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Evaluation of sensors for mine fire detection using an atmospheric monitoring system

by C.D. Litton and I.E. Perera

Abstract ■ This report presents the results of experiments to evaluate different types of mine fire sensors in an underground mine environment using a commercially available atmospheric monitoring system. To determine how well carbon monoxide (CO) and smoke sensors respond for purposes of fire detection, experiments were conducted using test fires of different mine combustibles and for both flaming and nonflaming combustion. The experiments were designed to assess the response of fire sensors to different contaminants and different contaminant levels produced from the test fires. The experiments were performed in the Safety Research Coal Mine at the U.S. National Institute for Occupational Safety and Health's Bruceton Research Facility in the presence of an average ventilating air velocity of 1.6 m/s (315 fpm). Five fire sensor stations were located downstream of the test fire at fixed locations, with each sensor station consisting of four sensors: a CO fire sensor and three different smoke sensors, of which two were evaluated by the Mine Safety and Health Administration (MSHA) for intrinsic safety and the third was used extensively in underground mines overseas but not evaluated by MSHA for intrinsic safety. All four sensors were mounted near the center of the entry and in the upper one-third of the entry height. A UL-listed combination ionization and photoelectric smoke sensor was mounted near the roof at the first sensor station and its responses were compared against the responses of the four CO and smoke fire sensors. Sensor response data, contaminant travel times, and the impact of fire on the existing ventilation flow are discussed as they apply to early-warning fire detection. Of significance in the analysis is the need for performance standards for mine fire sensors in order to provide for consistent and timely early warning of developing fires.

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Introduction

The lifeblood of any underground coal mine is its ventilation system, providing breathable air and producing acceptable air quality, but once that system is contaminated, it acts quickly to transport contaminated air to areas far removed from the source of contamination, thus exposing personnel to contaminated air. Contamination from fire is of particular concern. Firstly, fires produce copious levels of smoke that can significantly obscure vision and impair the process of egress and evacuation from a fire-affected area. Secondly, fires may produce smoke that contains reactive gases that irritate the respiratory tract and confuse people's sensory perceptions, and, when allowed to grow uncontrolled, fires also produce debilitating, and often lethal, levels of carbon monoxide (CO) and, quite possibly, other toxic gases, depending upon the material that is burning (Litton and De Rosa, 1987; De Rosa and Litton, 1991). Thus, the early and reliable detection of developing fires is one of the tools that can be used to reduce the impact of underground fires on life and property, a major reason fire detection remains the subject of considerable research (De Rosa, 2004).

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Since the Coal Mine Health and Safety Act of 1969, fire detection systems have been mandatory in all underground coal mine entries where conveyor belt haulage systems are used. Early detection systems used point-type heat sensors that were based on the detection of elevated air temperatures resulting from the presence of a burning fire, but significant advances in the development of small, diffusion-type electrochemical cells made possible the detection of very low levels (ppm) of CO, a gas

Resumen ■ Este reporte presenta los resultados de experimentos para la evaluación de diferentes tipos de sensores contra incendio en minas en un ambiente subterráneo usando un sistema de monitoreo atmosférico comercialmente disponible. Para determinar que tan bien responden los sensores de monóxido de carbono (CO) y los detectores de humo con el propósito de detección de incendios, se realizaron experimentos usando fuegos de prueba con diferentes tipos de combustibles de minería para combustión inflamable e ininflamable. Los experimentos tenían el propósito de evaluar la respuesta de los sensores de fuego a diferentes contaminantes y diferentes niveles de contaminantes producidos por los fuegos de prueba. Los experimentos fueron realizados en el Safety Research Coal Mine y en el National Institute for Occupational Safety and Health's Bruceton Research Facility en presencia de una velocidad promedio de aire de ventilación de 1.6 m/s (315 fpm). Cinco estaciones de sensores contra incendio fueron ubicadas corriente abajo en ubicaciones fijas. Cada estación de sensores consistía de cuatro sensores: un sensor de fuego y de CO y tres detectores de humo diferentes, dos de los cuales estaban siendo evaluados por la Mine Safety and Health Administration (MSHA) por motivos de seguridad intrínseca y el tercero era de amplio uso en minas subterráneas en ultramar, pero no había sido evaluado por la MSHA para comprobar su seguridad intrínseca. Los cuatro sensores fueron montados cerca del centro de la entrada y en el tercio superior de la altura de la entrada. Se colocó un detector de humo combinado fotoeléctrico y de ionización certificado por UL cerca del techo en la primera estación de sensores y sus respuestas fueron comparadas con los cuatro detectores de humo y de CO. Los datos de respuesta del sensor, los tiempos de viaje de los contaminantes y el impacto del fuego en el flujo de ventilación existente son debatidos ya que son aplicables a la detección temprana de incendios. De mucha significancia en el análisis es la necesidad de estándares de desempeño para sensores contra incendio en minas a fin de proveer una alarma temprana consistente y oportuna a los incendios en progreso.

