fires. A comparison of these times should then show the relative effectiveness of the various alternatives.

Estimating contaminant levels

For an estimation of contaminant levels, it is assumed that a fast-growing belt fire occurs and that its growth rate is similar to that seen by the US Bureau of Mines (USBM) during recent belt-fire testing (Litton, Lazzara and Perzak, 1991). Figure 1 shows the growth of a typical fast-growing belt fire during these tests[2]. The change in

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[1] This term "escape entry" is chosen since the exit route may or may not be the officially designated escapeway.

[2] In this test, 320 kg (705 lb) of coal were ignited by electrical strip heaters. The burning coal then ignited an SBR (styrene-butadiene rubber) belt. The air velocity during the test was 1.25 m/sec (250 ft/min).

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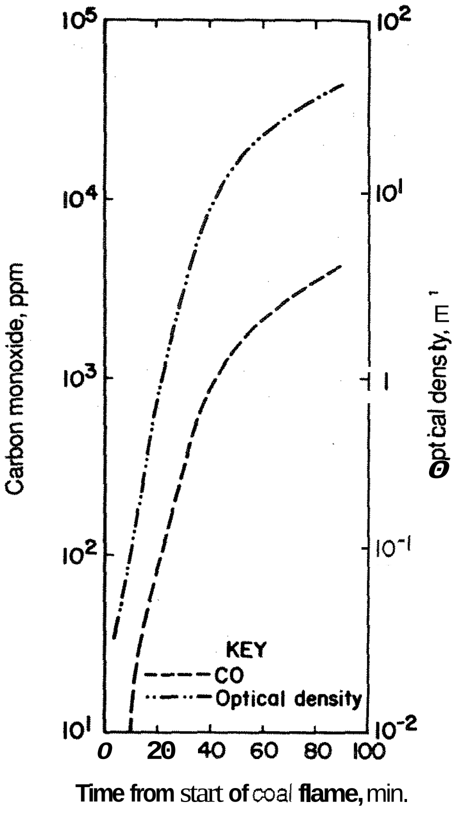

Fig. 1 — Downstream carbon monoxide and smoke density levels during the growth of a typical SBR belt-coal test fire.

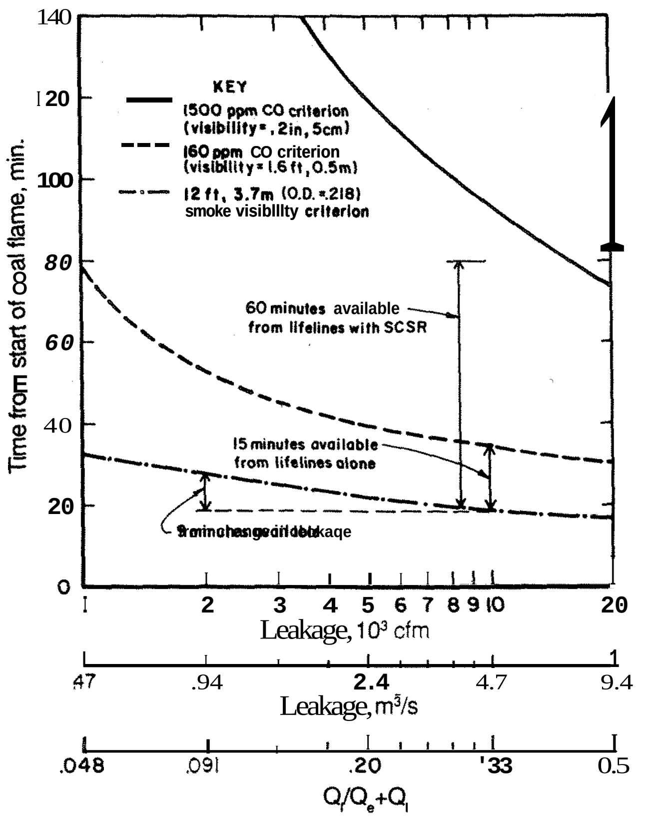

Fig. 2 — Time to reach unacceptable conditions in the escapeway vs leakage. Each curve represents a different criterion.

optical density is also shown since the visibility loss due to smoke impacts the ability to escape. Kissell and Litton (1992) have shown that serious visibility impairment can take place long before the CO concentration reaches the 1500-ppm toxic level.

