Mine Fire Detection in the Presence Of Diesel Emissions

J. C. Edwards, R. A. Franks, G. F. Friel, C. P. Lazzara, and J. J. Opferman
Pittsburgh Research Laboratory
National Institute for Occupational Safety and Health
Pittsburgh, PA 15236
U.S.A.

ABSTRACT

A series of four coal combustion experiments was conducted at the National Institute for Occupational Safety and Health's (NIOSH) Pittsburgh Research Laboratory (PRL) in the Safety Research Coal Mine (SRCM) to evaluate the response of fire sensors to a small 0.61 m square smoldering coal fire which transitions to flaming combustion in the presence of diesel emissions. An optical path smoke sensor alarmed earlier than a point type diffusion mode ionization smoke sensor, which alarmed prior to a co alert value of 5 PPM above ambient. The presence of steady state diesel emissions resulted in a decrease in the optical smoke sensor analog output voltage signal by less than 1.4 pct for the three coal fire experiments in which a diesel engine was operating, whereas the ionization smoke sensor output decreased between 10.8 and 26.7 pct after the initial surge of the diesel engine. A commercial diesel discriminating fire sensor did not alarm for a fire in the one experiment for which it was used. The results of the experiments demonstrated that an optical path smoke sensor might be used to detect a coal fire under the experimental conditions considered of starting a diesel engine followed by a slowly developing coal fire.

KEYWORDS

Mine Coal Fire, Smoke Detector, CO Detector, and Diesel.

INTRODUCTION

Mine fire detectors as a part of an atmospheric mine monitoring system are used to monitor temperature and products-of-combustion (POC). Alarm and alert values are based upon temperature, CO concentration, and smoke optical density. Carbon monoxide and smoke sensor cap-ability has been previously evaluated (Edwards and Friel, 1996) for in-mine diesel fuel fire conditions. In those experiments, the measurements were made in an ambient background of fresh air. With the introduction of diesel powered equipment in an increasing number of underground coal mines, the capability of mine fire detectors to discriminate a coal fire from diesel particulate and CO emissions is a concern for adequate underground mine fire protection. The change in the atmospheric CO concentration or optical density must now be referenced to a changing background of diesel emissions. There are several approaches to resolve this problem. If the CO is selected as the signature of interest, one method is to differentiate the CO produced by the fire from that produced by the diesel engine with a second POC signature which would be absent from the fire POC. A commercial diesel discriminating fire sensor compares the relative CO to NO ratio. This method relies upon a historical trend analysis of the CO associated with the NO produced by the diesel engine under different operating conditions. Evaluation of this technology was made for a rapidly developing coal fire (Litton, *et al.*, 1993). A second approach is to examine the rate of change in CO production as a stand alone POC signature. The rate of change in CO historically collected for a diesel engine can be used to differentiate the diesel from a fire based upon the rate of CO change associated with fire growth. A third approach to the problem is to differentiate particulate emissions of the diesel from that of the fire with smoke sensors. This method relies upon geometric properties such as the smoke particulate size and shape, and a physical property such as its index of refraction. Optical and ionization smoke sensors will respond differently to smoke. An optical sensor is generally more responsive to larger particles associated with smoldering combustion, whereas an ionization sensor is more responsive to smaller particles associated with flaming combustion. The characteristic response of a smoke sensor to diesel emissions is to be investigated.

The objective of this research is to investigate a fire detection method to discriminate a coal mine fire from diesel emissions. As part of the development of a mine fire detection strategy for discriminating a mine fire from diesel exhaust, a series of coal fire experiments was conducted in the National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Laboratory's (PRL) Safety Research Coal Mine (SRCM) to evaluate the response of fire sensors to a slowly developing coal fire in the presence of diesel exhaust. These experiments provide an opportunity to evaluate the response of standard CO and smoke mine fire sensors, a commercial gas-discriminating fire sensor, and a commercial optical smoke sensor to a slowly developing coal fire which could result from frictional heating of coal in an underground coal mine. The different response characteristics of an ionization and an optical smoke sensor to diesel exhaust and smoke from an incipient coal fire will provide guidance for future development of mine fire diesel discriminating sensors and strategies. The intent of using a slowly increasing coal fire is to demonstrate the capability of early and reliable mine fire detection.

