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Evaluation of detection and response times of fire sensors using an atmospheric monitoring system

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Abstract

Atmospheric monitoring systems (AMS) are required when using air from conveyor belt entries to ventilate working sections in U.S. underground coal mines. AMS technology has the potential to increase fire safety mine-wide, but research is needed to determine the detection and response times for fires of a variety of combustible materials. To evaluate the potential of an AMS for fire detection in other areas of a coal mine, a series of full-scale fire experiments were conducted to determine detection and response times from fires of different combustible materials that are found in U.S. underground coal mines, including high- and low-volatility coals, conveyor belts, brattice materials, different types of wood, diesel fuel, and a foam sealant. These experiments were conducted in the Safety Research Coal Mine (SRCM) of the U.S. National Institute for Occupational Safety and Health (NIOSH) located in Pittsburgh, PA, using a commercially available AMS that is typical of current technology. The results showed that through proper selection of sensors and their locations, a mine-wide AMS can provide sufficient early fire warning times and improve the health and safety of miners.

Keywords

Atmospheric monitoring system; Ventilation; Mine fire

Introduction

Technology has played an important role in making underground mining a much safer industry. During the late 1980s and early 1990s, U.S. 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 that contains 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, recommended use of an atmospheric monitoring system (AMS) in this situation. The system would use carbon monoxide (CO) sensors or 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.

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Appropriate smoke sensors could be used in parallel with the CO sensors or as replacements because of their early warning capability. However, there are no smoke sensors currently being used as the main detection device in U.S. underground coal mines (Perera and Litton, 2011). Specific language was written into the Title 30 Code of Federal Regulations, 30 CFR 75.350(b) (MSHA, 2016) 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 under 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. Because of the new regulations for fire detection, initial studies were conducted to determine how AMS systems respond to actual fires (Litton and Perera, 2015). Meanwhile, previous requirements for AMS deployment in belt entries (30 CFR 75.351) used to ventilate working sections remain in place, and it is of interest from a safety standpoint to determine how such systems might be utilized for more extensive mine-wide fire detection. To address this question, full-scale experiments using an AMS installed in the Safety Research Coal Mine (SRCM) at the Bruceton Research Center of the U.S. National Institute for Occupational Safety and Health (NIOSH) in Pittsburgh, PA, were conducted to determine the response and detection times of typical fire detectors to fires using a variety of common mine combustible materials. This paper describes the results of these experiments in terms of the contaminant—CO and smoke—levels attained, the travel times of these contaminants to various sensor locations, and their resultant concentrations at locations far removed from the fire.

Experimental design

The AMS used in the full-scale flaming and smoldering experiments in the SRCM consists of five sensor monitoring stations located strategically throughout the mine. Sensors at each station are connected by a fiber optics coupler to a central relay station located at the bottom of a borehole inside the mine. The fiber optic cable then runs vertically through the borehole up to the surface and connects to a dedicated personal computer (PC) in the control room. Each sensor station contains up to four different addressable sensor connections that connect to a single cable that then connects to the central fiber optic coupler. The sensor data are then displayed and stored on the PC using a software package that is dedicated to this particular AMS. The software enables the end user to set sensor alarm and alert levels and also to set the time interval at which the data are collected and stored on the PC for further analysis. Using this software, data can be displayed in different formats on a video monitor as a chart or table, or on a mine map with individual real-time sensor readings at each of the sensor locations.

Out of the five sensor stations, three of the locations are in the intake entries and the other two are in the return entries, as shown in Fig. 1. The measured airflow rates at the five sensor stations are also shown. These flow rates and the measured cross-section areas can be used to estimate the air velocities in the entries and the travel times of smoke and gases between sensor stations. Each station was equipped with a Conspec CO sensor, which is a diffusiontype electrochemical cell with a measurement range of 0 to 50 ppm of CO, and four different types of smoke sensors were used in the experiments: (1) a Conspec smoke sensor, which is an ionization-type sensor, (2) a Smoke Boss smoke sensor from Rel-Tek (Monroeville, PA), which is an optical-light-type sensor, (3) a Spero smoke sensor from Spero Group (Centurion, South Africa), which is an ionization-type sensor, and (4) a UL-listed combination optical/ionization smoke sensor manufactured by First Alert Inc. (Aurora, IL). The Conspec smoke sensor was placed at monitoring stations 1 through 4. The Spero smoke sensor was placed at stations 1 through 3. The Smoke Boss smoke sensor was placed at stations 1 and 2, and while the combination optical/ionization smoke sensor was only installed at station 1. Two types of air velocity sensors, from J-TEC (Cedar Rapids, IA) and Rel-Tek, were used in the tests. The J-TEC air velocity sensor with a measuring range of 0 to 5.08 m/s (0 to 1,000 fpm) was placed at stations 1, 2 and 3. The Rel-Tek air velocity sensor with a measuring range of 0 to 10.16 m/s (0 to 2,000 fpm) was placed at stations 4 and 5. Compared with previous tests conducted by Litton and Perera (2015), a lower ventilation velocity, 0.7 m/s (138 fpm) measured at station 1, was used in this study to represent a more realistic ventilation flow in the belt entry.

Two infrared (IR) gas analyzers were also used in the experiments to measure CO levels, from 0 to 100 ppm, and carbon dioxide (CO_2) levels, from 0 to 5 percent, and were located in the control room on the surface. A polypropylene tube with outer diameter of 0.95 cm (3/8 in.), extending from the control room down the borehole and along the entry to a position just downstream of sensor station 2, was used to draw gas samples back to the control room to both analyzers. The CO IR gas analyzer and combination optical/ionization smoke sensor were chosen to gauge the effect of using fire sensors that had passed rigorous performance tests and to compare their responses to those of the AMS fire sensors. Figures 2, 3, and 4 show the sensors used in the experiments.

The combustible materials used in the experiments are listed in Table 1. These combustion materials fall into six categories: wood, brattice, sealant, conveyor belts, coal and #2 diesel fuel. Wood is used extensively to build cribs in underground mines to support the mine roof. Line brattices may often be used to alter the airflow toward or away from a particular section of the mine. Sealants are primarily used to seal gaps from mine stoppings to stop the flow of combustible gases from passing through the stopping. Conveyor belts are used to transport the coal to the surface for subsequent processing and storage. In many underground coal mines, diesel-powered equipment is used extensively and diesel fuel is often stored underground for convenience.