Escape through the adjacent entry

The data shown in Fig. 1 only apply to the entry on fire. The contaminant concentration in the adjacent escape entry depends on the size of the fire and the amount of leakage. For instance, if Q_l is the total[3] leakage from the fire airway to the escape entry, and Q_e is the original amount of air flowing in the escape entry, then:

$$C_e = C_f \, [Q_l/(Q_e + Q_l)] \qquad (3)$$

where C_e and C_f are the contaminant concentrations in the escape entry and the fire airway, respectively. Using this simple dilution equation for a given leakage, a determination is sought regarding what concentrations of smoke and CO in the leakage from the fire airway will produce unacceptable conditions in the escape entry. Unacceptable conditions represent the point beyond which escape is unlikely.

For example, suppose $Q_e = 9.4$ m^3/sec (20,000 cfm). For CO, severe sensory irritation from the smoke of an SBR belt-coal fire was found (Kissell and Litton, 1992) when the measured CO was only 160 ppm. Thus this CO concentration was selected as representing unacceptable conditions in the escape entry[4]. If the leakage Q_l^3 is 4.7 m^3/sec (10,000 cfm), then the leakage ratio $Q_l/(Q_e + Q_l) = 0.333$. Using these values in Eq. (3), C_f in the fire airway is 480 ppm. From Fig. 1, this CO concentration is reached in 34 min.

Different leakage values may be selected. Also, this simple dilution applies to the smoke concentration expressed in optical density units. In the escape entry, unacceptable visibility is reached at an optical density of 0.218/m (Tewarson and Newman, 1981), which corresponds to 3.7-m (12-ft) visibility. If a leakage Q_l of 0.94 m^3/sec (2000 cfm) is selected, then $Q_l/(Q_e+Q_l) = 0.091$, and the optical density in the fire airway (and leakage air) is 2.40/m. Figure 1 shows that an optical density of 2.40/m is reached in 28 min.

By repeating this procedure, calculations can be made for the time it takes to contaminate the escape entry at different leakage levels and for several different contamination criteria (Fig. 2). For example, with a 4.7-m^3/sec (10,000-cfm) leakage ($Q_l/Q_e + Q_l = 0.333$), an escape entry visibility of 3.7 m (12 ft) is reached in 19 min, a CO concentration of 160 ppm is reached in 34 min, and a CO concentration of 1500 ppm[5] is reached in 92 min. Each of these contamination criteria represents obstacles to a safe withdrawal. The strategy is to deal with the most restrictive obstacle (the smoke) first.

Fire safety alternatives for increasing T_e

The alternatives for increasing T_e include:

- reducing air leakage,

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[3] The total leakage is that through many stoppings, not through a single stopping. The key assumption in this analysis is that air leaks from the entry on fire to the escape entry. This type of leakage generally occurs (Timko and Derick, 1989). Kissell and Timko (1991) have investigated the impact of checking off the intake escapeway to raise its air pressure during an evacuation.

[4] Measuring sensory irritation in terms of the equivalenr CO concentration is not entirely satisfactory. Hopefully, future research will establish better ways to measure sensory irritation and to establish appropriate limits more objectively.

[5] 1500 ppm is the critical CO level (Tewarson and Newman, 1981; Kissell and Litton, 1992).

[6] Lifelines are ropes installed in intake and/or return escapeways to guide miners through dense smoke.