EXPERIMENTAL PROCEDURE

The coal fire detection experiments in the presence of diesel engine exhaust were conducted in the mine entry and room section of the SRCM shown in figure 1. Room 10, in which the fire zone is located, has an average height and width of 2.0 m and 3.9 m, and F-Butt has an average height and width of 1.9 m and 4.5 m. The brattice at Room 10 and B-Butt was adjusted to regulate the air flow in Room 10 and F-Butt. Air quantity measurements were made at the fire zone and near the end of F-Butt, 7.6 m downwind of sensor station S2. A hot wire anemometer was used to make five point time averaged linear air velocity measurements. There was significant variation in the airflow over the cross section at the fire zone in room 10 because of the right angle split 18.4 m upwind of the fire station at B-Butt and because of the lack of thermal equilibrium in the airflow due to a temperature variation between B-Butt and F-Butt along Room 10. Near station S2, the air was transported 117 m along a straight entry and thermal equilibrium with the mine entry surface was established. The air quantity measurements at the fire zone and near the end of F-Butt are denoted by Q_u and Q_d respectively. The fire source consisted of 10-15 kg of Pittsburgh seam coal with diameter less than 6 cm distributed uniformly over a pan 0.61 m on each side. Less than 1 kg of pulverized coal dust was distributed over the coal for experiments 2-4 to enhance the smoldering combustion. Heating of the coal was provided with five, 60 ohm electrical strip heaters connected in parallel. Electrical power was supplied incrementally to the heaters over a maximum range of 1 to 2 kW. Table 1 shows the experimental air quantity conditions as well as the time of first observation of smoke production, (Smoke), and flaming combustion, (Flame), at the fire source. The increase in air quantity, $Q_d/Q_u > 1$, is due to leakage into F-Butt around brattice curtains along F-Butt from a parallel airway which was connected by a borehole to the surface. The smoke expected transport time τ_s from the fire to station S2 is estimated from the accessible entry volume and the measured volumetric flow rates, and is shown in Table 1. For experiment No. 1, there was no diesel in the entry; for experiment Nos. 2-4, there was a diesel scoop operational in F-Butt 79 m upwind of sensor station S2. In experiment No. 4 there was also a diesel locomotive operational in F-Butt approximately 15 m upwind of the diesel scoop. Diffusion mode CO sensors were located at stations S1 and S2. The sensors were mounted with the diffusion tube inlet approximately 0.8 m from the rib, and 0.41 m from the roof.

Table 1. Experimental conditions.

EXP	Q_u, m^3/s	Q_d, m^3/s	Time, s		
			Smoke	Flame	τ_s
1	4.52	5.31	240	4490	244
2	2.64	4.71	300	2520	348
3	3.73	5.72	945	3000	362
4	2.91	4.63	540	2640	330

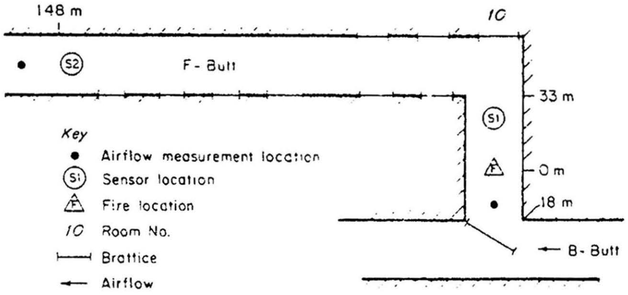

Figure 1. Plan view of mine section.

Two smoke sensors were positioned at station S2. One sensor, SA, sampled over a path, and the other, SB, at a point. Sensor SA was a commercially available optical type sensor with a transmitter and receiver. The receiver was positioned at S2 near one rib of the entry, and the transmitter was positioned near the opposite rib at a distance of 9.5 m upwind from the receiver. The optical path length was 9.65 m. Sensor SB was a commercially available diffusion mode ionization type mine smoke sensor. It was positioned at entry midwidth at S2 with the smoke inlet the same 0.41 m distance from the entry roof as the CO sensors. The analog voltage output from the smoke sensors provided an indirect measure of the smoke intensity.

A light obscuration monitor consisting of a light source and a photovoltaic cell separated by a distance of 1 meter was mounted mid-height at S2 with its optical path transverse to the airflow and parallel to the entry floor. The attenuation in the light by the smoke was measured by the voltage output from the photovoltaic cell. The smoke optical density D is defined by:

$$D = -\frac{1}{L}\log_{10}\left(\frac{I}{I_0}\right)\ \mathrm{m}^{-1} \qquad (1)$$

where the light intensity I is directly proportional to the voltage, I_0 is the intensity in ambient air, and L, equal to 1.0 m in this application, is the optical path length.

