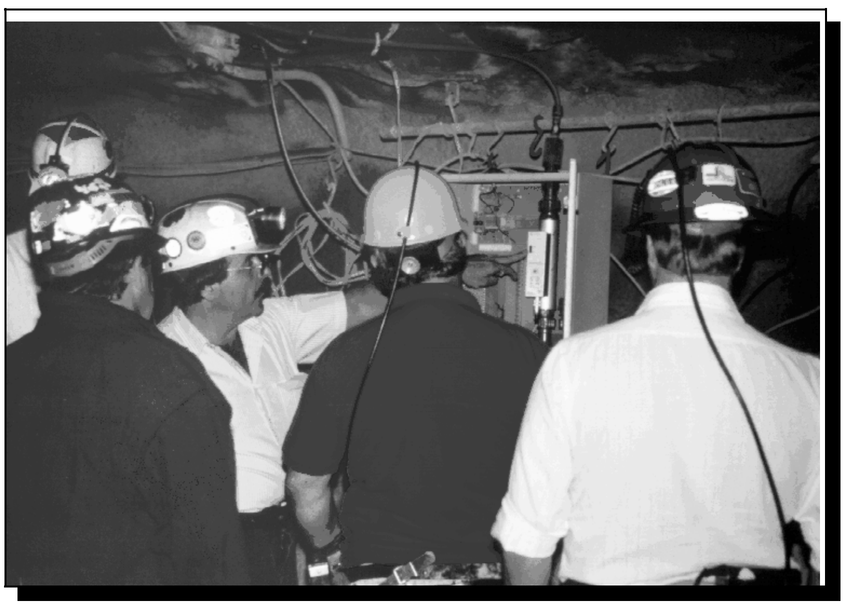
RI 9572

REPORT OF INVESTIGATIONS/1995

A Comparison of Mine Fire Sensors



UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

U.S. Department of the Interior Mission Statement

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

Report of Investigations 9572

A Comparison of Mine Fire Sensors

By R. S. Conti and C. D. Litton

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea Lydia Graham, Director

International Standard Serial Number
ISSN 1066-5552

CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	kW	kilowatt
g/m^3	gram per cubic meter	ppm	part per million
m	meter	s	second
m^2	square meter	V	volt
m/s	meter per second	$^\circ C$	degree Celsius
min	minute	$^\circ F$	degree Fahrenheit
kg	kilogram	$g/^\circ C$	gram per degree Celsius
kJ	kilojoule		

A COMPARISON OF MINE FIRE SENSORS

By R. S. Conti[1] and C. D. Litton[2]

ABSTRACT

This U.S. Bureau of Mines (USBM) report discusses the results of research conducted in the USBM experimental mine at its Lake Lynn Laboratory to determine the alarm times of smoke and carbon monoxide (CO) sensors, and a point type heat sensor (PTHS) to slowly developing coal-conveyor belt fires. The tests were conducted at air velocities of 0.44 and 0.97 m/s. The data clearly indicate that smoke sensors provide earlier warning of fire than 10 ppm CO sensors, and that 10 ppm CO sensors provide earlier warning than PTHS. A success rate of 1.0 (indicating detection of every test fire) was obtained for both smoke and CO sensors. For the PTHS, the success rate was 0.57 at the lower air velocity, decreasing to 0 at the higher air velocity. Data are also presented showing the sequence of fire events and detection events at the two air velocities as a function of time. Results show that early detection and warning of underground mine fires will improve the probability of miners' escape.

[1]Fire prevention engineer.
[2]Physical scientist.
Pittsburgh Research Center, U.S. Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

In a recent study[3] in which 214 miners from eight mines were asked about mine fire related experiences, 65% of these miners reported that they see or smell smoke (from any source) in the mines where they work at least once a month. Twenty percent of these miners reported being surprised or caught off guard by the sight or smell of smoke within the because of either a potentially serious situation or planned maintenance activities such as cutting and welding. The results of this study serve to reinforce the importance of early-warning fire detection systems in underground mines. Personnel may not always be available to sense the smoke or odor from a developing fire; whereas, an early-warning fire detection system can continuously monitor the environment and signal the presence of a developing fire, as long as the unit is operating properly.

Personnel must also be trained in the proper response to an early-warning signal from a fire detection system. When miners are not properly trained, the potential for disaster is imminent. As an example, a fire at the Bullitt Mine, Appalachia, VA, March 9, 1994 (*1*),[4] destroyed over 55 m of conveyor belt after the belting came in contact with an energized trolley wire. During the event, the carbon monoxide (CO) monitoring system responded at 9 ppm, however, the alarm warning was dismissed as "probably welding smoke." A short time later, the miner who was welding inadvertently discovered the fire while answering the mine phone, and initiated fire-fighting activities. In many cases, fire-warning systems respond to an incipient fire, but these responses are dispensed as glitches in a sensor or planned maintenance activities in the area. It is important that any significant response from an underground fire sensor be immediately investigated, and that a standard procedure be developed for response to sensor alerts and alarms.

During the period of 1983 through 1993, the Mine Safety and Health Administration (MSHA)[5] investigated 118 reportable underground mine fire incidents, or an average of 11 fires per year. Forty of these underground mine fires involved conveyor belts. Federal regulations, as spelled out in 30 CFR Part 75 Subpart L-Fire Protection (*2*), require that automatic fire-warning devices be installed on each underground belt conveyor. Sensors so installed shall give a warning automatically when a fire occurs on or near a belt and provide both audible and visual signals that permit rapid location of the fire.