Experimental procedure

The fire was located in the main intake entry approximately 75 m (246 ft) upstream of the first station (Fig. 1). The solid combustibles listed in Table 1 for the flaming and smoldering experiments were ignited by eight electrical heater strips. Each strip was 45.72 cm (18 in.) long, 3.81 cm (1.5 in.) wide and 0.635 cm (0.25 in.) thick and rated for a maximum surface temperature of 1,600 °C (2,912 °F). The combustible material for each experiment was positioned horizontally on strips, then the electrical heaters were placed evenly on top of the material so that the heater surface area in contact with it was consistent for each material tested. Another layer of test material was then laid over the electrical heaters. Figure 5 shows a smoldering conveyor belt test with the electrical heaters imbedded between strips of the conveyor belt material. Before the electrical heaters were turned on, two minutes of data from the sensors were recorded by the control room PC. After the electrical heaters were turned on, the time was recorded when the first visible sign of smoke appeared. In most of the experiments the material would eventually ignite and burst into flames. The time was also recorded when the first visible sign of a flame appeared. The electrical heaters were turned off when the material had burned for a sufficient period of time in order for the CO concentration to reach steady state at stations 1 and 2. The material was allowed to continue to burn until it flamed out on its own or when the CO concentration started to drop dramatically at stations 1 and 2.

For the flaming experiments using diesel fuel #2, different quantities of fuel were poured into steel pans of various sizes: 60.96 cm (24 in.) × 60.96 cm (24 in.), 45.72 cm (18 in.) × 45.72 cm (18 in.), and 38.1 cm (15 in.) × 22.86 cm (9 in.). The amount of diesel fuel being used in the experiments differed depending on the pan size. An acetylene burner was used to ignite the diesel fuel by applying the flame to the surface of the fuel in a corner of the pan. After the two minutes of data were recorded, the diesel fuel was ignited. Once the diesel fuel was ignited the acetylene burner was removed and the fire was allowed to burn until the diesel fuel was consumed or had self-extinguished.

Results and discussion

Full-scale experiments were conducted in the SRCM for each combustible material listed in Table 1. The detailed test results are listed in Table 2. Typical experimental results from four of the materials—conveyor belting, Pittsburgh seam coal, Douglas fir wood and diesel fuel —will be discussed. The results are representative of all the experimental results.

CO concentrations from different combustible materials

Figures 6, 7, 8 and 9 are plots of CO levels as functions of time measured by each sensor at the five monitoring stations as the CO produced from the burning material was carried throughout the mine by the ventilation airflow. Figure 6 shows the test results for the styrene-butadiene-rubber (SBR) conveyor belt; Fig. 7, for Pittsburgh seam coal with a 38 percent volatility; Fig. 8, for red oak wood; and Fig. 9, for Vintex brattice. The control room CO data were used to verify the accuracy of CO sensor measurement. In Fig. 6, CO data were not reported at station 4 due to a sensor malfunction.

The CO levels at stations 1 and 2 were roughly the same for all the experiments, as shown in Figs. 6, 7 and 8. The control room CO concentration mirrored the CO concentration at station 2. The greatest drop in CO concentration occurred between stations 2 and 3. There are several factors that may have contributed to this decrease. One could be the mixing of the combustion products as the gases traveled downstream from station to station, producing more uniform concentrations over the entry cross-section. Another could be leakage through the line brattices used to seal off parts of the mine. As the combustion products traveled further downstream from station 3, the CO concentrations continued to drop at stations 4 and

5. It is worth noting that in all of these experiments, the sharp decreases in CO concentrations between stations 2 and 3 were relatively consistent at around 50 percent.

For all of the experiments using line brattice, flaming ignition did not occur. In these experiments, those materials exhibited only a smoldering stage producing low levels of CO and visible smoke that were undetected by our sensors. Therefore, no data are presented here.

Smoke concentrations from different combustible materials

Smoke levels were also measured as a function of time at the different monitoring stations in the tests using different smoke sensors. Figures 10, 11 and 12 show the test results for the Douglas fir wood. The results show that the Conspec smoke sensor functioned differently in detecting the arrival of smoke compared with the Spero and Smoke Boss smoke sensors. The Conspec smoke sensor reacted to the presence of smoke either in an “on” state (alarm) or in an “off” state (no alarm) while the Spero and Smoke Boss sensors reacted to smoke concentration fluctuations. As shown in Fig. 10, when the Conspec smoke sensor detected the presence of smoke it was in the on state. The sensor stayed in the alarm state until the smoke was not detected and then it returned to the off state. In this test the smoke was only detected at station 1 for a short duration due to the small amount of smoke generated during the combustion process.

Figures 11 and 12 show the results of the smoke measured from the combustion of Douglas fir wood using the Smoke Boss and Spero smoke sensors at stations 1, 2 and 3, designated as S1, S2 and S3, respectively. At station 1, both sensors detected the presence of smoke at roughly the same time. The smoke was measured in percent of full-scale, 0 percent being no smoke detected and 100 percent indicating the sensor had detected the preset maximum level of smoke density. The Smoke Boss sensor reading was less than 1 percent of the full-scale reading while the Spero sensor was roughly 9 percent of the full-scale reading. At station 2, both sensors detected the presence of smoke at roughly the same time. The Smoke Boss reading was still less than 1 percent of the full-scale while the Spero sensor reading was 19 percent of full-scale, more than doubled. At station 3, no smoke was detected by the Smoke Boss sensor while smoke was detected by the Spero sensor. The reading was 10 percent of the full-scale. These results indicate that the Spero smoke sensor was more sensitive to the smoke than the Smoke Boss smoke sensor.

Figures 13, 14 and 15 show the results of smoke generated from the combustion of 5.7 L (1.5 gal) of diesel fuel. The Conspec smoke sensor detected smoke at all four stations (Fig. 13). At station 1 the sensor remained in the on state for the longest time, while at station 3 the sensor was in the on state for the shortest time. All three kinds of smoke sensors detected smoke at about the same time at stations 1 and 2. The results were different for station 3. The Spero smoke sensor detected the presence of smoke earlier, at 770 s, than the Conspec smoke sensor, at 930 s. There was no Smoke Boss sensor at station 3 for this experiment. These results indicate that the Spero smoke sensor reacted more quickly to smoke than the Conspec smoke sensor. In the diesel fuel test, a large quantity of smoke was generated compared with the smoke generated from the Douglas fir wood. As a result, the smoke generated from the diesel fuel was detected at stations 1 through 4. The period of detecting the smoke in the on state at each of the four monitoring stations was much longer than that for the Douglas fir wood. In the Douglas fir wood experiment both the Smoke Boss and the Spero sensors detected smoke levels very early, at 500 s, and prior to the alarm of the Conspec smoke sensor, at 1,520 s. This is probably due to the Conspec smoke sensor being less sensitive to smoke from smoldering fires than the Smoke Boss and Spero sensors.