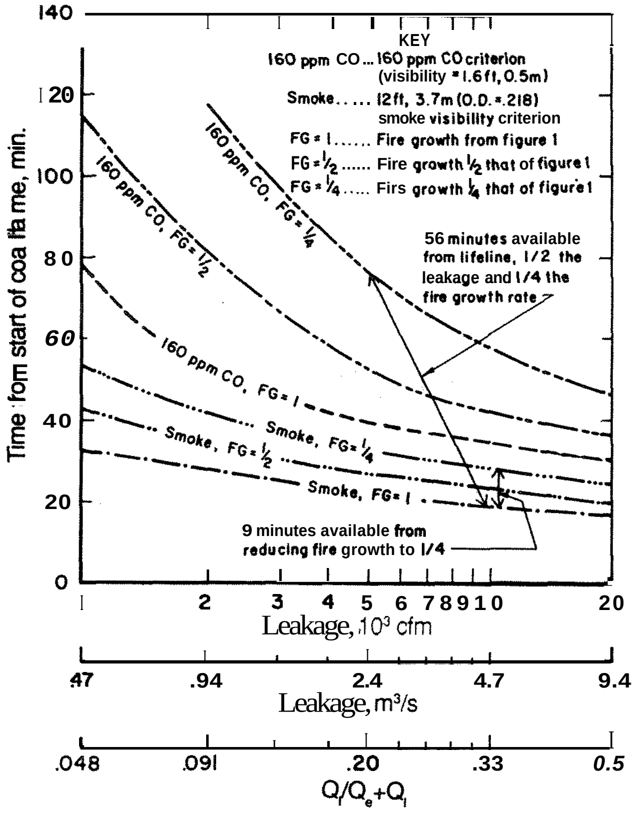

Fig. 3 — Impact **of** fire growth added to **Fig.** 2's time to reach unacceptable conditions **in** the escapeway vs. leakage.

- providing lifelines[6] and
- reducing the fire growth rate.

Figure 2 is useful for showing how much time these save.

Reducing leakage

As Eq. (3) indicates, the contaminant concentration depends on the leakage amount. The objective is then to relate a leakage change to an amount of time saved. To do this, an escape criterion must be selected. For instance, since the lack of visibility is the most restrictive obstacle and most mines do not have lifelines that permit travel through dense smoke, the 3.7-m (12-ft) visibility criterion is employed as the point beyond which escape is unlikely. With 4.7-m^3/sec (10,000-cfm) leakage into the 9.4-m^3/sec (20,000-cfm) escape entry, 3.7-m (12-ft) visibility arrives in 19 min (Fig. 2). At 0.94-m^3/sec (2000-cfm) leakage, the equivalent time is 28 min. Thus under this set of conditions, the 80% decrease in leakage has saved only 9 min.

Providing lifelines

A similar approach can be used for lifelines, which are necessary for travel through smoke when the visibility drops below 3.7 m (12 ft). When lifelines are available, the 3.7-m (12-ft) visibility criterion can be dropped. Then the next most restrictive obstacle can be used, the sensory irritation limit represented by 160 ppm CO. Like before, at a leakage of 4.7 m^3/sec (10,000 cfm), 3.7-m (12-ft) visibility is reached in 19 min. At the same leakage rate, however, the sensory irritation limit of 160 ppm CO is reached in 34 min. Thus, lifelines have saved an extra 15 min.

Figure 2 also shows the 60 min saved by the combination of lifelines and a 1-hr, self-contained self-rescue (SCSR) device. But since much of this time extends into the range of severely restricted visibilities and severe **sensory** irritation, factors like panic and confusion (Jin, 1981) could impede escape[7].

Reducing fire growth rare

Reducing the fire growth rate also saves time. Lower growth rates may be achieved by reducing the flammability of materials used in mines and by removing loose coal that collects on the mine floor. **In** the belt fire tests used to collect the Fig. 1 data, 320 kg (705 lb) of lump coal were placed directly under the belt. This coal was then ignited by electrical strip heaters (Litton, Lazzara and Perzak, 1991).

A 320-kg (705-lb) pile of loose coal under the belt could be a "worst case" test. Thus, it is important to assess the impact of lower fire-growth rates that might result when less loose coal is present. This would indicate the importance of removing **loose** coal accumulations from fire sources.

The lower fire-growth rates were set at 50% and 25% of that shown in Fig. 1. It is assumed that the entire curve shifts downward by the same proportion[8]. In Fig. 1, for example, the CO concentration at 40 min is 860 ppm. So at 50% and 25% growth rates, the CO concentrations at 40 **min** would be 430 and 215 ppm, respectively.

In the same manner, the optical density curve shifts downward for every time value, and Fig. 3 shows how much time is saved by these revised growth rates. In every instance, the criterion curve is shifted upward; a slower-growing fire means that it will take longer to reach either the 3.7-m (12-ft) visibility limit or the 160 ppm CO limit. Using the 3.7-m (12-ft) visibility criterion as the most restrictive obstacle and assuming a 4.7-m^3/sec (10,000-cfm) leakage, only 9 min **are** saved by reducing the fire growth rate to 25% of that shown in Fig. 1.

