GAS AND SMOKE
MONITORING SYSTEMS

By Dr. Inoka Eranda Perera and Mr. Charles D. Litton

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ABSTRACT

A series of experiments were conducted to obtain the characteristic sensor responses of commercially available gas, smoke, and flame sensors to fires of common combustible mine materials. The experiments were conducted in a large-scale fire gallery located at the National Institute for Occupational Safety and Health (NIOSH) Lake Lynn Laboratory (LLL) in Fairchance, PA, using Ponderosa Pine, Red Oak, Douglas-fir, high and low volatile coals, PVC and SBR conveyor belt, No. 2 diesel fuel, and diesel exhaust. The sensors included a diffusion-type carbon monoxide (CO) sensor, photoelectric- and ionization-type smoke sensors, a video smoke/flame detector, and an optical flame detector. Simultaneous measurements were obtained for average gas concentrations, smoke mass concentrations, and smoke optical densities in order to quantify the levels of combustion products at the alert and alarm times of the sensors. Because required sensor alarm levels are 10 ppm and 0.044 m^{-1} optical density for CO and smoke sensors, respectively, the different sensor alarm times are compared to the times at which the CO and smoke reach these alarm levels [1]. In addition, the potential impacts of using smoke sensors that have met the performance standards from accredited testing laboratories are also evaluated and discussed using the response data of an Underwriters' Laboratory (UL)-listed combination photoelectric/ionization smoke detector. These test results are further discussed relative to fire sensor needs and improvements that can have a positive impact on mine fire safety.

INTRODUCTION

Analysis of Mine Safety and Health Administration (MSHA) mine accident investigation data indicates a total of 75 underground coal mine fires occurring from 2000 through 2009, resulting in 10 injuries and 2 fatalities. In order to improve the level of fire safety and to guard against the disastrous consequences that can result from mine fires, federal regulations mandate the use of automatic fire detection in certain underground locations, such as conveyor belt entries, diesel fuel storage areas, and power centers. Clearly, life safety is critically dependent upon the adequacy of these fire sensors to provide for early-warning detection for a broad range of fires that are possible. In order to address this need, research was undertaken to evaluate and compare both smoke and gas detection devices that are available for use in atmospheric mine monitoring systems. Experiments were conducted using a wide range of common combustible mine materials to measure the performance of these devices in response to both non-flaming and flaming fires in order to determine their suitability for early-warning fire detection.

Research conducted by NIOSH and others has revealed the importance of early-warning fire detection techniques and recommended a range of sensor criteria that will maintain the required sensitivity without interferences from other sources [2, 3, 4]. These sources can include, but are not limited to, diesel exhaust, methane, humidity, coal dust, and other gases that may be produced during the combustion process. Some of these interferences, such as diesel exhaust and coal dust, have been studied extensively for their impact on mine fire sensors.

It is known that the two most common types of smoke sensors, photoelectric-type and ionization-type, respond differently to flaming and non-flaming fires due to their different operating principles. Photoelectric-type smoke sensors generally work on a light-scattering principle where, typically, a light-emitting diode (LED) is projected across an open cell and a detector located at an angle on the opposite side measures the light scattered when smoke particle aggregates enter the cell. In the typical design of ionization-type smoke detectors, a radioactive material is used to generate ions in the air space between two electrodes, and the potential difference of a third collection electrode, which is placed in between the first two electrodes, is measured. When smoke aggregates enter the air space between the electrodes, the ions attach to the aggregates, reducing the ion concentrations and resulting in an increase in the potential difference at the collection electrode. For ionization-type smoke sensors, the sensitivity decreases as the particle size increases, opposite to the behavior of photoelectric-type sensors.