In a mine fire, early detection maximizes the potential for escape from, and control of, the fire because more time is available to execute successfully these procedures. Generally, miners responding during the incipient stage of a fire (a fire too small to present a significant safety threat), increase their chance of extinguishment, provided they have adequate fire-fighting equipment and skills. To optimize the detection process, the choice of fire parameter to detect plays a major role. However, this choice is also tempered by the availability and sensitivity of the detectors used. A related factor is the number of sensors required, because cost, both in capital expenditures and in labor needed to maintain a system, tend to increase as the number of sensors increases.

Optical sensors and PTHS must be spaced closely in a mine entry. This is because optical sensors require a line of sight to the fire. For PTHS, close spacing is necessary because the hot gases from a fire cool rapidly once expelled into the mine's ventilation airflow. Smoke and carbon monoxide sensors may be placed at fairly large intervals because the ventilation airflow carries the CO and smoke to the sensors and because the CO and smoke are not dissipated once they are produced. However, these spacings cannot be too distant, or the early-warning capability CO and smoke sensors provide will be lost due to long transit times between sensors.

Previous studies (*3-4*) examined the effects of buoyancy on the alarm times of fire sensors. The results of these investigations indicated that maximum spacings for CO and smoke sensors may be in the range of 300 to 600 m without serious degradation of early-warning capability. To evaluate CO and smoke sensor responses at these distances, and to compare their response time to that of typical PTHS, a series of tests using small coal-conveyor belt fires was conducted in the Lake Lynn Experimental Mine (LLEM). Seven tests were conducted at an average air velocity of 0.44 m/s and seven tests at an average air velocity of 0.97 m/s. During these tests, the relative alarm times for three types of sensors (CO, PTHS, and smoke) were measured and compared. Such information is vital to assess the relative level of fire protection that can be provided for underground mines.

EXPERIMENTAL PROCEDURE

The USBM Lake Lynn Laboratory, formerly a limestone mine (*5*), is now a multipurpose mining research facility. Figure 1 shows the laboratory's underground layout and aboveground quarry area. The average entry dimensions in the underground research mine (new workings) are 2.16 m high and 5.97 m wide, for an average cross-sectional area of 12.9 m^2.

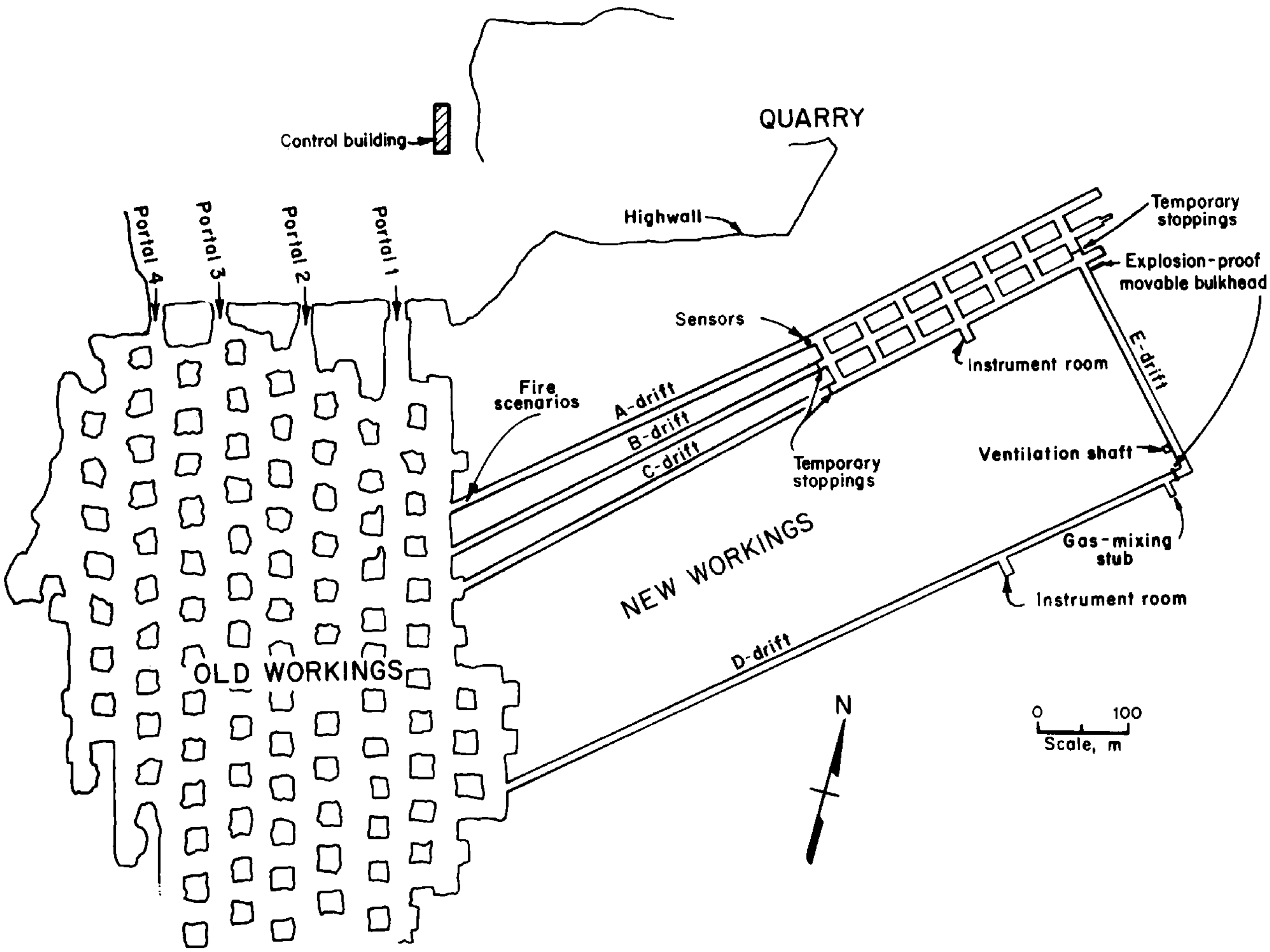
The fire detection studies reported here were conducted in A-drift. A detailed layout of a typical underground fire and detection scenario is shown in the perspective view in figure 2. During the experiments the normal airflow in the mine was reversed, so that the combustion products were exhausted through the main fan. The airflows can be adjusted by

[3]Based on a recent research study conducted by Conti and ohters, USBM, 1994.