Analysis of T_e

Without lifelines, **the** 3.7-m (12-ft) visibility **criterion** must be used **as** the point beyond which escape is unlikely. ***An*** examination of Figs. 2 **and** 3 shows that when this **most** restrictive obstacle is used, the fur: safety alternatives save little time. **For** example, **reducing** leakage from 4.7 **m^3/sec (10,000** cfm) to 0.94 **m^3/sec (2000** cfm) saves only 9 min **(Fig.** 2). **With the leakage fixed at** 4.7 **m^3/sec** (10,000 cfm), reducing **the** fire growth **rate** to 25% of that shown in Fig. 1 also saves only 9 min (Fig. 3).

The problem is that with any leakage into the escape entry, smoke contamination occurs so early that none of the obvious alternatives by themselves saves much time. Although using lifelines alone will save about 15 min (Fig. 2), this, by itself, is not much. However, by using lifelines, the 3.7-m (12-ft) visibility obstacle can be bypassed and the less restrictive 160-ppm CO criterion can be applied. With this new criterion, reducing the leakage or fire growth rate has more impact. Furthermore, with lifelines, the SCSR device can be used.

Note, also, that a combination of the alternatives has a synergistic effect in that the impact on time saved is multiplica-

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[7] Note that even at 160 ppm CO, the smoke is already thick enough to prevent the miner from seeing the ground. Also, other limitations may arise, like the improper donning of the SCSR. This may include either failing to isolate the lungs (Kovac, Vaught and Bmich, 1990) or wearing the goggles improperly (Kissell and Litton, 1992).

[8] To shift the entire curve downward by the same proportion is a simplification. Belt fires, as well as other mine fires, go through different stages that involve burning different materials. Action taken to reduce fire growth will involve some materials more than others and thus affect the fire-growth-rate curve unevenly. For example, at 25% of the fire growth rate, the time to ignite the belt is much longer, and the probability of belt ignition may also be less.

tive rather than additive. Figure 3 shows that 56 min **are** saved from lifelines in combination with 50%of the leakage and 25% of the fire growth rates. While the sum of these individual changes is only **28** min, the synergistic effect produces a total time saved that is double the sum of the parts. Similar results were obtained in an earlier fault-tree study conducted by Goodman and Kissell (1989). This earlier study found that with the exception of delays, single-factor changes had minimal impact. Significant reductions in fire fatalities only occurred with multiple-factor changes.

Fire safety alternatives for decreasing T_3

Decreases in T_3 (the fire detection time) will result in an improved survival index. For conveyor belt entries, estimated detection times may be obtained from a recent study conducted by Litton, Lazzara and Perzak (1991). They continuously measured **fire** products in the air **as** a pile of coal under a belt first smoldered. broke into flame and then set the belt afire. The purpose was to establish appropriate CO, sensor alarm thresholds, given factors such **as** detector spacing, entry size, airflow and detection time. They assumed that the alarm is initiated by ***CO*** from the burning coal fire that precedes the belt ignition. The relevant equations (Litton, Lazzara and Perzak, 1991) **are:**

$$(t_A)_{CO} = \frac{(CO_A)\,(V_0A_0)}{(B_{CO})\,(a_{coal})} \qquad (4)$$

where:

$(t_A)_{CO}$ = time (min) required for the sensor alarm threshold ***CO,*** to be reached at the fire,
CO, = sensor alarm threshold (ppm).
V, = air velocity (m/sec),
A_O = entry area (m^2),
B_{CO} = a production constant ((ppm·m^3)/kJ) relating the amount of CO produced to the air velocity, and
a, = a parameter (kW/min) relating the fire growth rate of flaming coal fires to air velocity.

For flaming coal fires, $a_{coal} = 1.65 + 0.90\ V_O$, **and**

$$(t_D)_{CO} = (t_A)_{CO} + 1/2[l_S/(60\ V_O)] + t_R \qquad (5)$$

where:

$(t_D)_{CO}$ = total time for fire detection (min), taking into account the transport time from the fire location to the sensor and the sensor response time;
I, = sensor spacing (m) and
t_R = sensor response time, assumed to be 1 min.

