In mine evaluation of discriminating mine fire sensors

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ABSTRACT: A National Institute for Occupational Safety and Health's (NIOSH) mine fire detection research project was undertaken to evaluate multiple mine fire sensor types for nuisance alarm discrimination. The response of multiple fire sensor types to three small coal fire and three small conveyor belt fires in the presence of diesel emissions was evaluated in NIOSH's Pittsburgh Research Laboratory (PRL) Safety Research Coal Mine (SRCM). An array of fire sensors which included an optical and ionization smoke sensor, a chemical cell CO sensor, and Metal Oxide Semiconductor (MOS) sensors, was used to sample the diesel engine and fire source emissions. The mine fire detection experiments demonstrated the ability of a MOS sensor with a bimodal response to NO_x and products-of-combustion (POC) to respond to the onset of smoldering combustion in the presence of CO and POC particulates from a diesel locomotive. As part of an in-mine evaluation in an operating coal mine, the MOS NO_x responsive sensor and an ionization smoke sensor was demonstrated as a method to discriminate diesel emissions and cross-interference of H_2 on a CO chemical cell fire sensor at a battery charging station. The reinforcement of mine fire sensor information with the use of multiple sensor types, such as an MOS sensor and ionization and optical smoke sensors, is shown to be important for nuisance alarm discrimination and early mine fire detection.

1 INTRODUCTION

NIOSH's mission to protect the health and safety of workers has a unique role in underground mines where the miner's escape from toxic POC in the event of a fire is severely restricted. One aspect of the miner's protection is reliable early in-mine fire detection. Another equally important issue is discrimination of true fire alarm signals from nuisance emissions produced alarm signals associated with normal mining activities. The in-mine use of an atmospheric mine monitoring system to monitor hazardous conditions has increased significantly over the past decade (Panigrahi & Ghose, 1999).

Previous research (Edwards et al., 2001) investigated the response of multiple sensors to coal, electrical cable insulation, conveyor belt, and diesel fuel combustion. It was demonstrated for the solid fuel combustion experiments that in the absence of background diesel emissions, smoke and MOS (metal oxide semiconductor) fire sensors with an alarm value set to be a ten standard deviation (S.D.) change in the signal from its ambient value, alarmed before the carbon monoxide (CO) sensor measured a 5 ppm CO concentration increase. If the fire state and nuisance emissions state are considered to be two modes of combustion characterized by bimodal gas signatures, then a sensor with a clear bimodal discrimination would be a practical method to discriminate the fire and false nuisance emissions alarm. It was also determined that a MOS sensor sensitive to oxides of nitrogen (NO_x) had a bimodal response to NO_x producing nuisance events, such as diesel emissions and acetylene cutting, and products-of-combustion (POC) from open fires. The extension of that research is to evaluate the capability for fire detection in the presence of diesel emissions. CO and POC particulates from diesel emissions and a CO sensor's chemical cell's cross-sensitivity to hydrogen gas (H_2) can cause false fire sensor alarms in a mining operation. An additional undesirable consequence of false alarms is the unintended learning by miners to ignore false alarms, which can result in ignoring true fire alarms. For the purpose of determining the mine fire-nuisance alarm discriminating capability of fire sensors, a series of experiments were conducted in the NIOSH/PRL Safety Research Coal Mine to evaluate the capability of multiple sensors to differentiate an incipient coal or conveyor belt smoldering fire from diesel emissions.

An additional phase was the implementation of a select combination of fire sensors in an operating mine to evaluate their capability to identify nuisance events such as battery charging and diesel emissions. To accomplish this, an operational mine was selected in which battery charging occurred daily and diesel equipment was moved occasionally. The interpretation of the data strictly in terms of alarm values set relative to clear air would lead to nuisance alarms from non-open combustion in-mine events with isolated unimodal POC gas response sensors. A sensor with bimodal response to diesel emissions and open combustion would provide a measure of discrimination, but would not be advantageous for discriminating other non-combustion signatures, such as H_2 from a battery charging operation. In this latter situation a smoke particulate sensor would provide the discrimination. These inherent fire detection limitations associated with isolated fire sensors suggests the solution to mine fire discrimination from nuisance alarms could reside in the deployment of multiple sensor types.