In order to better evaluate the performance of gas and smoke sensors, it is important to understand how the levels of smoke and CO relate to each other for the different types of fires that are possible. For smoke sensors, smoke aggregate properties are also very important in assessing their performance using detailed quantitative data such as that found in Reference [5]. For this study, however, the relative levels of smoke and CO produced from the different fires are of greatest interest since these levels provide important indications as to the best type of sensor to be used for certain applications. It is also important to note that gas and smoke sensors for fire detection in underground U.S. coal mines are not required to meet or exceed any consistent set of standard performance tests. Currently, CO and smoke sensors are evaluated by MSHA based solely upon the characteristics of electrical permissibility or intrinsically safe electrical equipment. For CO sensors, this procedure does not represent a significant problem, since CO sensors are required to alarm at specific levels of CO (ppm). For smoke sensors, however, the respective alarm levels are set individually by each manufacturer without the devices undergoing any standard performance testing. As a result, the relative levels of smoke at which the various sensors may alarm can have significant variations that can drastically affect their early-warning capabilities. To address these issues, this paper describes the results of large-scale experiments conducted to evaluate the response characteristics and alarm times of smoke and gas sensors commercially available to the mining industry, and presents additional data on the relative levels of CO and smoke produced from a variety of combustible mine materials.

EXPERIMENTAL PROCEDURE

Fire Gallery and Experimental Setup

Large-scale experiments were conducted in the Lake Lynn Laboratory (LLL) fire gallery, Fairchance, PA, shown in Figure 1.

Figure 1. *Lake Lynn Laboratory fire gallery*

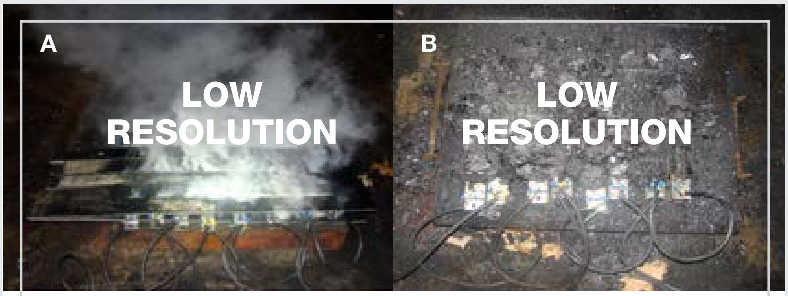

Figure 2. *Experimental setup with heaters embedded in (A) smoldering wood and (B) coal*

A total of seven combustible materials were used in the experiments: Pittsburgh seam coal (high vol A bituminous coal lumps), a mixture of Upper Freeport and Lower Kittanning seam coals (low vol bituminous coal lump mixture), Douglas-fir (2-in x 4-in pieces), Ponderosa pine (2-in x 4-in pieces), red oak (2-in x 4-in pieces), No.2 diesel fuel, and two different types of fire-resistant conveyor belts known generically by their primary polymer component as styrene butadiene rubber (SBR, 3-ft pieces) and polyvinyl chloride (PVC, 3-ft pieces). Additional tests were also conducted to determine the sensor responses to contaminants produced by the exhaust of a diesel engine. In all of the experiments except those using diesel fuel and the diesel exhaust experiment, the combustible materials were heated via contact with electrical strip heaters, initially producing smoldering combustion that later erupted into flames. Specific details of the experiments are reported elsewhere [6]. Photos of two typical fires are shown in Figure 2. The array of sensors used in the study and positioned near the exit of the fire gallery are shown in Figure 3.

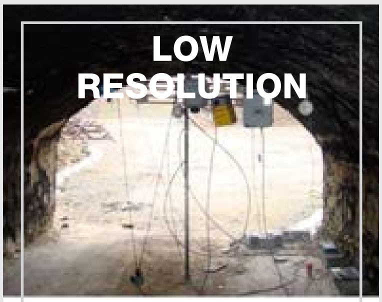

Figure 3. *Gas averaging probe (vertical pipe) at the tunnel exit and the array of fire sensors mounted near the roof*

Gas and Smoke Sensors

The sensors evaluated in this study included both photoelectric- and ionization-type smoke sensors, a diffusion-type carbon monoxide (CO) sensor, a video smoke/flame detector, and an optical flame detector. Because smoke sensors, in particular, are not required to meet any performance standards, the response times of a UL-listed combination photoelectric/ionization smoke detector that has met rigorous UL performance standards was also used in this study. This detector was used in order to directly compare the responses of the two types of conventional smoke detectors (photoelectric- and ionization-types) and, perhaps more importantly, to compare the response of a smoke sensor that has passed rigorous performance standards to the responses of the smoke sensors available for use by the mining industry that have not passed any uniform set of performance standards. The results of this comparison are discussed further in the following section to demonstrate the improvement in early-warning capability that is possible when smoke sensors are used that pass rigorous performance standards. The smoke sensors and the CO sensor are shown in Figure 3 mounted near the roof at the exit of the large-scale fire gallery. All of the smoke and CO sensors used in this study are also depicted in Figure 4.