known to be produced during underground mine fires (Litton and Furno, 1982; Miller and Turcic, 1979). Simultaneously, advances were being made in the development of inexpensive smoke sensors of high sensitivity and reliability that were also potentially useful for the early and rapid detection of mine fires (Litton et al., 2004; Edwards et al., 2006).

During the late 1980s and early 1990s, mines that were attempting more efficient use of their underground entries and coal transport systems began to petition the Mine Safety and Health Administration (MSHA) for variances to use the air coursing through an entry containing a conveyor belt transport system to ventilate a working section. To grant these variances, MSHA, working in cooperation with the mining industry, the United Mine Workers of America, and the former U.S. Bureau of Mines, devised the idea of an atmospheric monitoring system (AMS) as a solution to the problem. The system would use CO (and, if available, smoke) sensors to continuously monitor the air along a conveyor belt system that was being used to provide intake air to ventilate a working section. Appropriate smoke sensors, if and when they became available, could be used in parallel with the CO sensors or as replacements because of their early-warning capability (Perera and Litton, 2011). Sensors to detect the levels of oxygen and methane in the belt intake air were also required as part of the system. Subsequently, specific language was written into Title 30, Code of Federal Regulations (30 CFR) defining the requirements for these systems when belt air is used to ventilate a working section.

On Jan. 1, 2010, the fire detection sensors mandated by law (30 CFR 75.1103-4) for conveyor belt entries were changed from point-type heat sensors to CO sensors, or other sensors that could provide protection equivalent to that provided by CO sensors. With this new regulation, CO or smoke sensors, or their equivalents, must now be used in all conveyor belt haulage entries for early-warning fire detection. Meanwhile, previous requirements for AMS deployment in belt entries (30 CFR 75.351) used to ventilate working sections remain in place. Because of these regulations for fire detection, it is of interest to determine how such systems respond to actual fires using fire sensors that are typical of an AMS.

To begin to address some of these issues, an AMS, along with gas and smoke sensors, was purchased and installed in the Safety Research Coal Mine (SRCM) at the U.S. National Institute for Occupational Safety and Health (NIOSH)'s Bruceton Research Facility in Pittsburgh, PA. Once the system was operational, a series of fire tests were conducted within the mine, where the fire products were transported by the ventilation airflow along the mine entries to the various sensor stations. This report describes the results of these experiments in terms of the contaminant travel times; resultant concentrations of products at locations far removed from the fire and the effects of mixing; and the impact of the fire on the preexisting ventilation air velocities.

Experimental

Atmospheric monitoring system. The installed system consisted of sensor stations located at specified underground locations and connected to a central station (a fiberoptic coupler) at the bottom of a borehole running to

Figure 1

Commercially available sensors tested in the study.

the surface. Underground, each sensor station contained up to four different addressable sensors connected to a single cable that connected all of the sensors to the central fiberoptic coupler. A fiberoptic cable running to the surface through the borehole connected the underground central station to a dedicated PC located in an aboveground laboratory. Software installed on the PC was used to control the functions (such as sensitivity, alerts and alarms) of the underground sensors, and the sensor and mine information from the PC could be displayed on a video monitor in a number of ways, such as tables, charts or a mine map with individual, real-time sensor readings at each of the sensor stations. The sensor data could also be collected at some preselected data acquisition interval and stored for subsequent reduction and analysis.