The "1/2" in the transport term results from an assumption that the average fire is halfway between the sensors.

Sensor setting

Assume that A_O = 10 m^2 (108 ft^2), V_O = 0.5 m/sec (100 ft/min), and I, = 305 m (1000 ft). From Litton, **Lazzara** and Perzak (1991), B = 4.5 and a, = 2.1. These authors also selected a flaming-coal-fire detection time of $(t_D)_{CO}$ = 14.25 min[9]. For this detection time, the recommended sensor alarm threshold, CO_A, from the above equations is 15.4 ppm.

The question is, how much time would be saved by a lower sensor setting **of** 10 ppm? Using CO, = 10 ppm in the above equations, $(t_D)_{CO}$ = 11.4 min, a savings of about **3** min.

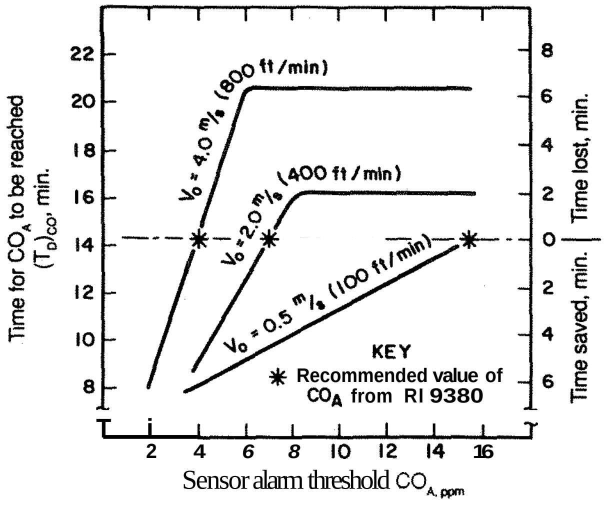

Fig. 4 — Time saved **or lost by** changing the CO, **sensor** alarm threshold.

Figure 4 gives the time saved and lost by lowering and raising the CO sensor settings. These data are provided for three different air velocities: 0.5 m/sec (100 ft/min), 2.0 m/sec (400 ft/min), and 4.0 m/sec (800 ft/min). The impact of sensor setting changes is slightly greater at higher air velocities.

Note in Fig. 4 **that the 4.0 m/sec curve does not extend beyond** a 6.4-min time loss. Similarly, the 2.0 m/sec curve does not extend beyond a 2-min time loss. These limits on the time lost occur because the belt catches fire soon after the recommended alarm threshold is reached. When the belt catches fire, the fire growth rate is much greater. Thus within the next minute, enough CO is produced to alarm any sensor set at or below 15 **ppm.**

For example, suppose the air velocity is 4.0 m/sec (800 ft/min). From Litton, Lazzara and Perzak (1991, Fig. 4), t_f (the average time between coal ignition and **SBR** belt ignition) is 18 min. An additional minute is added to the belt ignition time to achieve a burning rate sufficient to alarm any ***CO*** sensor. Also, another 0.64 min **is** required for the **transport** time, and 1 min is necessary for the sensor to respond, **as** indicated by the above equation. **The total** is thus ***20.64*** min. Comparing this value with the 14.25 min necessary for the sensor alarm threshold to be reached, it is obvious that the high CO levels from the burning belt reach **the** sensor only 6.4 min after it alarms from the coal fire. Then, if the sensor alarm threshold is raised above the recommended 4 ppm, the time **lost** will not **exceed 6.4** min. At 2.0 m/sec (400 ft/min), a similar approach gives a maximum time lost of **2** min.

Sensor spacing

The time lost or gained from sensor spacing changes is calculated from the transport term $1/2\,[l_S/(60\ V_O)]$ **in Eq.** ***(5).*** For example, if V, = 0.5 m/sec (100 ft/min), and the sensor spacing I, is 610 m (2000 ft) then $1/2\,[l_S/60\ V_O]$ = 10.2 min. **If** I, is reduced **to** 305 m (1000 **ft),** then the equivalent time is 5.1 min, for a time saved of 5.1 min. **At** higher velocities, the time saved

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[9] **The 14.25-min value was selected by Litton,** Lazzara **and Perzak because their testing showed this as the average time between flaming ignition of the coal and belt ignition. Whether the 14.25-min detection time is appropriate is disputable. However, even if a different time is selected, it will not change the conclusions regarding the impact of sensor setting changes.**

Table 1 — Time saved or lost by different detectors during an underground belt-fire test (Dobroski and Conti, 1991). The 15-ppm CO detector provides a baseline, and the air velocity was 0.633 m/sec (127 ft/min).