Figure 4. *MSHA approved under the Reltek sensor*

In addition to the point-type sensors, the response of a smoke/flame video monitoring system manufactured by axonX was also evaluated. This video imaging system uses changes in light contrast to detect the presence of smoke liberated during the early stages of a smoldering fire.

RESULTS AND DISCUSSION

Table 1 shows the times of appearance of visible smoke and flame and the sensor alarm times for each material tested, for all the sensors evaluated in this study. The table also shows the times for the bulk average CO concentration, as measured at the end of the tunnel with the gas averaging probe, to reach 10 ppm. Irrespective of the combustible materials used, all the measured sensor alarms occurred after the onset of smoldering, but only some of the sensor alarms occurred before onset of the flaming stage.

As evidenced in Table 1, all of the combustible materials produced visible smoke within 4 minutes from the time that electrical power was supplied to the strip heaters. All of the materials, with the exception of the PVC belt, which generated only non-flaming smoke, reached flaming combustion between 13 and 24 minutes. Of the solid combustibles tested, the SBR belt and mixture of Lower Kittanning and Upper Freeport coal took the longest times to ignite. Of the four smoke sensors, only the VESDA and Conspec alarmed in all the experiments. The VESDA, in particular, was found to be extremely sensitive

TABLE 1. APPEARANCE TIMES FOR SMOKE, FLAME, AND THE VARIOUS SENSOR AND AVERAGE CO ALARM TIMES MEASURED FOR THESE EXPERIMENTS

Burning material	Time to visible smoke, min	Time to visible flame, min	Smoke sensor time to alarm, min				UL-listed combination smoke sensor		axonX video smoke	CO sensor time to alarm (10 ppm), min	
			Spero Smoke	Reltek Smoke	Conspec smoke	VESDA	Optical	Ion		Conspec CO	Bulk Average CO
Douglas-fir	2.50	9.75	13.70	No alarm	8.10	7.53	N/A	N/A	6.46	8.30	8.23
Ponderosa pine-1	3.30	9.97	No alarm	No alarm	10.20	8.17	N/A	N/A	5.10	8.53	7.73
Ponderosa pine-2	3.66	13.08	No alarm	No alarm	6.80	4.93	4.40	6.10	5.73	7.00	5.23
Red oak-1	3.02	10.20	No alarm	No alarm	7.60	4.80	N/A	N/A	4.02	7.03	6.50
Red oak-2	3.88	13.00	No alarm	No alarm	8.13	5.63	5.10	5.10	5.92	8.57	6.90
Red oak-3	2.92	8.68	No alarm	No alarm	9.27	5.20	5.10	6.70	7.17	8.07	6.80
Pittsburgh seam coal-1	3.08	11.12	No alarm	No alarm	8.83	7.60	7.60	6.60	6.22	10.07	9.37
Pittsburgh seam coal -2	3.08	12.45	No alarm	No alarm	9.47	8.03	7.50	7.50	7.00	8.87	8.10
Lower Kittanning mix-1	3.10	14.15	No alarm	No alarm	N/A	7.86	No alarm	9.83	11.36	11.76	10.53
Lower Kittanning mix-2	3.03	20.10	N/A	No alarm	20.06	8.33	N/A	N/A	N/A	12.83	N/A
SBR belt-1	3.13	18.00	19.30	13.30	12.23	8.77	N/A	N/A	13.46	13.30	11.00
SBR belt-2	2.30	24.00	17.26	10.80	9.03	5.43	7.98	9.73	5.25	10.97	9.57
PVC belt	1.92	N/A	No alarm	9.96	9.03	4.80	5.10	6.50	3.63	12.90	12.83
Diesel fuel-1	N/A	0.50	N/A	No alarm	0.87	1.07	1.10	0.90	N/A	1.67	2.07
Diesel fuel-2	N/A	0.50	1.90	No alarm	0.70	1.07	1.20	0.80	N/A	1.20	1.17
Diesel exhaust	N/A	N/A	N/A	No alarm	4.03	2.23	No alarm	3.50	No alarm	4.36	4.63