[4]Italic numbers in parentheses refer to items in the list of references at teh end of this report.

[5]The mine fire statistics were obtained from the file of Federal Mine Safety and Health Administration (MSHA) mine fire investifation reports maintained at MSHA's Pittsburgh Safety and Health Technology Center.

Figure 1



Plan view of Lake Lynn underground mine, showing configuration for fire detection tests.

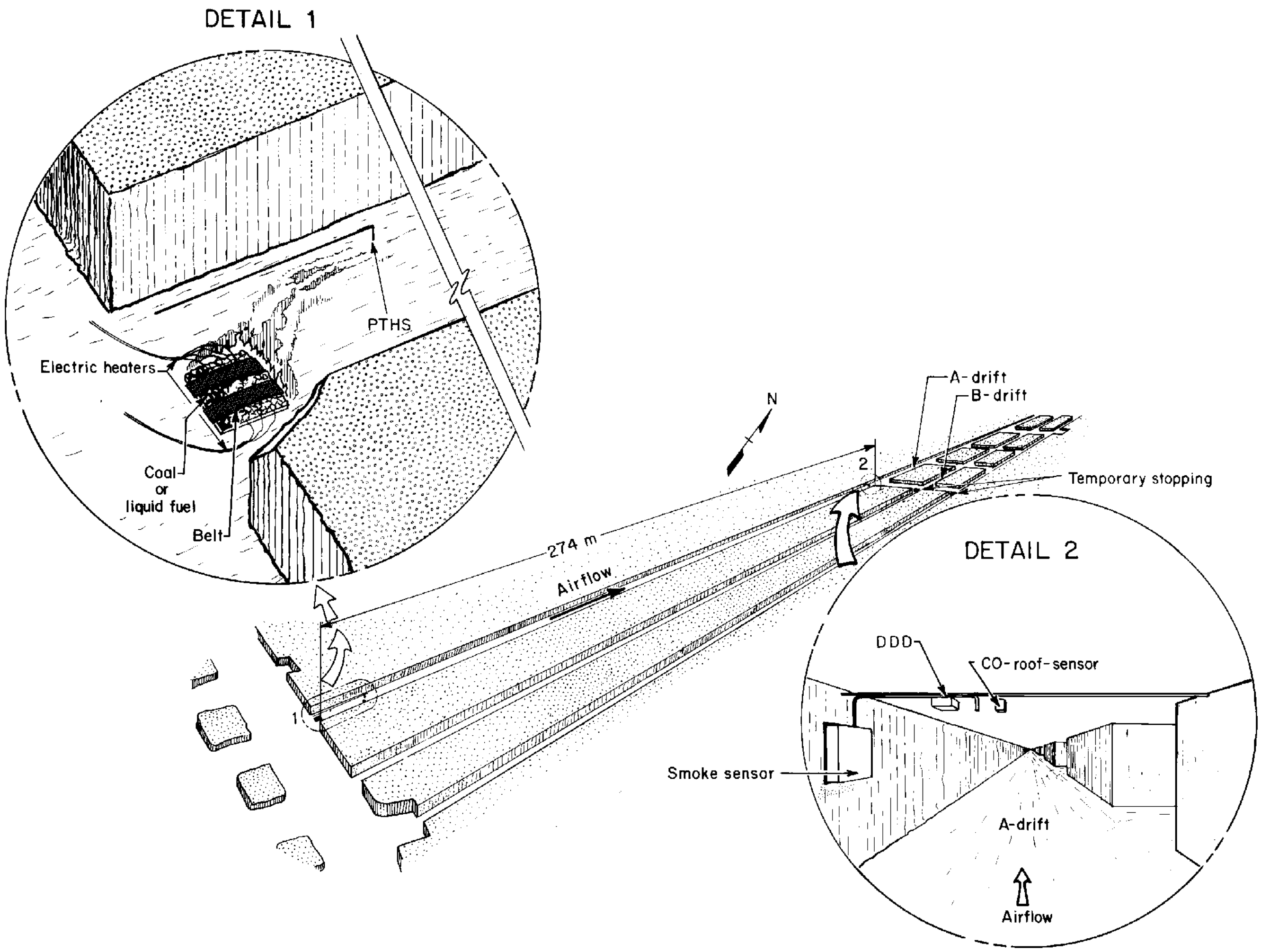
selecting one of the four speeds of the main fan, positioning the moveable bulkhead door in D-drift and E-drift, and erecting temporary stoppings at the last crosscuts of B- and C-drifts. The air velocity was measured with a handheld vane-anemometer 15.2 m downstream of the fire zone prior to starting the test. The crosssection of the entry was divided into 12 quadrants; the measured values from each quadrant were averaged. A PTHS (a K-type thermocouple, detail 1 of figure 2) was placed near the roof 3.65 m downstream from the center of the test fire and was considered to be in alarm when the measured air temperature exceeded 57.2 °C (135 °F), the lowest alarm temperature for point-type heat sensors (6).