Alarm	Time saved (min)	Time lost (min)
Smoke sensor	3.7	—
Fiber optic	3.5	—
CO, 5 ppm	3.5	—
CO, 10 ppm	2.0	—
CO, 15 ppm	—	—
Thermocouple 10 ft from fire with:		
2° C rise	—	5.7
10° C rise	—	9.8

by a closer sensor spacing is much less.

Substitution of CO detectors for heat sensors

The average alarm time for point-type heat sensors in USBM testing (Litton, Lazzara and Perzak, 1991) is 18 minutes for an air velocity of 0.5 m/sec (100 ft/min) and an entry area of 7.53 m^2 (81.1 ft^2). For a more realistic entry area of 10 m^2 (108 ft^2), the alarm time is 22 min. Since the detection time used for the recommended CO sensor settings was 14.25 min, it follows that substituting CO detectors saves about 8 min. At 2.0 m/sec (400 ft/min), substituting CO detectors saves about 16 min. And at 4.0 m/sec (800 ft/min), it saves about 30 minutes[10].

Multiple detector test

Dobroski and Conti (1991) have measured the response times of several different detector types during an underground belt-fire test. The air velocity during their test was 0.633 m/sec (127 ft/min). Using the 15 ppm CO detector as a baseline, the times lost or saved by the other detectors are shown in Table 1. These values are consistent with this analysis. That is, at the fire growth rate given by Fig. 1, sensor settings have little impact when compared to the alternatives.

Fire growth rate and sensor settings

In the section that examined alternatives for increasing T_e, it was found that a lower fire-growth rate could enhance the impact of the other factors. As a result of this synergism, the total impact of multiple changes could be greater than the sum of the parts. In this regard, it is useful to look at the impact changing sensor settings has with the lower fire-growth rates more typical of an average belt fire.

Lower values for a_{coal} in Eq. (4) represent lower fire-growth rates. For example, if the fire growth rate is 25% of that shown in Eq. (4), then a_{coal} is also 25% of that shown. Also, for a given value of CO_A, $(t_A)_{CO}$ is four times higher. It follows that for a given *change* in CO_A, the *change* in $(t_A)_{CO}$ is also four times greater. In Fig. 1, when V_O was 0.5 m/sec (100 ft/min), reducing the sensor setting CO, from 15.3 to 10 ppm saved 3 min. If the fire growth rate is reduced to 25% of that shown in Fig. 1 (a_{coal} = 0.525 instead of 2.1), the time saved is 12 min instead of 3 min.

Fires in other entries

It is difficult to quantify the fire detection process in entries where no fire detection system is used. In such areas, reliance is instead placed on the observations of those working underground. Given no clear way to model this, one can only assume that the time required to detect a fire depends on the velocity with which the smoke and fumes spread through the mine. For example, if the smoke and fumes must travel 1525 m (5000 ft) for the fire to be detected, at an air velocity of 0.5 m/sec (100 ft/min), 50 min are required. With a 2.5-m/sec (500-ft/min) air velocity, however, only 10 min are required. The 50-min value is considerable when contrasted to those times associated with the other factors.

Analysis for T_3

Fires in belt entries

The impact of sensor settings was small when the airflow in the belt entry was low. But when the airflow was high, sensor settings became slightly more important. Also, at moderate and high airflows, the substitution of CO sensors for point-type heat detectors can save a considerable amount of time. The impact of CO sensor spacing, however, is only significant at very low air velocities, as one might expect. Like before, the fire growth rate is important, and the sensor setting becomes more critical as the fire growth rate diminishes.

Fire in other entries

It is difficult to make generalizations regarding areas where fire detection systems are unavailable. One can say, however, that unattended equipment located outby is more hazardous when the air velocity is low.