2 EXPERIMENTAL PROCEDURE

Figure 1 shows a schematic of the section of the SRCM in which the mine fire experiments were conducted. A diesel locomotive was positioned in B-Butt upwind of its intersection with Room 10 to supply diesel emissions to the ventilation current which was split at Room 10 for the coal combustion experiments, and was positioned at its intersection with Room 10 for the belt combustion experiments. For the belt combustion experiments the diesel exhaust was fed into Room 10 through a hose attached to the diesel. The exhaust end of the hose was directed at a vertical plate in Room 10 within 5 m of B-Butt to provide a well mixed diesel contaminant distribution at the first downwind sensor station in Room 10 located 36 m downwind of B-Butt. Room 10, in which the fire is located, has an average height and width of 2.0 m and 3.9 m, respectively. F-Butt has an average height and width of 1.9 m and 4.5 m, respectively. For the experiments conducted, the average air quantity at the fire zone was 2.66 m^3/s, and at the end of F-Butt was 4.73 m^3/s. The increase in air quantity downwind of the fire zone was caused by leakage into F-Butt around brattices shown along the ribs in figure 1 which block crosscuts connecting F-Butt and parallel airways.

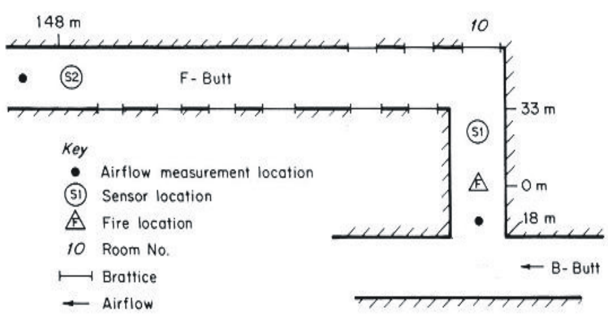

Figure 1. Plan view of a portion of the SRCM.

The three coal combustion experiments, numbered 74-76, utilized the heating of approximately 14 kg of lumped coal with a diameter less than 5 cm in a 0.61 m square pan with embedded electrical strip heaters. The electrical resistive heating rate was increased slowly to a maximum rate of 2.4 kW to produce conditions which would challenge the fire sensors with an initially weak signature in the diesel emissions background. The three conveyor belt section heating experiments, numbered 77-79, were conducted with the heating of a 0.53 m square belt section about 1.1 cm thick. The belt was mechanically attached to a 0.48 cm thick steel plate which was heated on the non-belt side with electrical strip heaters. The plate produced a uniform conductive heating of the belt. The maximum heating rate was 3.3 kW.

The fire sensor types used for the experiments are listed in table 1. Sensor SA is an optical path smoke sensor which operates at an infrared wavelength with a transmitter-receive separation of 9.25 m in Room 10, and 9.65 m in F-Butt. The ionization sensor SB, MOS sensors MA, MB, and MC, and the chemical cell CO sensor are all diffusion mode point sensors. Sensor MA is more sensitive to CO than volatile organic compounds (VOC), whereas MB is more sensitive to VOC than CO. Duplicate sensors are positioned at S1, 18 m downwind from the fire, and at S2, 148 m downwind from the fire. At each sensor station a light obscuration monitor was positioned to determine the smoke obscuration. The light obscuration monitor consisted of an ordinary visible light source and a photovoltaic cell separated by one meter to measure the optical attenuation by the air transported smoke particulates. From the optical attenuation, the smoke optical density can be calcu-

Table 1. Fire sensor types used.

Sensor	Type
SA	Optical Smoke
SB	Ionization Smoke
CO	Electrochemical Carbon Monoxide
MA, MB, MC	MOS (MA, MB volatile organic compound (VOC); MC bimodal NO_x , POC)

lated. The sensor analog output data were collected with a data acquisition system at 2 s time intervals.

3 RESULTS AND DISCUSSION

For the data analysis, the CO alarm value was set to a concentration rise of 5 ppm above ambient. The alarm value for each smoke and MOS sensor was defined to be a ten standard deviation change in the signal from its measured clear air ambient value which occurred prior to the diesel emissions. For sensors SA, SB, and MC the average ratio of the mean to standard deviation for the twelve data sets was 247, 388, and 86, respectively. These two orders of magnitude ratios indicate a relatively noise free signal prior to the detectable event. The response of the unimodal sensors CO, SA, and SB, and the bi-modal sensor MC to diesel emissions and fire POC for the six combustion experiments in the presence of diesel emissions are evaluated relative to the first visual observation of smoke. The sensor-smoke lag time, defined to be the time of the fire sensor alarm, as defined for sensors CO, SA, SB, and MC at sensor stations S1 and S2, less the time of the first observation of smoke, is shown in tables 2 and 3 respectively.