Three other sensors were located, as shown in detail 2 of figure 2, in the entry cross section at a point 274 m downstream of the fire zone. A diffusion-type electrochemical CO sensor was mounted at the roof and denoted as CO roof. An ionization-type smoke sensor with internal sampling pump was mounted on the rib, with the intake sampling port located beside the CO-roof sensor. A prototype diesel-discriminating smoke detector (DDD) was mounted beside the intake sampling port of the smoke sensor. The CO sensor was calibrated and smoke detectors functionally tested before each experiment. The outputs of the fire sensors were connected to a 24-channel analog to digital (A/D) converter that transmitted the data to a computer for storage. The data were logged at 1 s intervals.

The CO alarm level was set at 10 ppm. The smoke sensor and DDD were arbitrarily set to alarm when the threshold voltages reached 0.5 and 0.02 V, respectively. A detailed description of typical output traces and response times of the various fire sensors used in similar experiments can be found in reference 7.

The DDD (*8*) is a novel device that can be used to discriminate between smoke produced by a fire and smoke produced by a diesel engine. The detector uses a pyrolysis technique whereby a sample of smoke-laden gas passes through a short, heated tube. Within this tube, fire smoke particles pyrolyze (or re-burn), increase in number concentration, and decrease in average size; diesel smoke particles are unaffected. The DDD was developed by the

Figure 2



Perspective view of underground mine, showing configuration for fire detection tests.

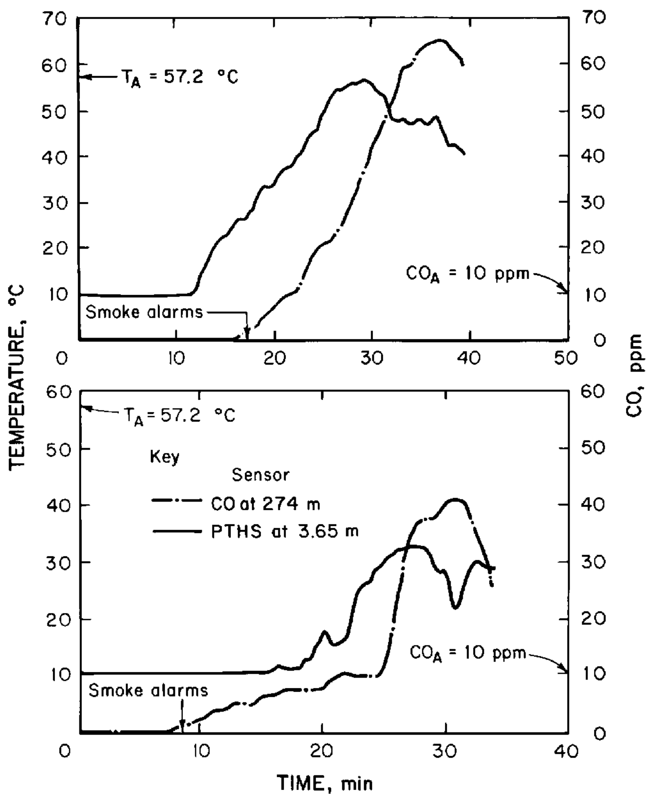
USBM to reduce the numerous false alarms in mines that utilize diesel equipment, which makes detection of fires complicated because of the background levels of diesel emissions. This detector was incorporated in99999to the current tests to compare its response time to a more conventional smoke detector and to CO sensors.

The scenario studied was a slowly developing coal-conveyor belt fire. Seven 220-V electric strip heaters, with a combined power rating of 9.5 kW, were embedded into a 1.2- by 1.2-m coal pile containing 75 kg of Pittsburgh coal. Six 10.2- by 22.8- strips of rubber conveyor belting, 1.1-cm thick, were evenly distributed throughout the coal pile. Additionally, two 22.8-cm by 61-cm strips of the same belt were placed on top of the coal pile and the pile was seeded with approximately 0.75 kg of pulverized Pittsburgh coal dust. Full electrical power was applied to the heating elements at the start of each test. Visible smoke from the coal pile was usually observed in 3 to 4 min, with flames emanating from the coal about 9 min later. The strips of conveyor belting on top of the coal pile ignited at some later time during the tests.

RESULTS

Figure 3 shows typical traces of the air temperature near the roof at a distance of 3.65 m downstream from the center of the fire and the bulk average CO levels at a distance of 274 m downstream of the fire as a function of time. The alarm level of the thermocouple, T_A, is 57.2 $^\circ$C; the alarm level of the CO sensor, CO_A, is 10 ppm. The levels of CO measured are the actual levels produced at the fire at some earlier time because the airflow must transport the CO from the fire to the sensor.

Figure 3



Comparison of CO and PTHS alarm times of 0.44 m/s (top) and 0.97 m/s (bottom).

For the lower air velocity (v_o = 0.44 m/s, figure 3 top), this transport time is 10.4 min; while the transport time at the higher air velocity (v_o = 0.97 m/s, figure 3 bottom) is 4.7 min. Once the smoke and DDD sensors alarmed (274 m downstream from the fire) at the lower air velocity (figure 3 top), more than 3 min elapsed before the average CO level reached a 10-ppm alarm. At the 10-ppm alarm, the thermocouple 3.65 m downstream from the center of the fire indicated a 28 °C rise in the ambient temperature (T_o = 10 °C), some 19 °C below the PTHS alarm level. When the CO alarmed (10 ppm) at the higher air velocity (figure 3 bottom), the temperature was 8 to 9 °C cooler than the temperature measured at the lower air velocity. The average alarm time of both smoke and DDD sensors at the higher air velocity was 9.8 min, nearly 13 min before the 10 ppm CO alarm measured at the lower air velocity. The average alarm time of both smoke and DDD sensors at the higher air velocity was 9.8 min, nearly 13 min before the 10 ppm CO alarm.