There were five underground sensor stations: three located in intake entries and two in return entries. For the intake entry stations, four sensors were used: a Conspec diffusion-type electrochemical CO sensor, a Conspec smoke sensor, a Reltek smoke sensor (SmokeBoss) and a Spero smoke sensor from South Africa (Fig. 1).

Two addressable interface modules were used to connect the Reltek and Spero smoke sensors to the connecting trunk line of the AMS. These modules converted the 4-20-mA outputs of the two sensors into digital signals that were compatible with the AMS software. Sensors located in the return entries had to be permissible, with their outputs connected to a permissible barrier located nearby in an intake airway. Because of the permissibility requirement, the Conspec smoke sensor (nonpermissible) could not be used at the two return stations, leaving only the other three permissible sensors. In addition to these sensors, a polypropylene tube with outer diameter of 0.95 cm (3/8 in.), extending from the aboveground laboratory control room down the borehole and along the entries to a position just downstream of sensor station 2, was used to pump gas samples back to the control room. In the control room, an infrared gas analyzer with a range of 0 to 100 ppm was used to measure the CO in the pumped gas samples, and we refer to the data as "extracted CO." In addition, three UL-listed combination optical/ionization smoke sensors manufactured by First Alert Inc. were mounted near the roof of the entry just upstream of the sensors at station 1 in order to gauge the effect of using fire sensors that had passed rigorous UL performance tests and compare their responses against those of the

Figure 2

Schematic of the Safety Research Coal Mine.

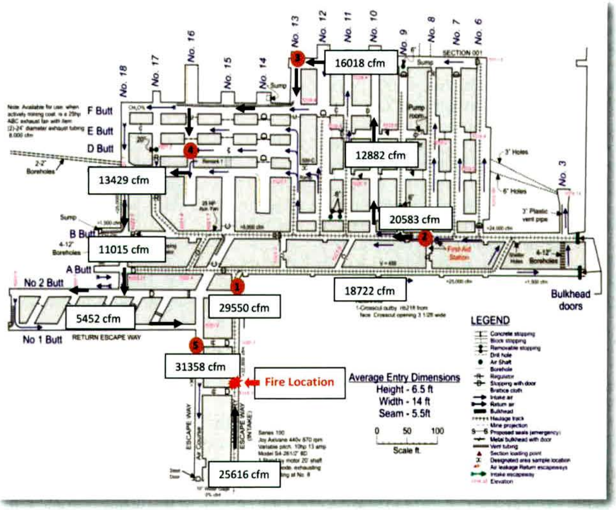
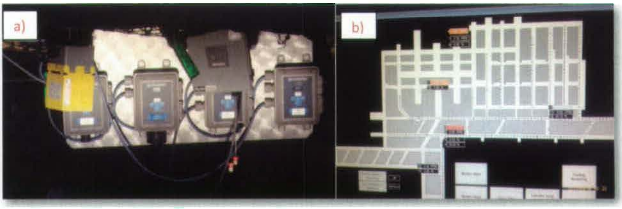


Figure 3

Photographs of (a) a sensor station showing the sensors near the roof, and (b) the monitor screen of the atmospheric monitoring system showing mine map and sensor locations.



AMS fire sensors. The three AMS smoke sensors were set to sound alarms when their individual output voltages reached some preset levels, and the Conspec CO sensor was set to sound an alarm when the CO concentration reached 10 ppm above an ambient level that varied from 0 to about 1 ppm during these experiments.

Figure 2 is a mine map showing the locations of the five sensor stations, the barrier and the borehole. Also shown are the measured airflows at various points along the travel route presumed for the combustion products. These flows, and the measured entry cross-sectional areas, can be used to define the approximate air velocities along the entries which, in turn, can be used to estimate the travel times of smoke and gases between sensor stations.