As part of the fire monitoring system for experiment No. 4, a commercial discriminating mine fire sensor (SC) was located at station S2 at entry midwidth with its diffusion tube inlet port 0.41 m from the entry roof. This sensor, which operates in the diffusion mode, contains two chemical cells. One cell detects CO, and the other cell detects NO. Based upon a historical collection of data over a 2-hour period, the sensor through an internal processor associates CO with NO produced by the operational diesel equipment. Any subsequent changes in the ratio of CO to NO determines the excess CO produced by the fire.

Prior to each experiment, the sensors were calibrated. The diesel engines were moved into the entry after the sensor calibration and ventilation measurements. Their presence in the entry increased the entry's aerodynamic resistance which would be expected to reduce the airflow. Data from each of the fire sensors was collected in a real-time mode and transmitted to an above ground mine monitoring computer. The data collection occurred every 2 seconds.

RESULTS

At station S2, the CO reached an alert value of 5 ppm above ambient for experients Nos. 2—4, and the smoke optical density reached an alarm value of 0.022 m-1 for all four experiments. A CO concentration of 5 ppm above ambient is designated the alert value for a CO sensor when used as part of a coal mine atmospheric mine monitoring system (CFR, 1997a). An optical density of 0.022 m^{-1} is designated a smoke sensor alarm value (CFR, 1997b) when used at an underground coal mine compressor station. These values are relative to the prefire airflow conditions which includes the diesel emissions.

Table 2 shows the average background values of smoke detectors SA and SB, and the light transmission measured by the optical light monitor before the diesel emissions and before the fire. The prefire values are averages within a 5-minute time period before the heating of the coal. Startup of the diesel engine resulted in a surge in diesel emissions with a transient less than 5 minutes in duration before the emissions settled into a steady production rate. The pre-fire analog signal of sensor SA in the presence of diesel emissions decreased by less than 1.4 pct from its value in clear air, whereas sensor SB's signal decreased between 10.8 and 26.7 pct.

The CO sensors at S1 and S2 were used to determine the POC transport time, τ_m, listed in Table 2 based upon the time difference in a 1 ppm rise in the CO above the ambient value when the fire was initiated. These values are augmented by the expected transport time from the fire to S1. The measured values of τ_m exceed the expected values τ_s in table 1. This is due to the dispersion of the fire POC through turbulent transport along the airway and dilution due to leakage into the airway around brattices which block rooms connected to parallel airways. This effect is partially offset by the increased air velocity in the entry due to leakage. Measured and predicted values of the transport time are in closer agreement in experiments 2 and 3 than in experiments 1 and 4 due to the greater use of pulverized coal dust in experiments 2 and 3 to produce increased quantities of CO. An increased CO production rate will reduce the effect of concentration reduction due to dispersion for a given airflow rate. In experiment No. 1, no pulverized coal was used and in experiment No. 4, half as much was used in comparison with experiment Nos. 2 and 3. The new ambient values for SA and SB in the diesel environment were achieved only after quite different transient responses to the onset of the diesel emissions. An examination of the response of SA and SB to the diesel emissions is shown in Figures 2 and 3 for experiment No. 4. The diesel emissions are tracked by the CO measurement in Figures 2 and 3. The maximum rate of increase in CO was 0.127 ppm/s with an average rate of 0.0716 ppm/s over the320 second period from -9,574 s to -9,254 s. These times are relative to initial heating of the coal at zero time. Figure 2 shows that SA responds rapidly to the onset of diesel emissions when the diesel engines were started, as it would to a fire, but returns to an equilibrium value slightly offset from its prediesel ambient value.

Table 2. Smoke sensor and light transmission.