Comparing Figs. 14 and 15 shows that the Spero sensor appeared again to be much more sensitive to detecting smoke than the Smoke Boss sensor. At station 1, the Smoke Boss sensor had a maximum reading of 4.4 percent of full-scale while the Spero sensor's maximum reading was 30 percent of full-scale. The trend continued at station 2. The Smoke Boss sensor's maximum reading was 3.5 percent of full-scale while the Spero sensor's maximum reading was 58 percent of full-scale. It is interesting to note that the Spero smoke sensor's maximum readings at stations 1 and 3 were roughly the same at 30 and 32 percent of full-scale, respectively, while at station 2 the maximum full-scale reading was at 58 percent. The Spero smoke sensor is a type of ionization detector and is more sensitive to smoke from flaming fires.

Figures 16, 17 and 18 show the results of the smoke generated from the combustion of Pittsburgh seam coal with a volatility of 38 percent. In this experiment the combustion process was much longer than in either the Douglas fir wood or diesel fuel experiment. The Conspec sensor only detected the presence of smoke at station 1 (Fig. 16). However, the sensor stayed in the on state for a longer time than in the Douglas fir wood and diesel fuel experiments at the same station. It is also worth noting that smoke was detected by all three smoke sensors at roughly the same time in this experiment.

The results for the Smoke Boss and Spero smoke sensors in Figs. 17 and 18 followed the same trend as in the previous tests. Both sensors detected the presence of smoke at roughly the same time, 1,500 s, at station 1. Because a small quantity of smoke was generated, the reading at station 1 for the Smoke Boss was only detected at 0.5 percent of full-scale while the reading of the Spero smoke sensor at station 1 was at 11 percent of full-scale. At station 2, the Smoke Boss reading was roughly at 0.3 percent of full-scale—less than the reading at station 1. The Spero smoke sensor's reading at station 2 was 19 percent of full-scale. As in the previous experiments, the maximum smoke reading at station 2 for the Spero smoke sensor was almost doubled compared with the reading at station 1. The reading at station 3 for the Spero smoke sensor was roughly the same when compared with the reading at station 1. For this experiment there was no Smoke Boss smoke sensor at station 3. These results indicate that the Spero sensor was more sensitive to detecting smoke than the Smoke Boss sensor under the conditions tested in this study.

Effect of material type on CO and smoke concentrations

Figure 19 shows the maximum CO concentrations and the maximum smoke readings in percent of full-scale for the Smoke Boss and the Spero smoke sensors for the different combustion materials in the flaming and smoldering experiments at station 1. For the different types of brattices tested in this study, very little CO and smoke were generated. The Spero smoke sensor was more sensitive in detecting the smoke than the Smoke Boss sensor. When the different woods were tested, more CO and smoke were produced than when brattices were tested. The Smoke Boss sensor barely detected the presence of smoke, while the Spero smoke sensor did detect its presence.

The different conveyor belts tested gave some interesting results. The SBR non-fire-resistant and the SBR 2G belt tests did not reach the maximum CO concentration of 50 ppm. The SBR non-fire-resistant belt produced a CO concentration of 20 ppm and the SBR 2G belt produced a CO concentration of 35 ppm, while the polyvinyl chloride (PVC), chloroprene and neoprene conveyor belts produced a maximum CO reading of 50 ppm on the Conspec CO sensor. The maximum reading for the Smoke Boss smoke sensor for the conveyor belts tests was 10 percent of full-scale while the Spero smoke sensor recorded 30 percent of full-scale. Therefore, the Spero sensor continued being more sensitive to the presence of smoke.

The two different types of coal tested did not produce much CO. The maximum CO detected by the Conspec CO sensor was 10 ppm for the Pittsburgh seam coal while the Kittanning coal produced a 6 ppm CO concentration. The results from the different quantities of diesel fuel used in the test series—5.7, 2.8 and 1.9 L (1.5, 0.74 and 0.5 gal)—were as expected. The maximum CO level was detected using 5.7 L (1.5 gal) of diesel fuel and the minimum CO level was detected using 1.9 L (0.5 gal) of diesel fuel. The results exhibited the same pattern for the smoke. The 5.7 L (1.5 gal) of diesel fuel test produced the most smoke detected by the Smoke Boss and Spero smoke sensors, and the least amount of smoke was detected using 1.9 L (0.5 gal) diesel fuel.

Alarming times for different combustibles

Table 2 summarizes the measured alarm times at stations 1 to 5 using the Conspec CO sensor for all of the tests. It should be noted that the CO concentration is indicative of the amount of combustible material used in this study. None of the brattice materials tested produced alarms at any of the five stations. Combustion of the Silent Seal foam (Fomo Products, Norton, OH) produced an alarm only at stations 1 and 2 in two tests. With the exception of the SBR non-fire-resistant belting, all the conveyor belts tested produced alarms at the five stations. For the SBR belt, there were alarms at stations 1, 2 and 3 but no alarm at station 5. Station 4 was not online for this test. Comparing the alarm times of the belts tested, the SBR non-fire-resistance belt took longer than the other belts for the CO level to reach 10 ppm to trigger the Conspec CO sensor to alarm for each station.

The three woods tested gave mixed results. In the first test using Douglas fir wood, the Conspec CO sensor alarmed at stations 1, 2 and 3 while in the second test it alarmed at stations 1, 2, 3 and 4. In the first test using red oak wood, there was not enough CO generated from the combustion process to produce an alarm. But in the second test, the Conspec CO sensor alarmed at stations 1 and 2. In the first test using ponderosa pine wood, not enough CO was generated from the combustion process to activate the alarm, while in the second test the Conspec CO sensor alarmed at stations 1 and 2.

The Pittsburgh seam coal tests also showed mixed results. In the first test the Conspec CO sensor only alarmed at station 1, while in the second test there was not enough CO generated to produce any alarms. For both of the Lower Kittanning coal tests, not enough CO was generated to alarm the Conspec CO sensors.

The different quantities of diesel fuel used in the test series showed mixed results as well. The results for the three tests using 5.7 L (1.5 gal) of diesel fuel were the same. The Conspec CO sensor alarmed at stations 1, 2 and 3 but not 5, and station 4 was not online for these tests. Using 2.8 L (0.74 gal) of diesel fuel, the Conspec CO sensor only alarmed at stations 1 and 2 in two of the tests. In the third test insufficient CO was generated to produce any alarms of the Conspec CO sensors. In the first test using 1.9 L (0.5 gal) of diesel fuel, the Conspec CO sensor alarmed at stations 1 and 2, while in the second test no alarms occurred at any of the stations. The different results for the same material may be attributed to small differences in the heating rates for the samples that led to flaming ignition.