Figure 3(a) is a photograph of one of the sensor locations within the intake entries showing the four sensors mounted near the roof of the entry and the Reltek Smoke Boss and Spero sensors connected to the interface modules of the AMS. Figure 3(b) is a photograph of the video monitor in the aboveground control room displaying the mine map and sensor locations.

Experimental procedure. Fires were located along the main intake entry approximately 75 m (246 ft) upstream of the first sensor station (Fig. 2). Fires of different combustibles, namely, ponderosa pine, red oak, Douglas fir, Pittsburgh seam coal (~38 percent volatility), Lower Kittanning seam coal (~18-23 percent volatility), a styrene butadiene rubber (SBR) conveyor belt, a polyvinyl chloride (PVC) conveyor belt (both belts approved by MSHA), and No. 2 diesel fuel, were conducted to determine if there were any differences in their combustion products, and hence the sensor alarm times. For all of the solid combustibles, both nonflaming and flaming experiments were conducted. For the nonflaming experiments, the samples were heated in various configurations using eight electrical strip heaters with maximum surface temperature of 1,600°C (2,912°F). For the woods and the conveyor belts, strips approximately 0.05 m (2 in.) wide were used with a bottom layer on which the electrical strip heaters rested and a second, top layer resting on top of the electrical strip heaters. For consistency, the number of strips in contact with the heaters was kept constant so that the heated surface area was also constant from one material to the next. In most of these experiments, the samples did eventually burst into flame, and data were subsequently acquired for the flaming periods as well. Figure 4 is a photograph of a typical combustible material in contact with the electrical strip heaters just prior to the start of an experiment.

For the flaming experiments, ignition was achieved using an acetylene burner. The flames were allowed to impinge upon the combustible surfaces for a period of time sufficient to achieve sustained burning of the material (typically, around five minutes), at which time the burner was removed and the fire allowed to burn until either the combustible was consumed or the fire self-extinguished.

For all of the experiments, the fires were allowed to burn for a sufficient period of time to produce an approximately steady-state concentration of CO at the first two sensor stations. Once these steady-state levels were reached, the fires were allowed to burn for another five to 10 minutes before being extinguished. The ventilation airflow was then used to clear the mine of the CO and smoke before another experiment was initiated.

Results and discussion

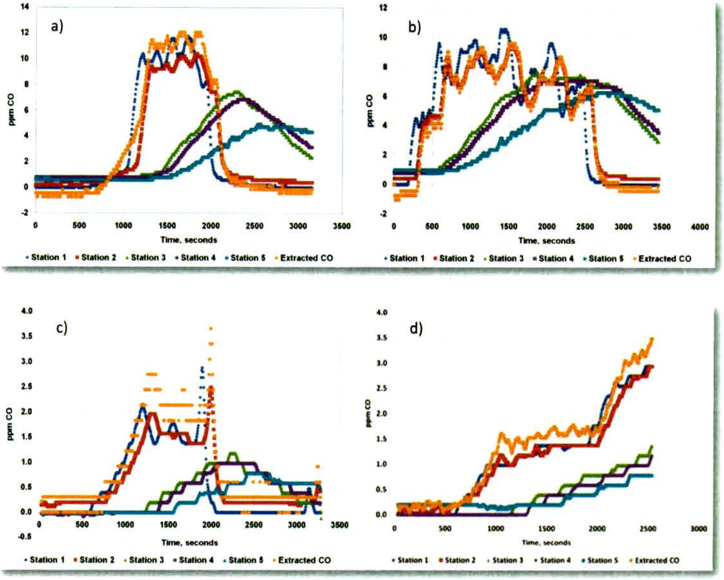
AMS sensor response data. Figure 5 shows CO levels as a function of time measured at the five monitoring stations for (a) SBR conveyor belting, (b) Douglas fir wood, (c) Pittsburgh seam coal, and (d) Lower Kittanning seam coal. The bulk average CO levels (Extracted CO), measured via the sampling tube located just downstream of

Figure 4

Wood slats with electrical heaters imbedded between.