	SA, volt		SB, volt		Time, s		
Exp. No.	Pre-diesel	Pre-fire	Pre-diesel	Pre-fire	Pre-diesel	Pre-fire	τ_m
1	NA	4.025	NA	0.914	NA	96.28	859
2	3.991	3.935	0.897	0.800	98.59	97.49	405
3	3.997	3.951	0.913	0.780	99.6	99.39	426
4	4.010	3.959	0.899	0.659	98.6	96.6	646

NA = not available

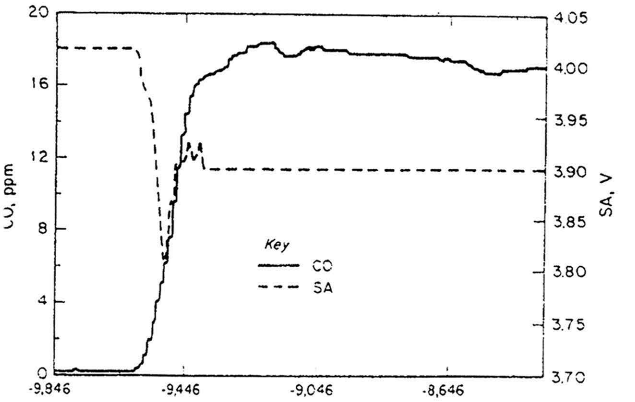

Figure 2. CO and sensor SA response to diesel emissions for experiment No. 4.

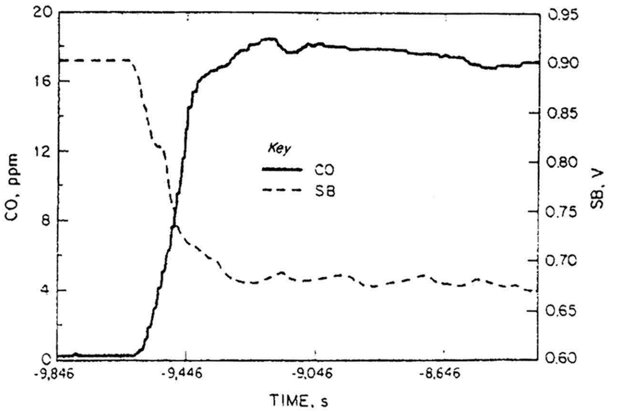

Figure 3. CO and sensor SB response to diesel emissions. for experiment No. 4.

Smoke sensor SB, as shown in figure 3, responds to the diesel emissions, but its output signal has an asymptotic signal decrease to a new equilibrium value. The new equilibrium voltages for sensors SA and SB 15 minutes after the sensors detect the diesel emissions are offset 3.0 and 24.8 pct, respectively from the prediesel emissions voltages. Figure 4 shows a comparison of the response of sensor SA and the light monitor. The light monitor's new equilibrium value is offset 1.1 pct from the prediesel value. Over the subsequent 2.7 hour period before ignition of the coal fire, these equilibrium values for the sensors shift to offset values of 1.2, 26.7, and 2.0 pct from the prediesel conditions for SA, SB, and the light monitor, respectively.

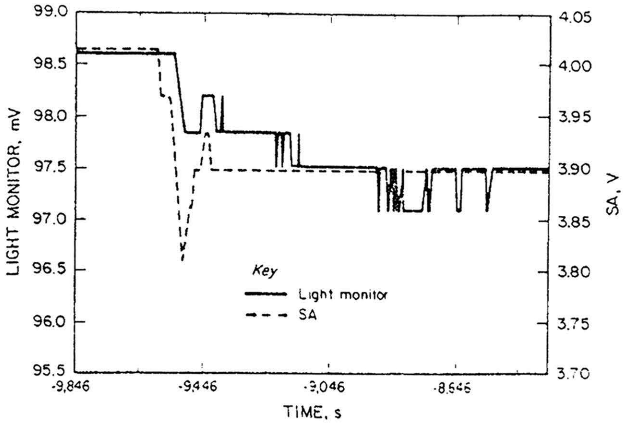

Figure 4. Sensor SA and light monitor response to diesel emissions for experiment No. 4.

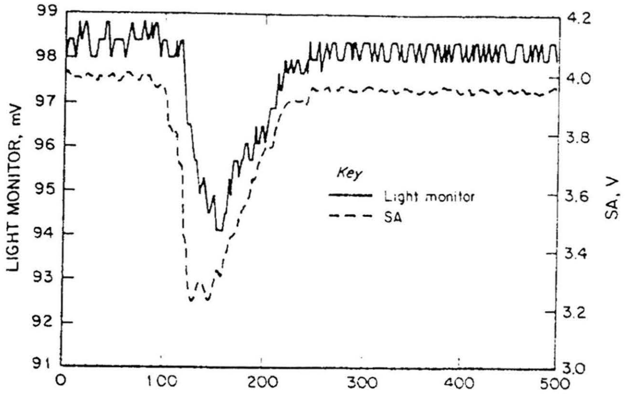

Figure 5. Sensor SA and light monitor response to diesel Emissions for experiment No. 2.