In summary, the Conspec CO sensor alarm response times in the table for the different materials tested indicate that the rates at which the combustible materials burn have an effect on the alarm response time. During the diesel fuel experiments, CO was generated much faster due to more rapid combustion when compared with burning of the other materials. For the conveyor belts tested, the burning process was slower compared with the diesel fuel, resulting in a longer period of time needed to generate an alarming level of CO. For all the brattices tested, no alarm was achieved because of low burning rates.

Comparison of alarm times for different sensors

MSHA had evaluated the CO and smoke sensors used in underground mines only for their intrinsic safety and permissibility relative to their electrical characteristics, not for their performance as fire sensors. In order to see what potential advantages the use of a smoke sensor that had passed strict UL performance standards might provide, the alarm times for the CO and smoke sensors used in the AMS in this study were plotted against the alarm times for the UL-listed combination photoelectric/ionization smoke sensor positioned at station 1 (Fig. 20). The alarm times falling below the solid curve for the optical (photoelectric) smoke alarm indicate earlier alarm, and the alarm times falling above the solid curve indicate later alarm. While some of the Conspec CO and smoke alarm times fall below the optical alarm curve, there are some with excessively long alarm times, and there are some tests where the UL-listed sensor alarmed but there were no alarms for either the Conspec CO or Conspec smoke sensor. These results and those previously obtained by Litton and Perera (2015) consistently indicate that underground fire sensors could benefit from performance testing.

Summary

For all of the experiments conducted in this study, there was a consistent trend in CO concentrations as the ventilation air carried the CO to the respective monitoring stations, even though for any given combustible material, there may have been significant variations in the measured CO levels. The trend, generally, was for the measured CO levels at stations 1 and 2 to be roughly the same with a significant decrease in concentration from station 2 to station 3, followed by further, but less dramatic, decreases at stations 4 and 5. These decreases are expected as the mine air dilutes the CO concentrations and as more complete mixing occurs as the distance increases from the initial fire source. The CO concentration measured by the infrared gas analyzer just downstream of station 2 mirrored the CO concentration measured at station 2.

The Conspec smoke sensor operates in the on or off state and is not as sensitive at detecting smoke as the Smoke Boss and Spero smoke sensors. This was evident where smoke from the combustion of Douglas fir wood was detected by the Conspec smoke sensor only at station 1. The Smoke Boss smoke sensor was able to detect smoke at stations 1 and 2, while the Spero smoke sensor detected the presence of smoke at stations 1, 2 and 3, indicating that the Spero sensor is more sensitive to smoke. Unlike the CO concentrations that decrease as the CO moves through the mine, the smoke does not decrease as rapidly as the CO concentrations. For the Spero smoke sensor, the smoke concentrations measured at stations 1 and 3 were virtually the same, while the Spero response at station 2 was about twice the station 1 and 3 values. This is most probably due to differences in the sensitivity of the sensors rather than to some physical abnormality.

When the Conspec CO and smoke sensor response times to alarm at station 1 were compared with the response times of the combination photoelectric/ionization smoke sensor, the latter smoke sensor performed much better and more consistently. This suggests that using such sensors may have the potential to improve fire detection reliability and early warning times in underground mines, thereby improving overall fire safety.

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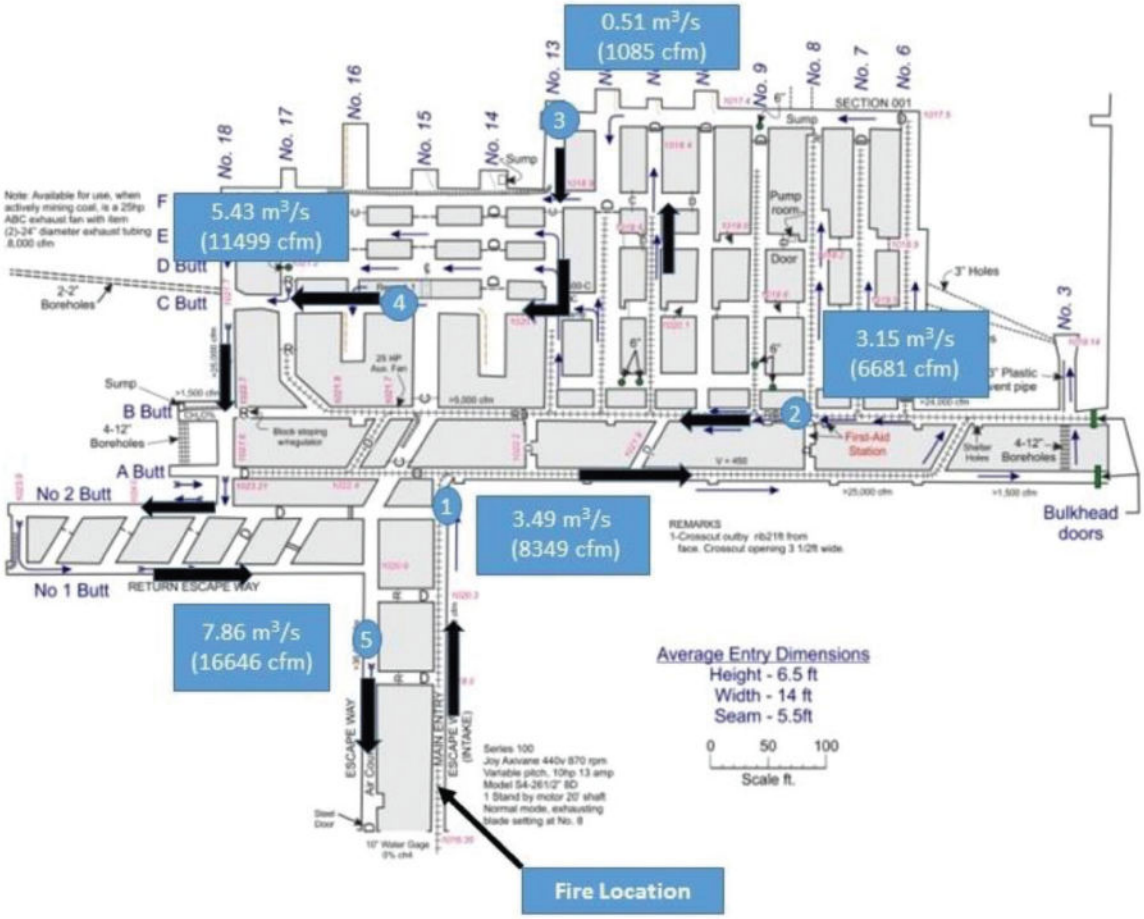

Figure 1.

Schematic of the Safety Research Coal Mine showing sensor station locations and air velocities at each station.

Figure 2.
Smoke and CO sensors that were evaluated in the study.

Figure 3.
Combination optical/ionization smoke sensor.

Figure 4.
CO and CO_2 IR gas analyzers.

Figure 5.
Conveyor belt with electrical heaters beginning to smoke.