Figure 5

CO concentrations measured at the five sampling locations for (a) an SBR conveyor belt, (b) Douglas fir wood, (c) Pittsburgh seam coal and (d) Lower Kittanning seam coal. The extracted CO was measured aboveground using an infrared CO analyzer.



sensor station number 2, are also shown for comparison against the AMS sensor measurements. For all the experiments there was little change in the CO levels between stations 1 and 2 but there were significant changes at the stations farther downstream as the CO continued to flow with the ventilation airflow. This is also true of the maximum observed CO concentrations.

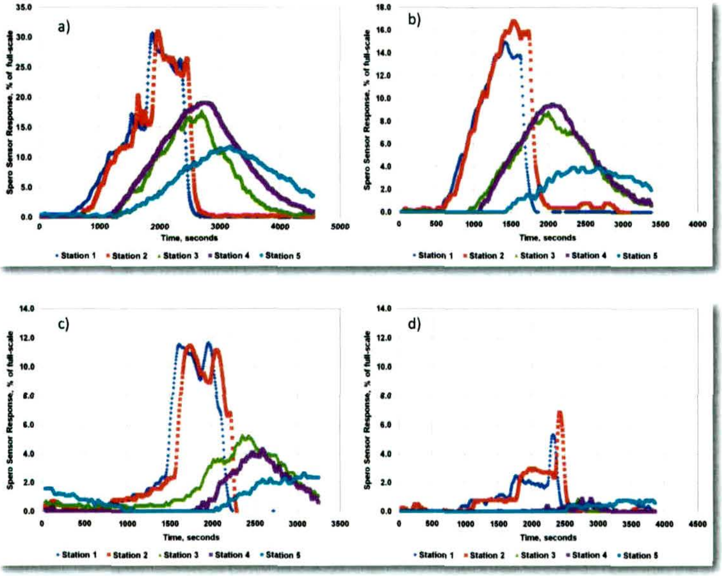
The significant drop in CO levels between stations 2 and 3 is most probably due to more complete mixing as the combustion products flowed downstream. There is also a possibility that there was some dilution from another area of the mine through leaking seals or line brattice that did not contain the fire contaminants. Once the contaminants have flowed past stations 3 and 4, the lower level of CO measured at station 5 would indicate that some dilution may still exist but that it is not as severe as it is between stations 2 and 3 or 2 and 4.

In addition to the measured CO levels, data were also available for the Spero smoke sensors in the form of percent of full-scale readings. They are shown in Fig. 6 for the same combustible materials of Fig. 5, where the relative sensor outputs are linearly proportional to the quantities of smoke produced. As in Fig. 5, there appears to be very little change in the smoke levels between stations 1 and 2, while at stations 3 and 4 there is a decrease of around 40 percent, and at station 5 the smoke levels are roughly 70 percent lower than their initial station 1 and 2 levels. It is worth noting that, although some losses of smoke to the roof and ribs of the mine entry should be expected as the smoke is carried downstream, the data indicate that there is little if any loss and that, surprisingly, the CO losses are greater than the smoke losses.

The Spero response data of Figs. 6(c) and (d) are interesting due to the significantly lower smoke levels produced by the lower volatility coal compared with the higher volatility Pittsburgh seam coal. The peak levels observed at stations 1 and 2 are 50 percent lower for the lower volatility coals, while for stations 3, 4 and 5 these levels are 70 to 90 percent lower. These differences are significant when assessing the criteria for fire detection in low volatility coal seams compared with high volatility coal seams. For CO, these differences are not as readily apparent as from Figs. 5(c) and (d). These observed differences for coals of different volatilities are in need of further study. The relative decreases for both smoke and CO can be seen more vividly in Fig. 7, where the ratios of the peak CO and smoke levels at stations 2 through 5 to the CO and smoke levels at station 1 are plotted as a function of distance from station 1. Perhaps the most interesting aspect of this graph is the clear indication that the CO

Figure 6

Smoke concentrations measured with the Spero sensor at the five sampling locations for (a) an SBR conveyor belt, b) Douglas fir wood, c) Pittsburgh seam coal and (d) Lower Kittanning seam coal.



reductions at stations 3 and 4 are around 60 percent, while for smoke the reductions are only 40 percent.