Table 1 shows the alarm times for the four sensors evaluated at the lower air velocity. The last row of table 1 is the average alarm time for all the tests for which alarm occurred. For the smoke, DDD, and CO sensors, alarm occurred for each test (100% success rate), while for the PTHS, alarm occurred in only four of the seven experiments (a 57% success rate). Even though the PTHS was located only 3.65 m downstream, it took significantly longer for this sensor to alarm than any of the others tested.

Table 1.—Alarm times, in minutes, for various sensors for tests conducted at an air velocity of 0.44 m/s

Test	Smoke	DDD	10-ppm CO	57.2 °C PTHS
1	14.4	17.6	18.9	26.3
2	17.1	18.0	21.2	26.6
3	14.7	16.5	20.0	25.0
4	16.5	15.6	19.2	NA
5	12.0	14.2	19.9	NA
6	15.9	17.7	22.7	NA
7	17.3	18.6	21.4	20.2
Average . .	15.4	16.9	20.5	24.5

DDD Diesel discriminating detector.
NA No alarm.
PTHS Point type heat sensor.
Observed averaging flaming 12 min.

Table 2 shows the alarm times for all tests conducted at the higher air velocity. For these tests, the PTHS did not alarm at all, indicating a 0% success rate for the data obtained. These data indicate that as the air velocity increases, it becomes much more difficult for the PTHS to alarm due to more rapid cooling of the buoyant hot gases. It is also possible that the hot gases passed underneath the PTHS at the higher air velocity, eventually contacting the roof at some farther distance downstream. This latter effect was observed in the stratification of CO reported previously (*4*), where, at the higher air velocity, a greater degree of roof stratification was detected at a distance of 45.7 m downstream of the fire than at a distance of 15.2 m downstream.

Table 2.—Alarm times for the various sensors for tests conducted at an air velocity Test of 0.97 m/s

Test	Smoke	DDD	10-ppm CO
1	8.7	11.7	22.4
2	8.6	11.0	24.8
3	9.1	9.9	22.7
4	7.6	11.2	23.3
5	7.4	10.4	22.3
6	9.6	12.3	21.2
7	8.5	10.7	22.1
Average	8.5	11.0	22.7

DDD Diesel Discriminating Detector
Observed average flaming 10.3 min

.

ANALYSIS

These data also allow for the comparisons of previous empirical expressions (*3*) derived for the air temperature near the roof and the bulk average CO levels that are produced as a function of air velocity and heat release rate. For air temperature, the heat release rate, $\dot{Q}_f$ necessary to produce an air temperature near the roof, T_R, at some distance downstream of the fire, ℓ, is given by:

$$\dot{Q}_f = \rho_o C_o v_o A_o \left(\frac{T_R - T_o}{9} \right) \ell^{1.75\ H/W}, \tag{1}$$

where, ρ = density of air = 1.2 x 10^3 g/m^3

C_o = heat capacity of air = 1.088 x 10^{-3} $\frac{kJ}{g/{\circ}C}$

A_o = entry cross section, m^2,

v_o = air velocity, m/s,

T_o = initial, ambient temperature, $^\circ$C,

ℓ = distance downstream from center of the fire, m,

H = entry height, m,

and W = entry width, m.

Equation 1 can be rearranged to yield an expression for the temperature increase near the roof

$$T_R - T_o = \frac{9\dot{Q}_f}{\rho_o C_o v_o A_o} \ell^{-1.75 H/W}. \tag{2}$$

From reference 3, the bulk average level of CO is given by

$$\text{ppm CO} = \frac{B_{CO} \cdot \dot{Q}_f}{v_o A_o}, \tag{3}$$

where B_{CO} is the production constant for CO. From reference 3, B_{CO} has a value of 5.68 for styrene butadiene rubber (SBR) conveyor belts and, for coal, is given by the expression

$$B_{CO} = 4.8e^{-0.175 v_o}. \tag{4}$$

From the experimental section, the surface area of exposed conveyor belt strips is 0.28 m^2 and the exposed top surfaceof the coal is 1.20 m^2. The ratio of belt surface to coal surface is 0.23. If a reasonable assumption are made that the fraction of total Q_f due to conveyor belt scales with the fraction of exposed surface area and the remainder of the total heat Q_f scales with the exposed surface area of the coal, then:

$$\dot{Q}_{BELT} \cong 0.23 \cdot \dot{Q}_f \tag{5a}$$

and

$$\dot{Q}_{COAL} \cong 0.77 \cdot \dot{Q}_f. \tag{5b}$$

The CO that is produced during the flaming stage of the firecan then be expressed as:

$$\text{ppm CO} = \frac{5.68 \cdot \dot{Q}_{BELT} + 4.8e^{-0.175 v_o} \cdot \dot{Q}_{COAL}}{v_o A_o}. \tag{6}$$

Combining equations 5a and 5b yields:

$$\text{ppm CO} = (1.31 + 3.70e^{-0.175 v_o}) \cdot \frac{\dot{Q}_f}{v_o A_o}. \tag{7}$$

The ratio of temperature rise near the roof, T_R-T_O, to the ppm of CO is equation 2 divided by equation 7. For ℓ = 3.65 m, H = 2.16 m, and W = 5.97 m, this ratio is

$$\left(\frac{T_R - T_o}{\text{ppm CO}} \right) = \frac{3.037}{(1.31 + 3.69e^{-0.175\ v_o})}. \tag{8}$$

At v_o = 0.44 m/s, equation 8 yields a value of 0.64, and at v_o = 0.97 m/s, the value is 0.68. Table 3 shows the average value of the ratio of temperature rise to CO increase for each of the test. The average measured values for all the tests during the flaming stage were 0.62 at v_o = 0.44 m/s and 0.65 at v_o = 0.97 m/s, in good agreement with the predicted values.