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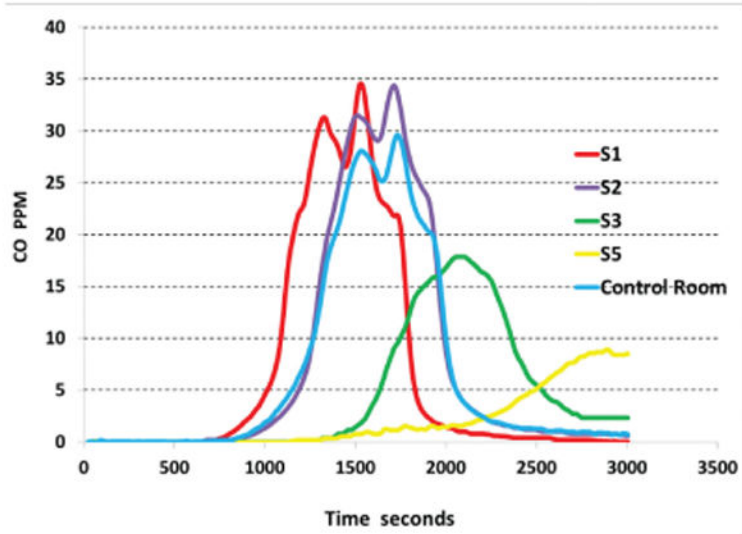

Figure 6.
CO concentrations for SBR conveyor belt at all five monitoring stations, plus control room CO concentration.

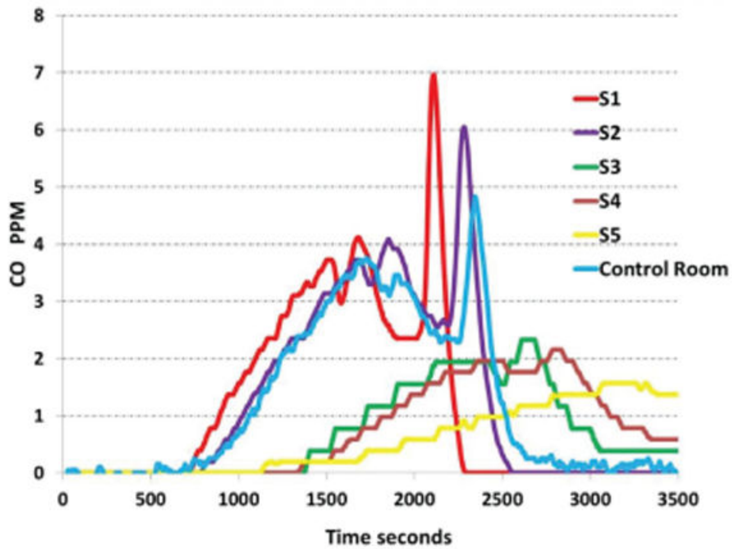

Figure 7.

CO concentrations for Pittsburgh seam coal 38% volatility at all five monitoring stations, plus control room CO concentration.

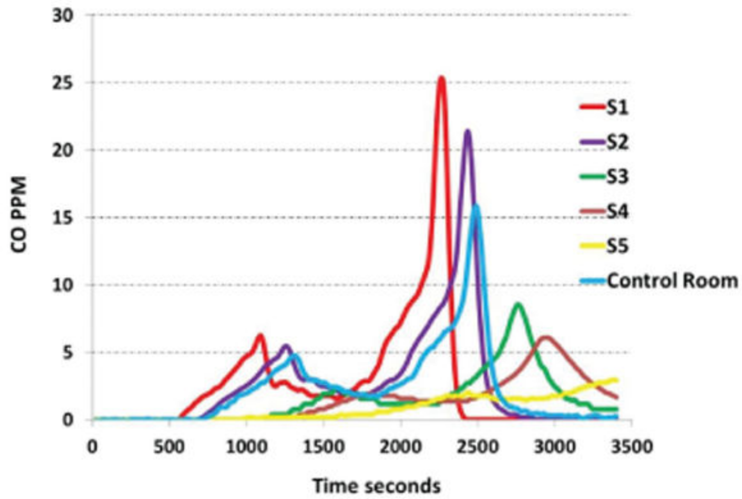

Figure 8.
CO concentrations for the red oak wood at all five monitoring stations, plus the control room CO concentration.

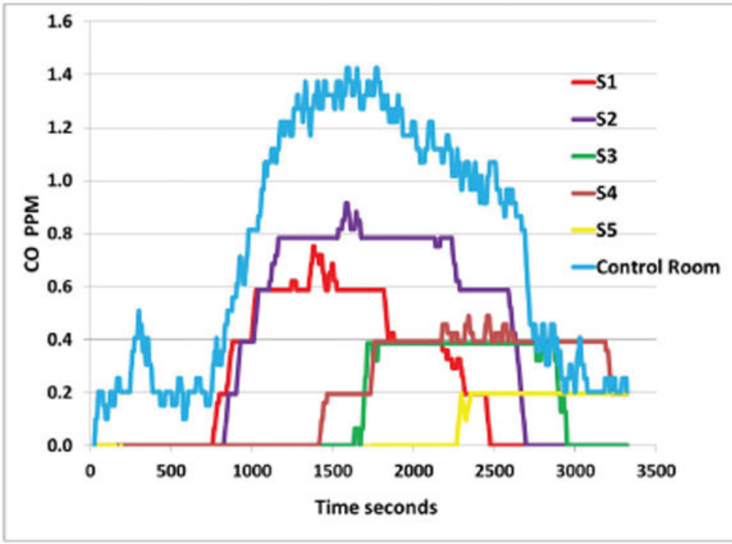

Figure 9.

CO concentrations for Vintex brattice at all five monitoring stations, plus control room CO concentration.

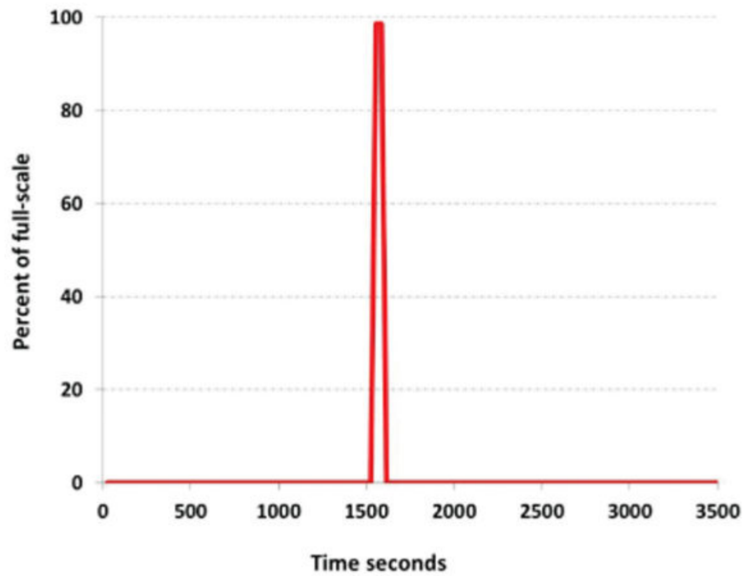

Figure 10.
Smoke concentrations for the Douglas fir wood using the Conspec smoke sensor at station 1.