The data in Figs. 5-7, along with the data from the remainder of the experiments, also allow for computation of the actual times needed for the contaminants to travel from one station to the next. The distances between sensor stations divided by the measured travel times from one sensor station to the next yield the average ventilation air velocities. There are basically two ways to compute these travel times, namely, from the first moment of arrival of the gases at each point and/or from the moment the peak concentrations are reached at each point. These two methods give consistent, but slightly different, travel times with the travel time based on peak concentrations consistently longer.

Plots of distance versus average travel times between the five sensor stations can thus be constructed for smoke and CO, respectively, and are shown in Figs. 8(a) and (b). Along the straight path between stations 1 and 2 where little, if any, dilution is observed, the measured travel times (the arrival times of the leading edge of either CO or smoke) are in very good agreement with the predicted travel times based upon an air velocity of 1.60 m/s (315 fpm). For the peak concentrations of CO and smoke, the travel times are longer in this section of the mine due to a reduced, or "throttled," airflow that results when fire is present, causing an increase in entry resistance.

When the entry resistance increases during a fire, the ventilation air velocity decreases, resulting in longer travel times observed for the peak CO and smoke concentra-

Figure 7

Maximum peak ratios of smoke and CO concentrations at each sensor location.

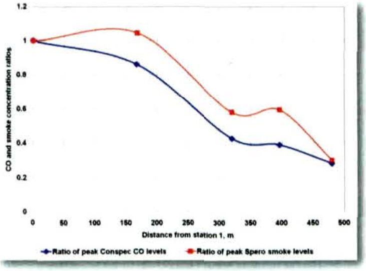
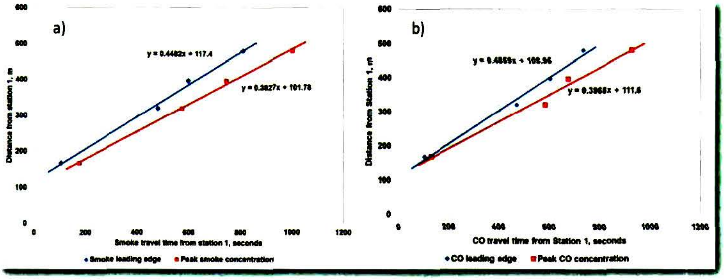


Figure 8

Distance from sensor station 1 versus the average arrival time of the (a) leading edge and peak concentration of smoke, and (b) leading edge and peak concentration of CO.



tions. In Fig. 8, the measured travel times for the CO and smoke peak concentrations compared with those for the leading-edge concentrations from sensor stations 1 to 5 are clearly longer, indicating that the presence of a fire does play a role in reducing, or "throttling," the ventilation airflow. In fact, the slopes of the respective curves are the average air velocities both for nonfire (leading edge) and fire-affected (peak) airflows and show that the average air velocity during the fire is approximately 82 to 85 percent of the nonfire air velocity.

It should be noted that these test fires were quite small and that the theoretical increase in entry resistance is grossly insufficient to account for the 15 to 18 percent reductions in airflows that are produced. This result is of significance when mine ventilation codes, such as MFIRE or similar, are used to assess the flow of combustion products from a developing underground mine fire. The methodology previously developed by Litton et al. (1987) – to account for these enhanced ventilation reductions at small fire sizes as a function of entry dimensions until the fire intensity is of sufficient magnitude that the theoretical computations become valid – appears also to be valid in these experiments.

Sensor alarms and peak sensor responses. Clearly, the ability of fire sensors to detect a developing fire and to produce an alarm in a timely manner is paramount to the success of the AMS fire detection system. The three UL-listed combination optical/ionization smoke sensors mounted near the roof of the entry just upstream of the sensors at station 1 were used to gauge the effect of using fire sensors that had passed rigorous performance tests and to compare their responses against those of the AMS fire sensors. The results are shown in Fig. 9, where the times of AMS fire sensor alarms or the times of peak signal levels (if there was no alarm) and the alarm or peak

Figure 9

Fire sensor alarm times compared with the alarm times of the ionization smoke sensor in the UL-listed combination smoke sensor.