Table 3.-Average values of the ratio of temperature rise (T_R - T_o) to CO increase

Test No.	V_o = 0.44 m/s	V_o = 0.97 m/s
1	0.52	0.80
2	0.72	0.54
3	0.60	0.62
4	0.76	0.55
5	0.65	0.67
6	0.45	ND
7	0.63	0.73
Average	0.619	0.652

ND No data.
v_o Air velocity.

When only coal is present as the combustible (as is typically the case during the early stages of fire in conveyor belt entries), then it becomes possible to estimate the levels of smoke and CO that are produced at a given temperature rise near the roof and at a fixed distance from the fire. In particular, it is of interest to make this determination for point-type heat sensors with alarm temperatures of 57.2 $^\circ$C (*6*) and spaced a maximum distance of 15.24 m from the fire, the minimum spacing specified in the regulations (*2*).

Combining equations 2, 3, and 4, the level of CO can be expressed as a function of temperature rise near the roof by:

$$\text{ppm CO} = 0.70(T_R - T_O) \cdot e^{-0.175 v_o} \cdot \ell^{1.75H/W}. \tag{9}$$

Since the fire can originate at any point within this spacing of 15.24 m, the integral average of equation 9 from $\ell = 0$ to $\ell = 15.24$ m represents a reasonable estimate of the average level of CO as a function of temperature rise near the roof. Assuming H = 1.83 m, and W = 6.10 m, the integral average value becomes:

$$\text{ppm CO} = 1.92(T_R - T_O) \cdot e^{-0.175 v_o}. \tag{10}$$

For smoke, the level of optical density (D) is given by the expression (*3*):

$$D(m^{-1}) = \frac{0.037 e^{-0.10 v_o} \cdot \dot{Q}_f}{v_o A_o} \tag{11}$$

Combining equations 2 and 11 yields:

$$D(m^{-1}) = 0.0054(T_R - T_O) \cdot e^{-0.10 v_o} \ \ell^{1.75H/W}. \tag{12}$$

The integral average of equation 12 over the distance from $\ell = 0$ to $\ell = 15.24$ m at the assumed values of H and W yields:

$$D(m^{-1}) = 0.0149(T_R - T_O) \cdot e^{-0.10 v_o}. \tag{13}$$

Assuming that $T_R = 57.2$ °C and $T_O = 18.3$ °C (a maximum air temperature underground), then equation 10 indicates that, for air velocities greater than 2.3 m/s, the estimated CO is less than 50 ppm. Equation 13 would indicate that for any air velocity less than 9.7 m/s, the critical level of optical density for human escape for someone familiar with the escapeway (0.22 m^{-1}) (*9*) is also exceeded. At a typical air velocity of 1.0 m/s, the smoke optical density at PTHS alarm is 0.52, more than twice the critical level of optical density.

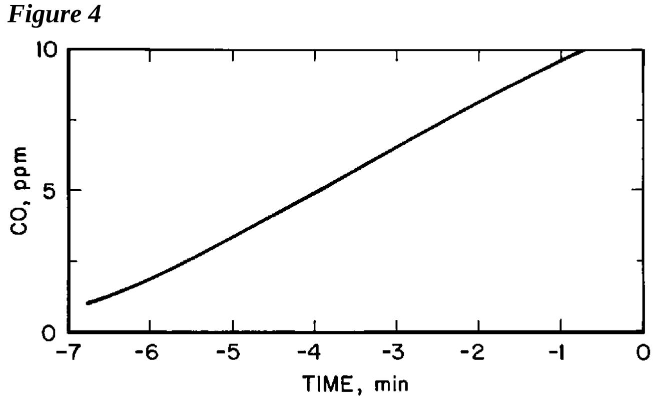
If the spacing for PTHS was increased to 38.1 m, then the estimated levels of CO and smoke at PTHS alarm would increase by about 60%. If a typical CO alarm level is taken to be 10 ppm at an air velocity of 1.0 m/s, then for the PTHS system to be equally sensitive, either the PTHS alarm temperature or the spacing, or both, should be reduced. For instance, if the spacing remains the same, then from equation 10, the value of T_R-T_O at the level of 10 ppm CO would be 6.2 °C, indicating an alarm temperature of 24.5 °C. If the alarm temperature were to remain 57.2 °C, then to reach this alarm temperature at 10 ppm CO, the spacing (from equation 9) would be reduced to 0.20 m.

These types of estimates clearly indicate the improvement in early-warning fire detection that can be realized using either CO or smoke sensors rather than PTHS. The use of CO or smoke sensors would, in many cases, result in the detection of smoldering fires, whereas PTHS would not.

While prolonged periods of sustained smoldering combustion are never guaranteed, it is instructive to assess the levels of CO produced during this stage of the fire. If the travel time of the CO from the fire to the sensor is subtracted from the actual times at which CO levels were measured by the sensor, then these levels correspond to the bulk average CO levels produced at the fire location. Figures 4 and 5 depict the bulk average levels of CO from the fire and the time required to produce sufficient levels of CO to reach its 10 ppm alarm level at both airflows, respectively. Time "0" corresponds to the instant of flaming ignition of the coal pile and not to the time when power was supplied to the electrical heaters. The negative time corresponds to the smoldering stage, the positive time to the flaming stage. At teh higher air velocity of 0.97 m/s (figure 5), at the time flame erupts, the CO level is 4 ppm and reaches its level of 10 ppm 9.4 min after flaming. Perhaps of greater interest is figure 4 for the lower air velocity of 0.44 m/s. At 0.7 min before flame erupts, the CO level has reached the 10 ppm alarm level. If flaming had never occurred, the heating would still have been detected by the CO sensor located downstream.