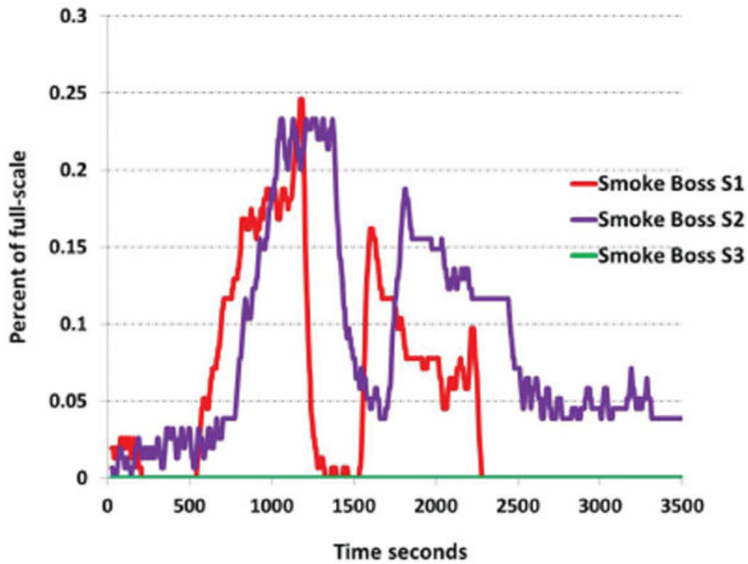

Figure 11.

Smoke concentrations for the Douglas fir wood using the Smoke Boss smoke sensor at stations 1, 2 and 3.

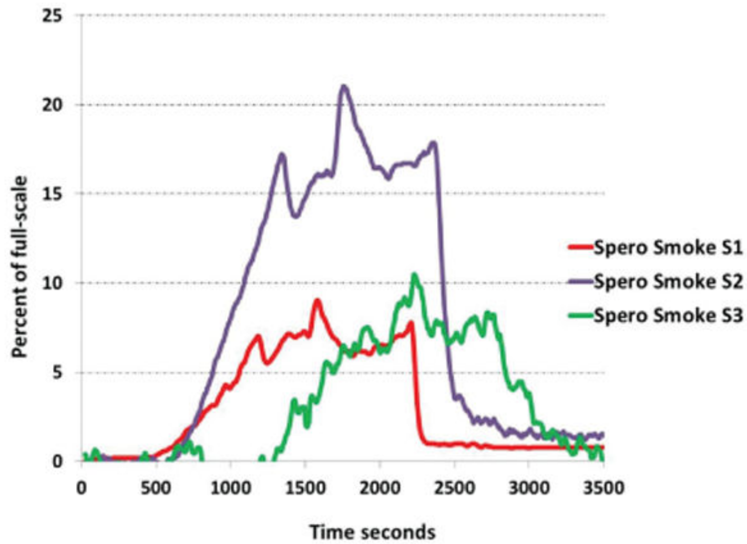

Figure 12.

Smoke concentrations for the Douglas fir wood using the Spero smoke sensor at stations 1, 2 and 3.

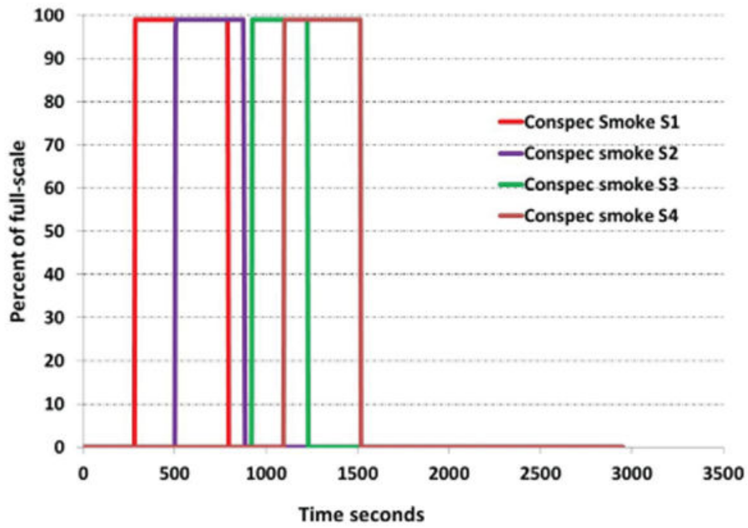

Figure 13.

Smoke concentrations for 5.7 L diesel fuel using the Conspec smoke sensor at stations 1, 2, 3 and 4.

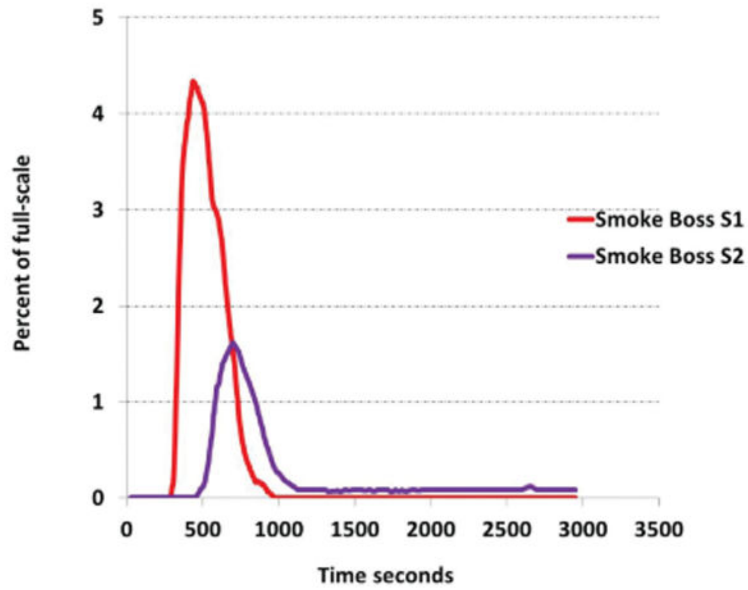

Figure 14.

Smoke concentrations for 5.7 L diesel fuel using the Smoke Boss smoke sensor at stations 1 and 2.