N/A- Not available

to smoke. The Reltek smoke sensor only alarmed during the SBR and PVC belt experiments, and did not alarm when burning any of the other combustible materials, including both types of coal. The Spero smoke sensor alarmed only for the burning SBR belt and Douglas-fir. The UL-listed combination sensor reached the ionization alarm threshold in all the experiments, while the optical alarm threshold was reached in all experiments except for the low vol coal mixture and the diesel exhaust. Both of these experiments produced smoke with very low optical densities.

The axonX smoke/flame video detection system was found to be very sensitive to the smoke generated for all the materials tested. However, it should be noted that because the axonX is an optical system that requires line-of-sight operation, its use underground may be limited to protection of local areas with high risk of fire such as belt drives, storage and maintenance areas, or electrical power centers. In addition, photoelectric-type smoke sensors are generally known to be more sensitive to smoke from non-flaming fires than to smoke from flaming fires, while the reverse is true for ionization-types. This behavior is readily apparent when comparing the earlier response times of the VESDA smoke sensor (photoelectric-type) to the later response times of the Conspec smoke sensor (ionization-type), and also the relative optical and ion response times for the UL-listed combination sensor. The CO sensor always alarmed after the smoke sensors alarmed, indicating that CO sensors are generally not as sensitive to the early stages of a developing fire as smoke sensors. There was very little time difference between the Conspec CO alarm and the time that the bulk average CO reached 10 ppm.

Figure 5 shows the maximum CO concentrations and the maximum optical densities observed at 532 nm for each combustible material used in these experiments. The diesel fuel fires and conveyor belt fires produced the highest smoke concentration, while the lowest optical densities were recorded for the diesel exhaust and low vol coal. One important point to note here is that the Reltek smoke sensor alarmed only at high optical densities produced from the conveyor belt fires. This is a much higher optical density than the MSHA-regulated 0.044 m^{-1} optical density level, a drawback that would need to be addressed before this sensor could be used effectively in underground mines. The highest concentration of CO was observed when burning Douglas-fir, while the lowest CO concentrations were obtained with Pittsburgh seam coal, the low vol coal mixture, and diesel exhaust. It is also interesting to note that both types of coal produced similar CO concentrations but two significantly different smoke optical densities. This latter result would tend to indicate that the two types of coal may have different chemical and physical properties.

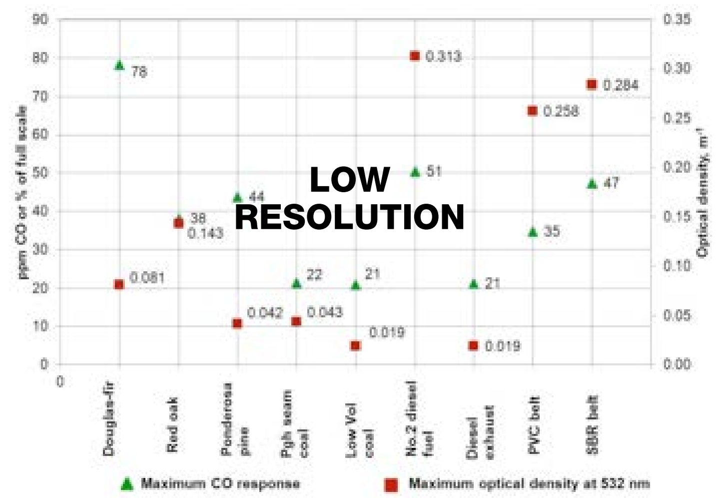

Figure 5. *Variation of maximum average CO peak and smoke optical densities for the different combustible materials used in these experiments*