Fire safety alternatives for decreasing T_4

T_4 is the time interval between fire detection and the beginning of worker withdrawal. Timely notification procedures for those underground must begin immediately when fire is discovered. The review of published coal-mine-fire reports revealed that the two worst fire-related disasters of the past 20 years claimed 36 lives. In both accidents, personnel on the surface and outby the fire had knowledge of the fire but delayed the withdrawal order.

Survey

Assigning a numerical value to T_4 is difficult because of the variability in how and when withdrawal orders are given. An informal survey was conducted in which safety personnel from 10 mining companies were asked to describe the decision-making process that typically occurs when smoke is discovered. The only provision was that they assume a smoke source located outby the working face in an intake entry where miners would not normally be working.

Most of the mines surveyed have CO detectors in the belt enmes. Some systems are more complex and include dual-level CO alarms. For additional protection, some mines also locate detectors in intake and return entries.

The survey responses varied from immediate withdrawal to a process where an initial warning is followed by an exploration to determine the exact location before a withdrawal order is issued. The person conducting the exploration evaluates the situation and determines whether withdrawal is necessary.

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[10] If the fire grows more slowly than that shown in Fig. 1, the relative ranking of some alternatives can shift. The data show how lower fire-growth rates can increase the time saved by changes in sensor settings. Recently, Litton, Perzak and Lazzara (personal communication) have conducted studies on lower growth rate fires in which the time saved by substituting CO detectors for conventional heat sensors was 58 min.

Although this places the responsibility on someone more likely to have firsthand information, it may cost time.

In mines having dual-stage alarms, a first-stage alert typically prompts the dispatcher or a section supervisor to send someone to investigate the cause. When the second-stage alarm sounds, the withdrawal to a point outby is begun. In other mines, the withdrawal order is given as soon as elevated CO is discovered at two detectors in the same aircourse or if *CO* values remain elevated during consecutive samples. Most of the officials surveyed had fire-fighting experience or are currently mining in conditions prone to spontaneous heating.

Everyone emphasized the importance of rapidly notifying those underground during a fire-related emergency. The problem some have with issuing immediate withdrawal orders is that once miners leave the working section, the ability to gain additional information regarding the fire is often lost. Moreover, the possibility of fighting the fire and preventing its spread is lost.

In most of the surveyed mines, the requirement for supervisory approval to start a withdrawal has been dropped. Withdrawal orders are most often given by someone located on the surface, usually a dispatcher or a warehouseman.

Communications

Roberts' equation implicitly assumes that communications are always maintained during the early stages of a fire, when withdrawal orders are likely to be given. If the fire destroys the telephone system, however, the time lost can overwhelm the other factors. It is thus useful to examine the location of phone wires near outby fire sources and ensure they are maintained at a considerable distance from these sources.

Fire safety alternatives for decreasing T_5

T_5 is the travel time to reach a safe location outby a fire. Following a withdrawal order, some miners automatically head for the primary escapeway. They believe that because this escapeway is isolated, it will remain free of fire byproducts. However, recent research (Kissell and Litton, 1992) has shown that if leakage occurs, even very low levels can reduce visibilities and make travel difficult.

Rail vehicles

Escapeway location depends on the type of transportation employed. If rail vehicles are used, the primary escapeway is usually another entry, isolated from the hack. The primary escapeway is an intake entry and is considered the safest route. Miners can follow this path to walk from the face until outby the fire.

A timesaving escape method involves riding a vehicle outby as long as the visibility is adequate. One possible visibility minimum would be the ability to see mandoors in the crosscuts. When the visibility becomes marginal, miners can abandon the vehicle, proceed to another airway and continue the withdrawal. Other criteria could be equally valid.

Rubber-tired vehicles

When the mine uses rubber-tired vehicles, the intake escapeway can be the same entry as the vehicle travelway. Thus, withdrawal by vehicle is more likely in mines using rubber-tired transportation since miners will already be located in the intake escapeway. When visibility restrictions occur in this entry, withdrawal can become more difficult. Here the only alternative is to abandon the vehicle, enter another airway and begin walking outby.