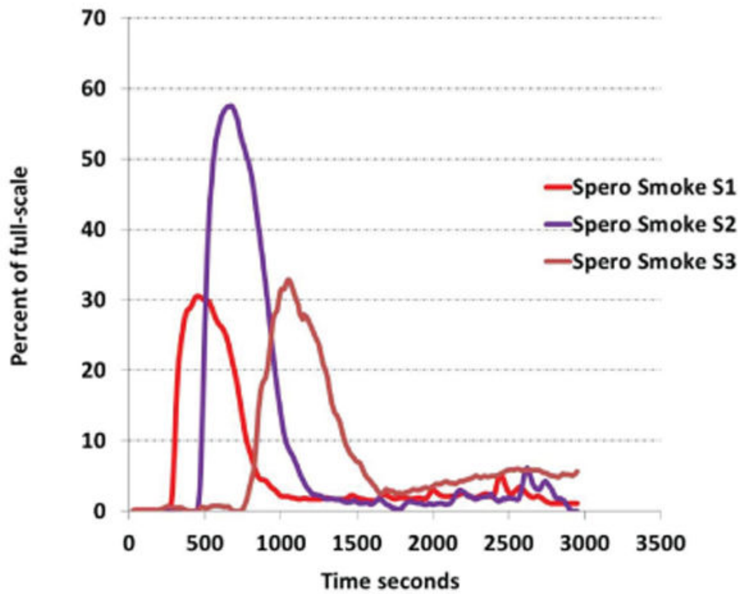

Figure 15.
Smoke concentrations for 5.7 L diesel fuel using the Spero smoke sensor at stations 1, 2 and 3.

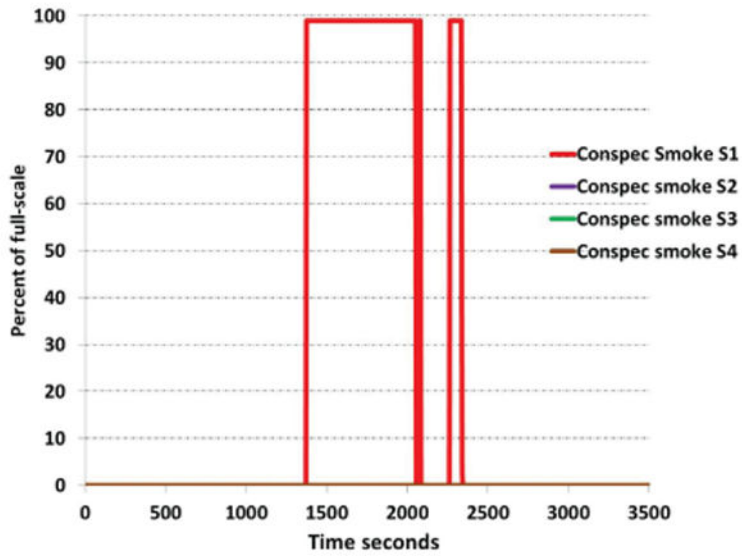

Figure 16.

Smoke concentration for Pittsburgh seam coal 38 percent volatility using the Conspec smoke sensor.

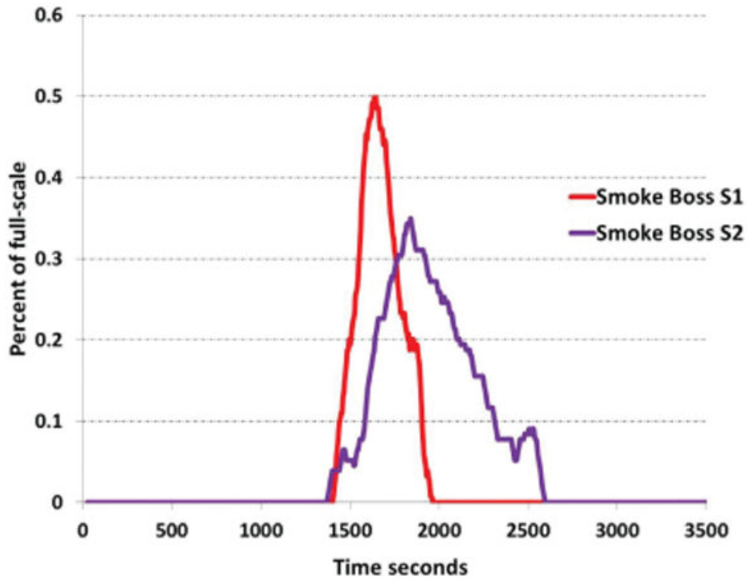

Figure 17.

Smoke concentration for Pittsburgh seam coal 38 percent volatility using the Smoke Boss smoke sensor.

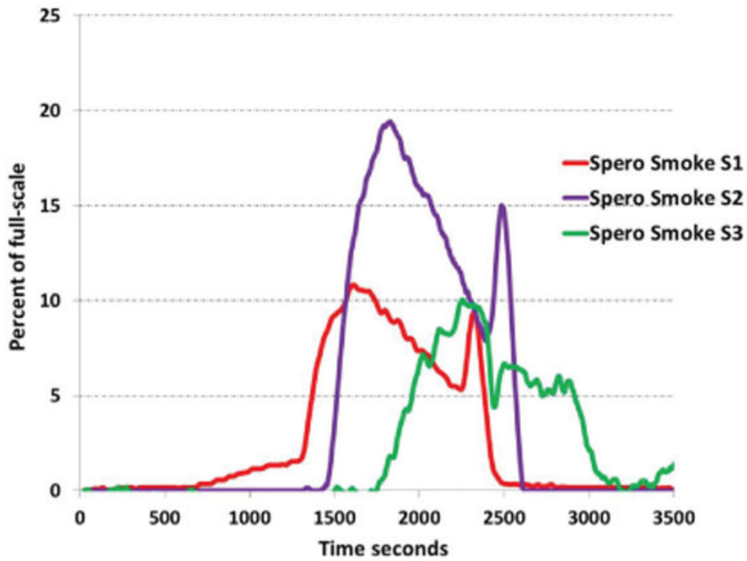

Figure 18.

Smoke concentration for Pittsburgh coal seam 38 percent volatility using the Spero smoke sensor.