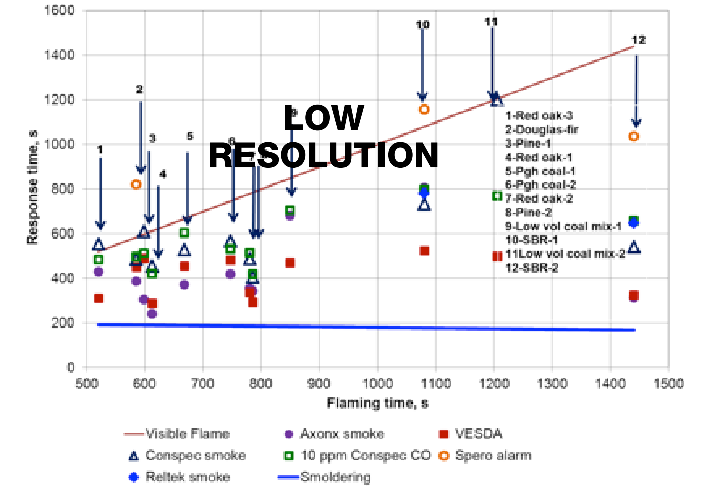

Figure 6. *Performance of the sensor alarms with respect to smoldering and flaming fires*

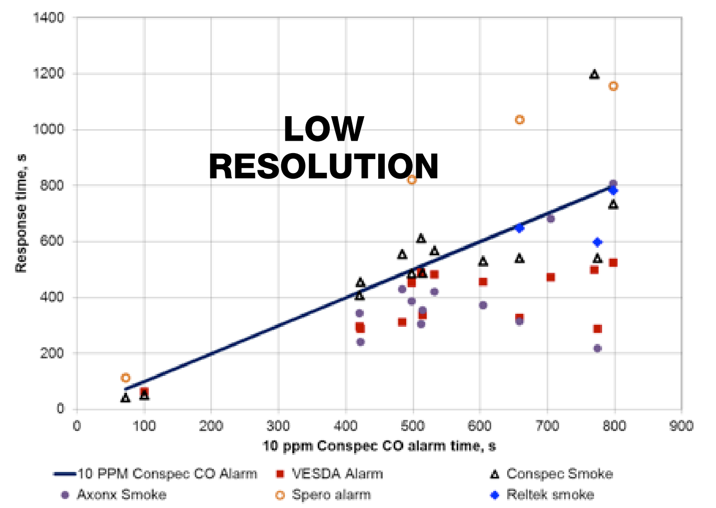

Figure 7. *Comparison of the sensor responses to 10 ppm CO alarm time*

COMPARISON OF SENSOR ALARMS TO MAJOR EVENTS AND RECOMMENDED CO AND SMOKE ALARM LEVELS:

Figure 6 shows the overall performance of the sensors tested relative to the onset of visible smoke and visible flame. The x-axis denotes the time taken for each material to flame and the y-axis denotes the time that each sensor alarmed relative to the smoldering and flaming times of each material. Arrows indicate the materials tested. In this figure, the closer the alarm time is to the appearance of visible smoke, the earlier the alarm and the more time that would be available for evacuation during an actual fire emergency. As noted in Table 1, some of the smoke sensors did not alarm at all. Irrespective of the material used, the VESDA and axonX smoke sensors alarmed first. With the exceptions of the Spero sensor and in two experiments the Conspec smoke sensor, all the sensors alarmed before visible flames were observed.

Figure 7 shows the alarm times of the sensors relative to the 10 ppm Conspec CO alarm time, irrespective of the materials used. The VESDA and the axonX smoke sensors alarmed before the 10 ppm CO alarmed, while the Conspec smoke sensor alarmed before the 10 ppm CO alarm in only about half of the experiments. In general, the experimental fires took longer to produce the 10 ppm CO than to produce the 0.044 m^{-1} OD. This result is indicative of the observation that, even for these rapidly developing fires, smoke sensors have the potential to provide for earlier warning than CO sensors—a result that can have life-saving benefits. Even though the Reltek smoke sensor alarmed only during the belt fires, when it did alarm the roof CO had not yet reached the 10 ppm alarm level. It should be noted that in all experiments the bulk average CO reached the 10 ppm alarm level before visible flames were observed. With the exception of the Spero smoke sensor, the gas and smoke sensor alarms almost always occurred prior to the appearance of visible flames.