Tables 2 and 3 show that there are no false alarms associated with the use of sensor MC for fire detection in the diesel emissions background. However, sensor MC would not be able to distinguish fire POC from the H_2 emitted at a battery charging station. The isolated use of sensor SB would result in false fire sensor alarms for each experiment at both sensor stations. Sensors CO and SA have mixed results as fire sensors in a diesel emissions background with no consistent pattern. The significant time difference in CO alarm time relative to first smoke observation time for the coal and belt experiments is due to the increased CO concentration in the diesel emissions regime for the belt experiments as a result of the direct feed of diesel emissions into Room 10. This shows that alarms from isolated sensor types may not provide reliable fire detection alarms. For this reason multiple fire sensor types should be evaluated simultaneously.

To provide an interpretation of the sensor response to the mine emissions events for characterizing fire growth and the combustion stage, the degree and rate of response of the sensors to a given event needs to be considered in addition to the sensor fixed alarm point. It is the sensor characteristic response that provides a utility for fire sensors that would not necessarily be considered for fire protection if only an individual sensor alarm point was

Table 2. Sensor-smoke lag time, seconds, at station S1*.

Experiment no. (type)	CO	SA	SB	MC	OD
74 (coal)	-320	-365	-2664	71	213
75 (coal)	-873	335	-1821	311	1468
76 (coal)	285	57	-2359	235	747
77 (belt)	-3715	224	-2221	533	591
78 (belt)	-3100	-3109	-3045	664	632
79 (belt)	-2929	106	-3039	298	711

Table 3. Sensor-smoke lag time, seconds, at station S2.*

Experiment no. (type)	CO	SA	SB	MC
74 (coal)	1394	71	-2138	394
75 (coal)	2319	796	-1507	732
76 (coal)	1864	819	-2011	378
77 (belt)	-2923	903	-2165	862
78 (belt)	-2216	-410	-2484	1040
79 (belt)	-2295	1078	-2650	830

*A negative time elapse indicates a sensor false alarm produced by the diesel emissions.

considered. Figures 2 and 3 show the response of the fire sensors SA, SB, and MC at S1 and S2 for coal combustion experiment no. 75. The sensor values were normalized by the ambient value prior to the diesel emissions generation. A comparison of the response of the optical (SA) and ionization (SB) smoke sensors at S1 and S2 in figures 2 and 3 for the diesel emissions only and the smoldering combustion region shows the ionization smoke sensor SB is more responsive than the optical smoke sensor SA in the diesel emissions only region, whereas the optical smoke sensor is more responsive than the ionization smoke sensor in the smoldering combustion region.

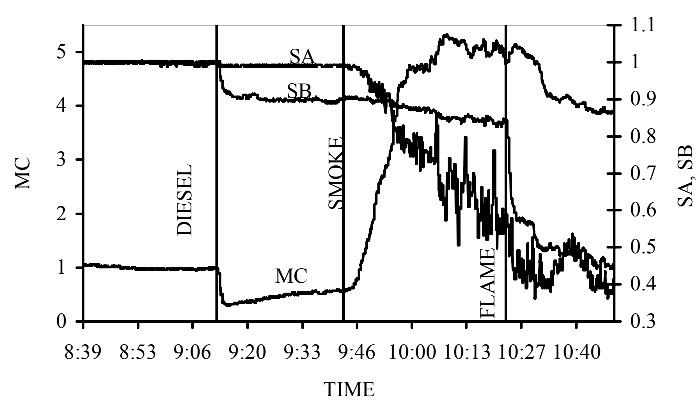

Figure 2. Response at S1 of optical and ionization smoke sensors and MOS sensor to diesel emissions and coal combustion for experiment no. 75.

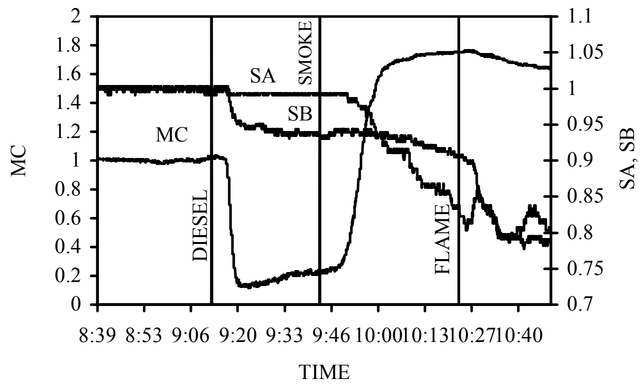

Figure 3. Response at S2 of optical and ionization smoke sensors and MOS sensor to diesel emissions and coal combustion for experiment no. 75.