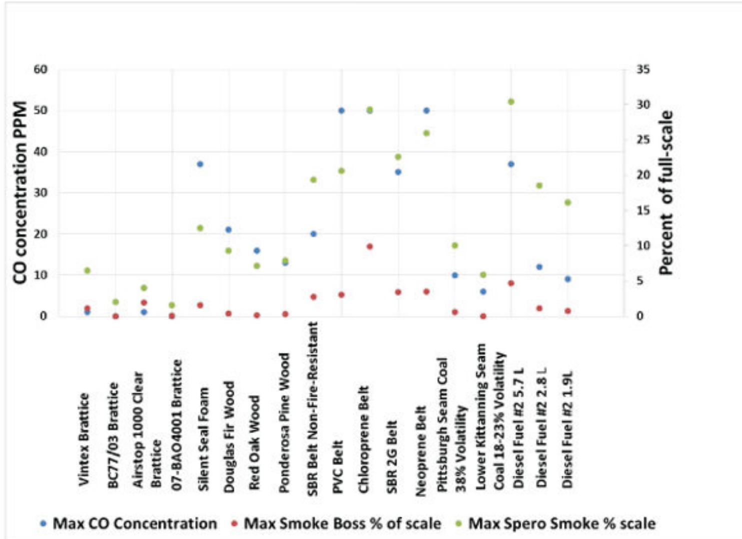

Figure 19.
Maximum CO and smoke concentrations for the different combustible materials at station 1.

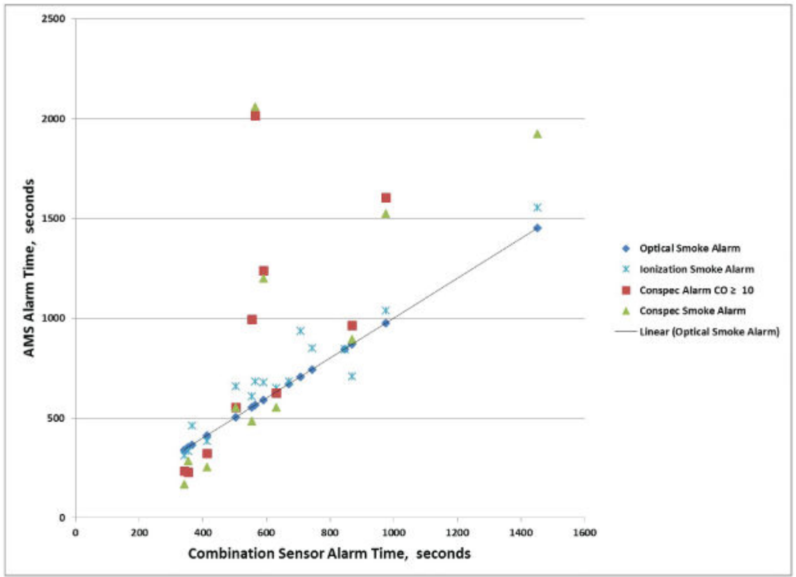

Figure 20.

The Conspec CO and Conspec smoke sensor alarm times plotted against the alarm times of the combination optical/ionization smoke sensor positioned at station 1.

Table 1

Materials tested in the study.

Vintex brattice.
BC 77/03 brattice.
Airstop 1000 clear brattice.
07-BA04001 brattice.
Silent seal foam.
Douglas fir wood.
Red oak wood.
Ponderosa pine wood.
SBR belt (non-fire-resistant).
PVC belt.
Chloroprene belt.
SBR (2G approved).
Neoprene belt.
Pittsburgh seam coal (38% volatility).
Lower Kittanning seam coal (18-23% volatility).
Diesel fuel #2 (60.96 × 60.96 cm pan, 5.7 L).
Diesel fuel #2 (45.72 × 45.72 cm pan, 2.8 L).
Diesel fuel #2 (38.1 × 22.86 cm pan, 1.9 L).

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Table 2

Times for the Conspec CO sensor to sound an alarm at the five stations for the different combustible materials.

	CO Alarm ≥ 10 PPM (seconds)				
	Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**
Vintex brattice test 1	No alarm	No alarm	No alarm	Not online	No alarm
Vintex brattice test 2	No alarm	No alarm	No alarm	No alarm	No alarm
BC 77/03 brattice	No alarm	No alarm	No alarm	No alarm	No alarm
Airstop 100 clear brattice test 1	No alarm	No alarm	No alarm	No alarm	No alarm
Airstop 100 clear brattice test 2	No alarm	No alarm	No alarm	No alarm	No alarm
07-BAO4001 brattice test 1	No alarm	No alarm	No alarm	No alarm	No alarm
07-BAO4001 brattice test 2	No alarm	No alarm	No alarm	No alarm	No alarm
Silent Seal foam test 1	710	915	No alarm	Not online	No alarm
Silent Seal foam test 2	580	750	No alarm	No alarm	No alarm
SBR belt non-fire-resistant	2,045	2,285	2,665	Not online	No alarm
PVC belt	1,340	1,535	2,010	1,730	2,910
Chloroprene belt	1,170	1,320	1,950	Not online	2,780
SBR 2G approved belt	1,415	1,595	1,955	Not online	No alarm
Neoprene belt	1,290	1,470	2,000	1,515	2,980
Douglas fir wood test 1	1,515	2,045	2,400	No alarm	No alarm
Douglas fir wood test 2	3,145	3,305	3,700	3,830	No alarm
Red oak wood test 1	No alarm	No alarm	No alarm	No alarm	Not online
Red oak wood test 2	2,145	2,315	No alarm	No alarm	No alarm
Pondarosa pine wood test 1	No alarm	No alarm	No alarm	Not online	No alarm
Pondarosa pine wood test 2	2,380	2,380	No alarm	No alarm	No alarm
Pittsburgh seam coal 38% volatility test 1	2,215	No alarm	No alarm	No alarm	No alarm
Pittsburgh seam coal 38% volatility test 2	No alarm	No alarm	No alarm	No alarm	No alarm
Lower Kittaning seam coal 18-23% volatility test 1	No alarm	No alarm	No alarm	No alarm	No alarm
Lower Kittaning seam coal 18-23% volatility test 2	No alarm	No alarm	No alarm	No alarm	No alarm
Diesel fuel #2 60.96 × 60.96 cm, 5.7 L	415	610	1,135	Not online	No alarm

	CO Alarm ≥ 10 PPM (seconds)				
	Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**
Diesel fuel #2 60.96 × 60.96 cm, 5.7 L	420	665	1,035	Not online	No alarm
Diesel fuel #2 60.96 × 60.96 cm, 5.7 L	575	785	1,185	Not online	No alarm
Diesel fuel #2 45.72 × 45.72 cm, 2.8 L	395	500	No alarm	Not online	No alarm
Diesel fuel #2 45.72 × 45.72 cm, 2.8 L	No alarm	No alarm	No alarm	Not online	No alarm
Diesel fuel #2 45.72 × 45.72 cm, 2.8 L	360	570	No alarm	No alarm	No alarm
Diesel fuel #2 38.1 × 22.86 cm, 1.9L	625	790	No alarm	No alarm	No alarm
Diesel fuel #2 38.1 × 22.86 cm, 1.9L	No alarm	No alarm	No alarm	No alarm	No alarm