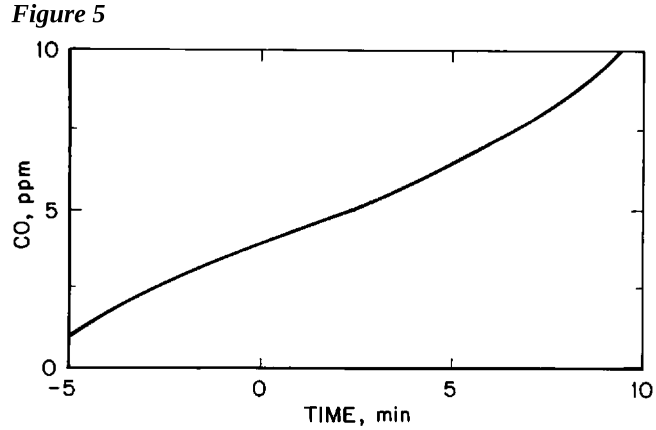
This is not the case for the PTHS. At the time flame erupts, there is virtually no increase in the air temperature. It is not until the flame has reached a significantly greater intensity that the air temperature near the roof at a distance of 3.65 m

Figure 4



Part per million during smoldering and flaming stages at an airflow of 0.97 m/s

Figure 5



Parts per million of CO during smoldering stage at an airflow of 0.44 m/s

downstream reaches 57.2 °C. The data from USBM RI 9380 (*3*) indicate that belt ig-nition (had one been present in a typical end-use config-uration) could have occurred at a much lower fire in-tensity (15 kW). At both air ve-locities, the smoke sensors alarmed 5 to 6 min before flaming occurred, and at CO levels in the range of 1 to 3 ppm, indicating their earlier warning capability.

CONCLUSIONS

The data and analysis clearly show for the experimental configuration considered that smoke sensors provide earlier warning of fire than 10 ppm CO sensors, and that 10 ppm CO sensors provide earlier warning than PTHS. For smoke and CO sensors including the DDD, the success rate was 1.0, meaning that every test fire was successfully detected. For the PTHS, at the lower air velocity, the success rate was 0.57; at the higher air velocity, the success rate was 0. Other thermal sensors such as a distributed fiber optics system have shown promise for early warning (*10*). When life and property depend upon the sensor's ability to detect a fire, these latter values for the PTHS are less than encouraging. The data also indicated that at the lower air velocity, 10 ppm of CO was produced prior to flaming, demonstrating that the detection of fires in their incipient, smoldering stages is a viable possibility in many instances. The use of smoke sensors enhances this possibility. The data also allow for estimates of CO and smoke optical density levels that would be present if detection was via PTHS spaced at intervals of 15.2 and 38.1 m. These levels are significantly greater than the recommended alarm thresholds for CO and smoke sensors. The data clearly indicate the effects of air ve-locity on the detection times that were realized for each type of sensor. Air velocity also impacts the relative se-quence of events observed during the stages of fire development (appendix). These results clearly indicate that the likelihood of miners' escaping from underground mine fires will improve with earlier detection.

ACKNOWLEDGMENTS

The authors wish to thank the following members of the USBM Pittsburgh Research Center for their important contributions: Kenneth W. Jackson and Fred-derick C. Bernick, electronics technicians, Richard W. Pro and Linda L. Chasko, physical science technicians for their assistance during experimental setup and running of the experiments.

REFERENCES

1. Roberts, G., D. McGlothlin, and M. Jackson. Bullitt Mine. MSHA Accid. Invest. Rep., Mar. 9, 1994, 16 pp.

2. .U.S. Code of Federal Regulations. Title 30--Mineral Resources; Chapter I–Mine Safety and Health Administration, Department of Labor; Parts 0 to 199, 1990, 762 pp.

3. Litton, C. D., C. P. Lazzara, and F. J. Perzak. Fire Detection for Conveyor Belt Entries. USBM RI 9380, 1991, 23 pp.

4. Conti, R. S., and C. D. Litton. Effects of Stratification on Carbon Monoxide Levels From Mine Fires. Paper in Proceedings of Sixth Ventilation Symposium, Salt Lake City, UT, June 21-24, 1993. Soc. Min. Metall., and Explor., Inc. (SME), Littleton, CO., 1993, ch. 73, pp. 489-494.

5. Mattes, R. H., A. Bacho, and L. V. Wade. Lake Lynn Laboratory: Construction, Physical Description, and Capability. USBM IC 8911, 1983, 40 pp.

6. Custer, R. L. P., and R. G. Bright. Fire Detection: State-of-the-Art. U.S. Dep. Commerce/NBS, NBS Techn. Note, TN 839, June 1974, 13 pp.

7. Conti, R. S., and C. D. Litton. Response of Underground Fire Sensors: An Evaluation. USBM RI 9412, 1992, 13 pp.

8. Egan, M. R. Diesel-Discriminating Detector Response to Smoldering Fires. USBM IC 9353, 1993, 9 pp.

9. Jin, T. Studies of Emotional Instability in Smoke from Fires. Fire and Flammability, V. 12, April 1981, pp. 130-142.

10. Dobroski Jr., H. and R. S. Conti. Distributed Temperature Sensing for Underground Belt Lines. Paper in Proceedings of New Technology in Mine Health and Safety (SME Annu. Meet. and Exhibit, Phoenix, AZ, Feb. 24-27, 1992). Soc. Min., Metall., and Explor., Inc. (SME), Littleton, CO, 1992, ch. 3, pp.21-28