In the flaming coal combustion stage, the ionization smoke sensor is more responsive than the optical smoke sensor. The estimated travel time from S1 to S2 based upon the measured airflow of 2.05 m^3/s and 3.91 m^3/s for experiment no. 75 at the locations shown in figure 1 is 373 s, which is 89 pct of the

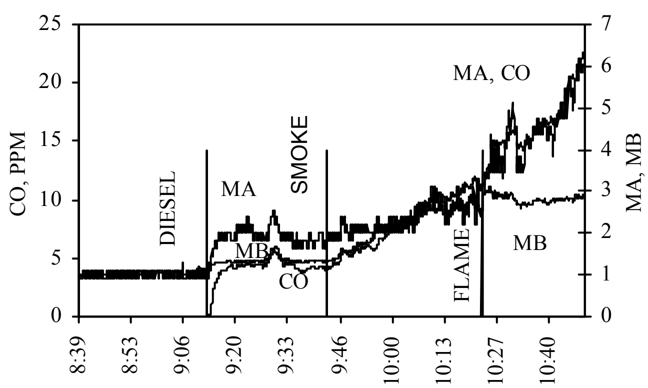

Figure 4. Response of CO sensor and sensors MA and MB at S1 for experiment no. 75.

421s time difference in alarm times for MC. Sensor MC shows an expected characteristic signal decrease associated with the NO_x component of the diesel emissions, and a signal increase to the fire POC. The signal decrease is associated with oxygen adsorption on the semiconductor surface from the decomposed NO_x. The disadvantage of sensor MC is its lack of quantitative precision when compared with CO sensors. Although MOS sensors are very sensitive to a wide spectrum of gases, they are not very species selective.

Figure 4 shows for experiment no.75 at S1 the response of the CO sensor, and the volatile organic compound (VOC) sensitive MOS sensors MA and MB to diesel emissions and coal combustion. There is a 5 ppm CO alarm at 9:29, which occurs in the diesel emissions zone prior to energizing the strip heater elements. Sensors MA and MB show a measurable response coincident with the CO sensor response. Comparison with figure 2 shows this is in contrast with the lack of response of smoke sensors SA and SB at the time of increased CO from the diesel locomotive. Figure 4 shows that sensors MA and MB are no more discriminatory of combustion than is the CO sensor in the diesel emissions environment. An evaluation of the response of sensors MA and MB at S1 for the three coal and three belt combustion experiments showed that sensor MA's response is no earlier than the CO sensor response to smoldering combustion, whereas sensor MB, which is more sensitive to VOCs, responds as rapidly as the CO sensor. For smoldering belt combustion with delayed CO emissions, sensor MB can respond earlier than the CO sensor. These different characteristic responses of MOS, smoke, and CO sensors demonstrate the utility of multiple sensor types for mine fire nuisance event discrimination.

The particulate emissions' optical density, which is determined by particulate size and concentration, can be used as a benchmark for smoke sensor alarm points. A smoke optical density equal to 0.022 m^{-1} is the alarm value (Code of Federal Regulations, 2001) for a mine smoke sensor. Column OD in table 2 show reports the time at which the smoke optical density equals 0.022 m^{-1} as measured by the light obscuration monitor at sensor station S1 less the first smoke observation time. In each experiment the smoke optical density alarm value did not occur in the diesel emissions period prior to smoldering combustion. However, the negative values in table 2 shows that the ionization smoke sensor SB alarmed prior to visible smoke particulates from the heated coal. This implies that smoke sensor SB alarm value in terms of a 10 S.D. change from ambient conditions is a more stringent smoke alarm value than an optical density of 0.022 m^{-1}. At an alarm value of 0.022 m^{-1}, sensor SB was determined at S1 for the six experiments to be between 30 and 71 S.D. from its ambient value in clear air. To increase the alarm value definition of SB in terms of the number of standard deviations from clear air value to delay sensor SB alarm would not be an adequate solution to the problem, since an increased alarm level required to discriminate open combustion from nuisance events would never be known with any definitive certainty due to the diesel emissions variable optical density. This would apply to the other sensors exclusive of MC, which has a definite bimodal response to differentiate diesel emissions from a fire signature.