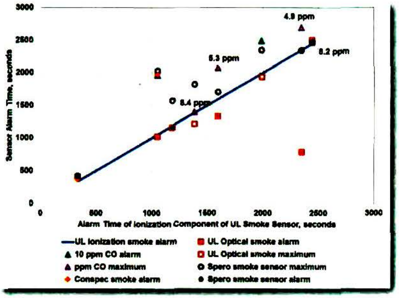
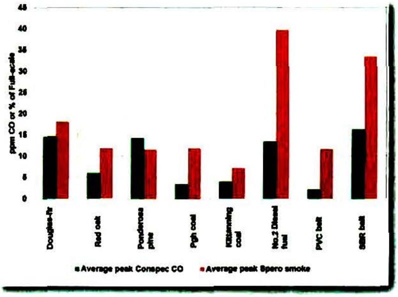


Figure 10

Variation of peak Conspec CO and peak Spero smoke concentrations at station 1 for the different combustible materials used in these experiments.



times of the optical component of the UL-listed combination smoke sensor are plotted as a function of the measured alarm time of the ionization component of the UL-listed combination sensor. The ionization component of the UL-listed sensor was the only sensor to register an alarm in all the experiments.

As shown in Fig. 9, the optical component of the UL-listed sensor registered alarms (solid squares) in half (4) of the experiments; the Conspec CO sensor registered alarms (solid green triangles) in half (4) of the experiments (but not all the same ones as the optical component alarms); the Conspec smoke sensor registered alarms (solid diamond) in only two experiments; the Spero sensor registered alarms (solid circle) in only one experiment; and the Reltek smoke sensor registered no alarms during these experiments. These comparisons indicate that a fire sensor that has undergone extensive performance testing (that is, the UL-listed sensor) clearly outperforms the smoke and CO sensors that are currently available but have not passed any rigorous performance tests and yet have been approved for use in the mining industry.

The relative responses, as well as the indications of which fires resulted in CO alarms, are shown in Fig. 10 *for the eight different combustibles used in these experiments.* It is worth noting that the two lowest responses, for both the Conspec CO and Spero smoke sensors, occurred for the two different coals. This is worth noting since it should be expected that an adequate fire sensor would respond adequately to a developing coal fire.

Conclusions

The AMS was able to respond quickly to the changing underground environment and provide real-time display of the spread of the fire contaminants. The rapidity of data acquisition allowed for timely measurements of gas and smoke travel times from one sensor location to the next, thus providing critical information on the fire's effects on the ventilation air velocity.

Overall, the sensor data revealed that smoke generally develops earlier than CO and that both smoke and CO concentrations decrease from one station to the next as the fire contaminants move downstream. The measured smoke and CO concentrations at each station allow for the calculation of the travel times from one station to the next, thus yielding the average air velocities in the mine. These data indicate that the presence of a fire plays a role in reducing, or "throttling," the ventilation airflow, and that the average air velocity during these small test fires is approximately 82 to 85 percent lower than that of the nonfire air velocity.

The sensor response data indicated that the only sensor to register alarms for all test fires was the ionization sensor component of the UL-listed combination smoke sensor. Of the two smoke sensors evaluated by MSHA, only the Conspec smoke sensor registered alarms, but only in two of the experiments, while the other smoke sensor (Reltek) never registered an alarm in any of the experiments. The third smoke sensor, the Spero sensor, reached its preset alarm in only one experiment. For the 10-ppm CO sensor and the photoelectric component of the UL-listed combination smoke sensor, alarms occurred in half the experiments. The inability of the MSHA-evaluated sensors to register alarms in many of the experiments is disconcerting and an indication that performance tests are warranted in order to modify their alarm responses and alleviate this serious problem. In addition, the inability of the two MSHA-evaluated smoke sensors to register alarms consistently, while the UL-listed smoke sensor was found to be very consistent in its response, reflects a need for the further investigation of fire sensors intended for use underground and for the development of rigorous performance standards for underground fire sensors. ■

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of NIOSH. Mention of company names or products does not constitute endorsement by NIOSH.

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