The dip in the output signal of sensor SA below its final equilibrium value in response to the diesel emissions was a characteristic of SA during all three experiments. The response of the light monitor to the diesel emissions was quite different for experiment Nos. 2 and 4. Figure 5 shows the response of SA and the light monitor for experiment No. 2. In experiment No. 2, the light monitor's output signal followed that of sensor SA with a characteristic dip in response to the initial surge of the diesel emissions. The difference in the light monitor's response between the experiments can be attributed to the emissions of the locomotive in experiment No. 4 which were absent from experiment No. 2.

There is a difference in optical wavelength between the light monitor and sensor SA. The light monitor operates in the visible, and SA operates in the infrared. The optical scattering and absorption properties of the diesel emissions as a function of the light wavelength also differentiates the response of optical sensor SA from ionization sensor SB. Sensor SB responds to smoke particulate number more effectively than particulate diameter.

The decrease in smoke sensor SA's signal followed by a signal increase in response to the diesel emissions while the measured CO increased was a characteristic of the diesel's performance in experiments 2-4. SA's signal reversal occurred prior to the CO reaching its alert value. The lag time between sensor SA's minimum and the CO alert and alarm times associated with a 5 and 10 ppm diesel emission CO rise above ambient is listed in table 3.

Table 3. Lag time of CO alert and alarm times relative to time of minimum in SA.

Exp.	Time, s	
	CO(5ppm)	CO(10ppm)
2	28	NA
3	40	690
4	0	32

A combination of the optical smoke sensor, SA, and the CO sensor signal characteristics provides the basis for a distinguishing signature for diesel emissions. This characteristic is to be compared with the response of smoke sensor SA and the CO sensor to a slowly developing coal fire.

The response of smoke sensors SA and SB to the coal fire POC in the presence of diesel emissions for experiment No. 4 is shown in Figures 6 - 7. The sensors respond continuously to a change in the POC associated with the increase in the measured CO concentration. Smoke sensors SA and SB respond similarly to the fire, as opposed to their characteristically different response to the diesel emissions in Figures 2 and 3.

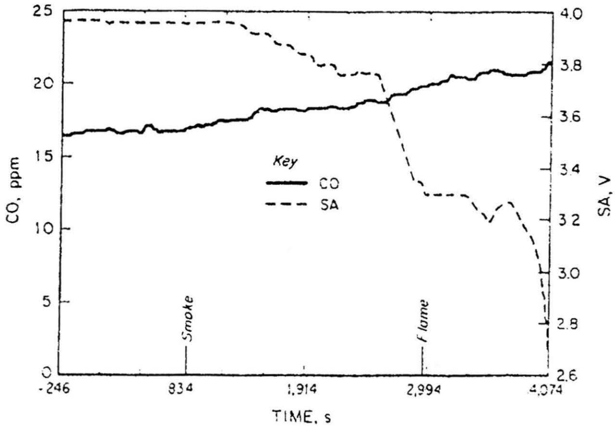

Figure 6. CO and sensor SA response to coal fire for experiment No. 4.

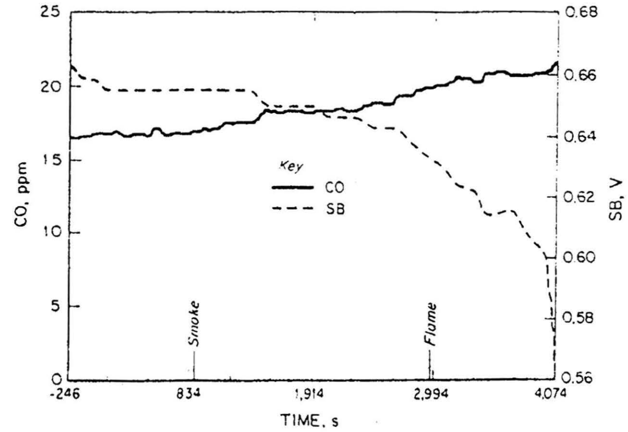

Figure 7. CO and sensor SB response to coal fire POC for experiment No. 4.

The expected time of arrival of the POC associated with smoke and flame generation is indicated in Figures 6-7.

Although it is not possible to infer the response of sensor SA to a variable diesel output from these data, the distinct sensor response characteristics to the diesel exhaust and coal combustion products indicate a capability for sensor