At sensor station S2 the smoke optical density only exceeded 0.022 m^{-1} for experiment nos. 74, 77, and 78. The lower optical density for experiment nos. 75, 76, and 79 was due to smoke dispersion over the entry cross-section and dilution from leakage around brattices. However, at S2, as was the case at S1, a definite alarm could be associated with MC's bimodal response to the combustion generated smoke superimposed upon the diesel emissions. Figure 5 shows for experiment no. 75 the average response of two CO sensors mounted near the roof and across the entry at S1, and the measured optical density at S1 for the coal combustion in the presence of diesel emissions experiment. A false CO alarm at 9:29 in the diesel emissions only regime produced by the diesel locomotive occurs at a smoke optical density equal to 0.0031 m^{-1}. The smoke optical density did not reach 0.022 m^{-1} until 10:08. As previously noted, the event at 9:29 was detected by VOC sensors MA and MB, but not detected by smoke sensors SA and SB. Reliance upon a CO sensor in the presence of diesel emissions or other nuisance sources of combustion without interpreting either the shape of the signal response or the data supplied by complementary fire sensors would lead to the erroneous conclusion of the occurrence of a fire. This particular CO signal increase is attributed to the diesel locomotive.

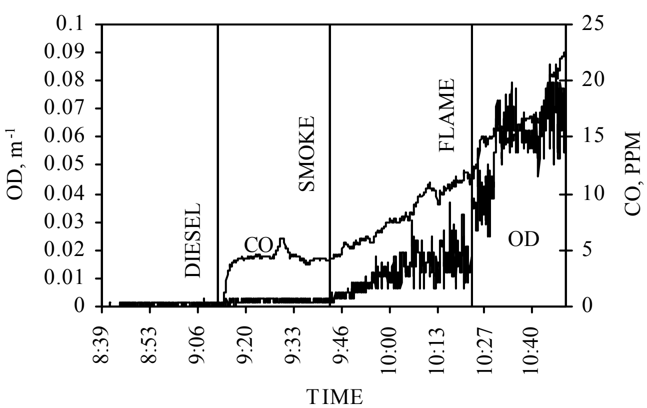

Figure 5. Optical density (OD) and CO at S1 for experiment no. 75.

The different response characteristics between smoke sensors SA and SB in the diesel and smoke emissions as shown in figures 2 and 3 suggests a combined signal as a possible metric for mine fire nuisance signal discrimination. Sensor SA, as an optical sensor, is more responsive to larger diameter particles associated with smoldering combustion, than is the ionization smoke sensor SB, which is more sensitive to the particulate number concentra-

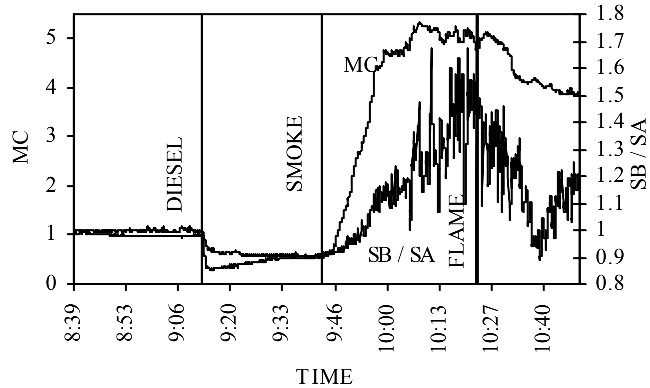

Figure 6. Response of MOS sensor MC and ratio of normalized ionization to optical smoke sensors at S1 for coal combustion experiment no. 75.

tion. One possible metric is the ratio of signal SB response to signal SA response. An analysis was made of the characteristic response of the MOS sensor MC and the ratio SB/SA to diesel emissions and to open fire combustion POC. For this analysis each sensor signal was normalized by its clear air value. Figure 6 shows the response of the normalized signals MC and the ratio SB/SA to the clear air, diesel emissions, and coal smoldering and flaming stages for coal combustion experiment no. 75. The observed pattern of a decrease in sensor MC due to the NO_x is coincident with the decrease in the ratio SB/SA during the diesel emissions only regime. The observed occurrence of smoke from the coal combustion is associated with the increase in both the MOS sensor MC and the ratio SB/SA above the clear air value of unity. Figure 7 shows a similar pattern for conveyor belt combustion in the presence of diesel emissions. This sensor response pattern was found to occur for all six experiments at sensor stations S1 and S2. The effect at S2 was less pronounced due to the dilution and dispersion of the POC. For experiment nos. 74-