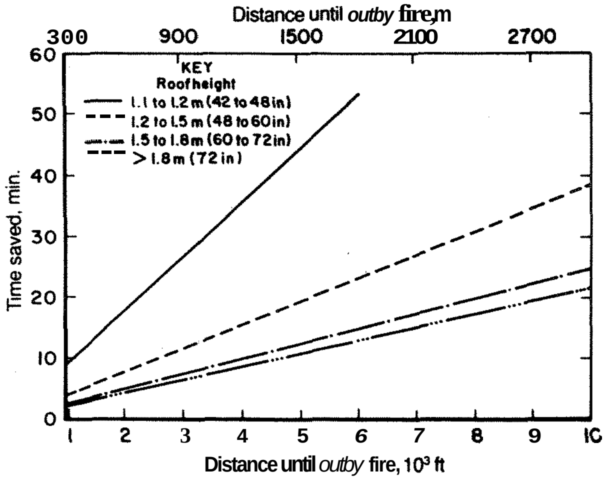

Fig. 5 — Time saved or lost by riding vs. walking in various entry heights.

Studies have been performed on walking speeds in various entry heights (Shumate, 1986). These vary from 0.12 m/sec (24 ft/min) in entries less than 0.76 m (30 in) high to about 1.5 m/sec (*300* ft/min) in entries with heights greater than 1.8 m (72 in). The time saved by riding vs. walking, as seen in Fig. 5, depends on the height of the seam being mined. In Fig. 5, a 4.5-m/sec (10-mph) vehicle speed is used, and no visibility restriction is assumed for either walking or riding.

Ranking of fire safety alternatives

For fires with a growth rate similar to Fig. 1[10], an overall ranking of alternatives for all of the **T** factors is as follows:

More than 30 min saved

- Installing lifelines permits one to bypass the 3.7-m (12-ft) visibility criterion and allows SCSR use. Thus up to 60 min are saved, subject to self-rescue limitations (for example, if the SCSR is not donned properly or panic occurs due to dense smoke).
- In those instances with considerable *synergism*, the *application* of multiple alternatives *can* yield significant time savings. The example given used lifelines, in combination with a 75% decrease in the fire growth rate and a 50% decrease in leakage, to yield 56 min saved.
- Riding vs. walking in entries under 1.2-m (48-in.) high.

10 - 30 min saved

- Installing lifelines.
- Shortening the withdrawal decision chain.
- Riding a vehicle instead of walking in entries over 1.2-m (48-in.) high.
- Substituting *CO* detectors for conventional heat sensors at all except low-air-velocity belt areas.

Less than 10 min saved

- Ventilation changes. Even large ventilation changes had a surprisingly low impact. The reason for this was that for the example given, the 3.7-m (12-ft) critical visibility was reached in a very short time (only 19 min). Changes in this baseline, even if large on a percentage basis, do not yield much in the way of absolute time.

- Decrease in fire growth rate. By itself, a 75% decrease in fire growth saved only a surprisingly low 9 min. However, combined with other factors, it gives a synergistic effect. Also, it was shown that lower fire-growth rates will magnify the impact of reducing the sensor settings.
- Adjustment of CO sensors.

Conclusions

This study indicates that significant improvements in mine fire survival can be gained by a few relatively simple measures. In priority order, these are:

- Install lifelines. The 3.7-m (12-ft) critical visibility represents a major impediment to safe withdrawal. Without lifelines, there are not many ways to gain improvements.
- Check that phone wires do not run close to outby fire sources.
- Pay very careful attention to the removal of loose coal at belt drives and transfer points. Such action can lower the fire growth rate, which has many synergistic benefits.
- At all belt areas, except those with low air velocities, use CO sensors instead of thermal detectors.
- Shorten the withdrawal decision chain-of-command. Decisions must be based on information collected within a short time frame.
- Instruct miners to withdraw from the section with a vehicle as long as the visibility is adequate.
- Minimize leakage air whenever practical. Note that a deliberate attempt to make leakage go in a specific direction involves some assumptions as to where the fire will be.
- Be aware that an outby fire source not protected by an alarm system is more hazardous if located in an airway with a low air velocity.

Note that these conclusions are based solely on the considemtion of time gained or lost. Other factors that might modify these priorities, such as instrumentation reliability, were not considered. In this study, it was assumed that the fire takes place in a belt entry, primarily because the data on fire growth and combustion products were readily available. Nevertheless, these authors feel that the conclusions are generally applicable to any outby fire that grows quickly.◆

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