APPENDIX—IMPACT OF AIR VELOCITY ON FIRE EVENTS

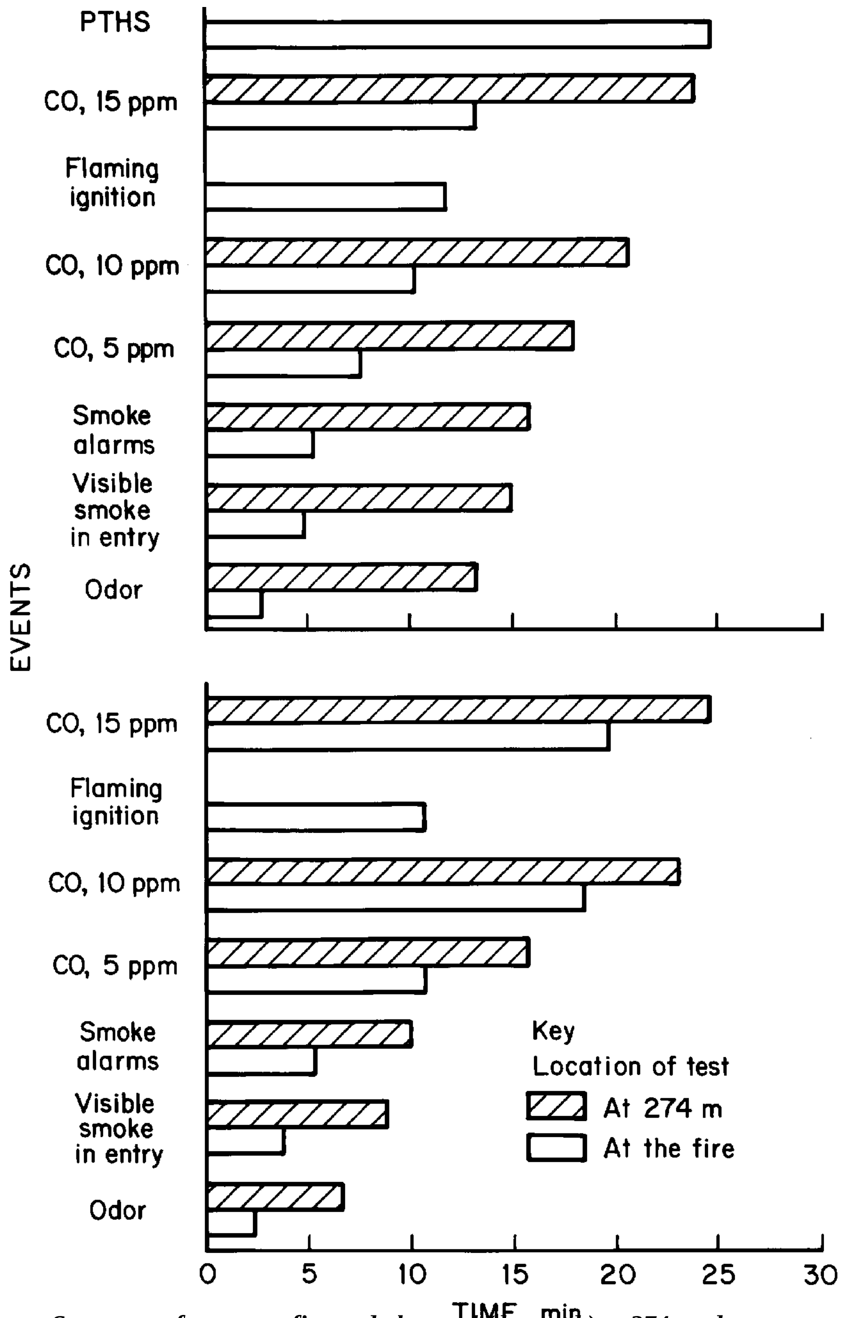
A developing mine fire triggers a sequence of events. The observation (or detection) of these events is a function not only of the location of an observer (or detector) relative to the location of the fire, but also of the air velocity. Figure A-1 shows the sequence of events observed (or detected) during the tests reported in this report. In the upper portion (figure A-1) are the events at $v_o = 0.44$ m/s, while in the lower portion are the events at $v_o = 0.97$ m/s. The open bars represent the events at the fire location; the diagonal-lined bars represent the events observed (or detected) at a distance of 274 m downstream of the fire.

At the lower air velocity there is a very consistent and regular sequence events at the fire and also at the observer (detector) location. The observed (detected) events are displaced by the travel time of 10.4 minutes from the events occurring at the fire. However, <u>all</u> the events observed (detected) actually transpire subsequent to flaming ignition of the coal due to this long travel time, even though odor, visible smoke in the entry, smoke alarms, 5 ppm, and 10 ppm CO actually occur at the fire location prior to flaming ignition. It should be realized that the time noted for the odor event could very well depend on the sensitivity of each olfactory sense.

At the higher air velocity the observed (detected) events are displaced by the travel time of 4.7 min from the events occurring at the fire location. The events of odor, visible smoke in entry, smoke alarms, and flaming ignition occurring at the fire location are almost identical to the same events at the lower air velocity. However, the levels of 5, 10, and 15 ppm CO at the fire location are recognized later due to their greater dilution at the higher air velocity. The observed (detected) events of odor, visible smoke in the entry, and smoke alarms at the 274 m location actually occur before flaming ignition of the coal due to the shorter travel time.

The air velocity impacts these events through both dilution and travel time effects. All the events observed (detected) at the 274 m location occur prior to alarm of a PTHS located at the fire source. The data clearly show the advantages of smoke and CO sensors compared with the PTHS that were evaluated during these tests.

Figure A-1



Sequence of events at fire and observed (detected) at 274 m. downstream from fire for test fires at two air velocities.