Figure 8 shows the times at which the smoke and the CO sensors alarmed compared to the times at which the optical component of the UL-listed combination photoelectric/ionization smoke sensor reached its alarm threshold. As shown in the graph, very few sensors alarmed before the optical alarm (even for the most sensitive smoke sensors tested, i.e., VESDA and axonX). In all the experiments, the 10 ppm Conspec CO alarmed long after both the photoelectric and ionization sensors reached their alarm levels. In most of the experiments, it is also evident that the optical component of the combination sensor alarmed before the ionization component, which is in keeping with the general observation that the photoelectric-type sensor is more responsive to smoldering combustion than the ionization-type. These results indicate that a combination photoelectric/ionization smoke sensor could be an ideal candidate for in-mine use to detect smoke generated from both flaming and non-flaming fires. In addition, the uniformity of response of this sensor, for both the optical and ionization components, demonstrates the increased reliability that is possible with sensors that meet performance standards.

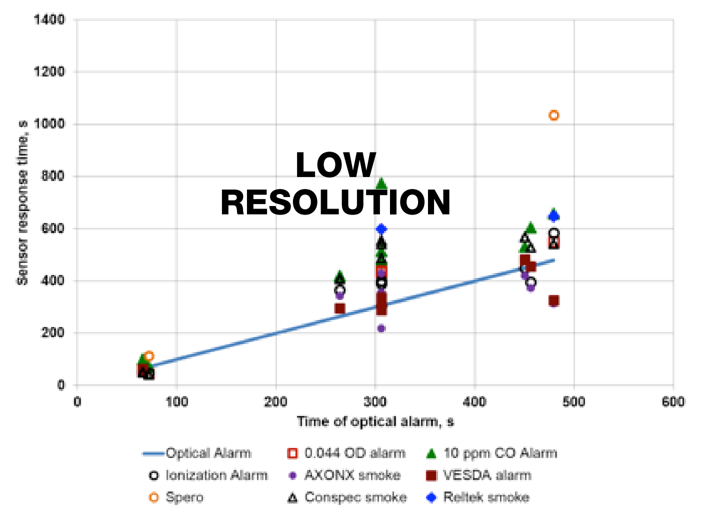

Figure 8. *Smoke and CO sensor responses with respect to UL-approved combination photoelectric/ionization smoke sensor responses*

SUMMARY

Overall, the experiments conducted to evaluate commercially available gas and smoke sensors revealed that for the types of combustible materials typically found in underground coal mines, smoke levels developed earlier than CO levels and smoke sensors responded earlier than the CO sensor. Of the four point-type smoke sensors evaluated in this study, the VESDA and Conspec smoke sensor alarmed in all the experiments, irrespective of the material used. The Reltek smoke sensor only alarmed when burning SBR and PVC belt and then only at very high smoke levels, while the Spero smoke sensor alarmed only when burning SBR belt, diesel fuel, and Douglas-fir. The axonX video smoke/flame detection system also alarmed in all the experiments, and the alarm times were very close to those of the VESDA. However, because of its principle of operation, this sensor may be better suited for use in more localized, high-risk areas, such as conveyor belt drives, fuel storage areas, or underground maintenance areas.

The data obtained for the UL-listed combination smoke sensor indicated a more uniform and consistent response than the responses from the other smoke sensors evaluated. This result would indicate that mine fire detection has significant room for improvement if smoke sensors targeted for use in underground mines were required to meet or exceed standardized performance tests. The performances of both the Reltek smoke sensor and the Spero sensor were found to be inadequate in these experiments, either producing no alarm in many of the experiments or alarming only at high levels of smoke optical density.

Even though the 10 ppm CO alarms occurred slightly later than the 0.044 m^{-1} smoke optical density alarms in almost all of the experiments, it should be noted that not all combustibles used in the experiments produced smoke optical densities equal to or greater than the required alarm threshold. While the maximum optical densities measured for Ponderosa pine and Pittsburgh seam coal were very close to the alarm threshold (0.042 and 0.043 m^{-1}, respectively), the maximum value observed for the low vol coal was only 0.019 m^{-1}. ■

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