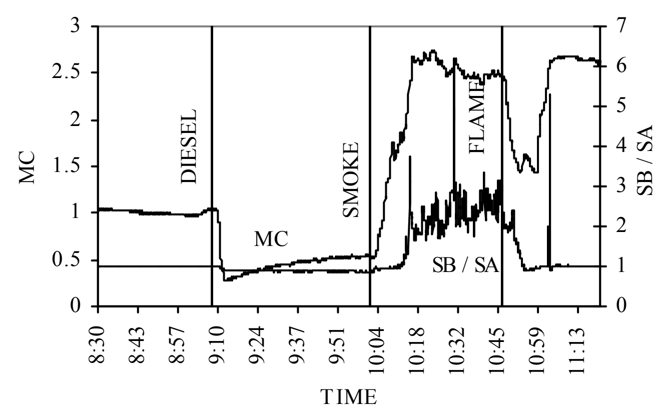

Figure 7. Response of MOS sensor MC and ratio of normalized ionization to optical smoke sensors at S1 for belt combustion experiment no. 79.

79 the average lag time of a 20 pct increase in the signal ratio SB/SA at S1 relative to the first visual observation of smoke was 11 min. This is greater than the 6 min average lag time for sensor MC based upon the values in table 2. The selection of the 20 pct signal increase as a criterion is motivated by the noise in the sensors' signal ratio. The noise is apparent from a comparison of the response of sensor MC with the ratio SB/SA in figures 6 and 7. A comparison of the individual sensor responses, SA and SB, in figure 2 shows that it is the extreme sensitivity of SA to fire POC which produces the strong variations in the ratio. Although sensor MC will respond to H_2 from a battery charging operation in a manner similar to its response to fire POC, the combination of sensors MC, SA, and SB could also be used to discriminate a battery charging operation from fire POC since the ratio SB/SA would not be affected by the H_2. This could indicate that the combined use of MC, SA, and SB would be suitable for discriminating diesel POC emissions and battery charging H_2 emissions from open combustion. The reinforcement of sensor information with the use of multiple sensor types is important for nuisance alarm discrimination and early mine fire detection.

An evaluation of multiple sensors was conducted in an operating underground coal mine immediately downwind of a battery charging station. The sensors used for the evaluation, which included a CO sensor, ionization smoke sensor SB, and MOS sensors MA, MB, and MC, were located upwind of a regulator in intake air. A portable data acquisition system was used to collect data at one-minute intervals. Interpretation of the data was based upon previously conducted sensor evaluation in the SRCM and the occasional presence of an observer during data retrieval and sensor maintenance. Figure 8 shows sensor response for one 24 hr period. The time period from 1:00 PM to 5:00 PM in figure 8 can be identified as one complete battery charging time period. This is based upon the increase in the CO signal with no decrease in smoke sensor SB's signal. The CO sensor response is the result of cross-interference from H_2. Sensors MA and MB are also responsive to H_2. Sensor MB is more responsive than MA to the nuisance emissions from the battery charging. The absence of a coincident increase in sensor MC's signal and a decrease in SB's signal over the 24 hr period eliminates any possibility of open combustion. Prior to this event at 11:37 AM diesel emissions were detected by sensor MC as indicated by its rapid signal decrease. Smoke sensor SB was not affected by the diesel emissions.

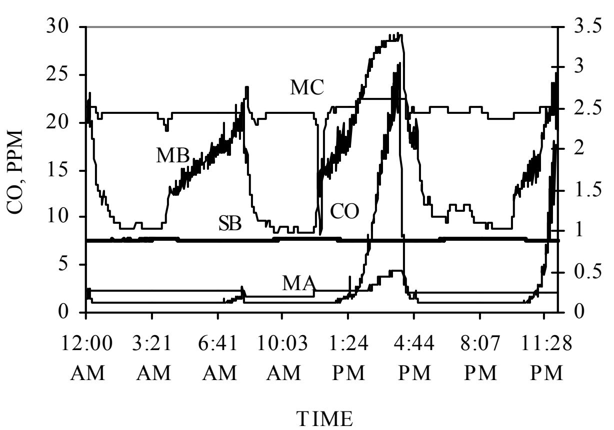

Figure 8. Sensor response to battery charging and diesel emissions in an underground coal mine.

Figure 9 shows the response of the CO sensor to a battery charging operation. At 9:45 and 9:46 AM two gas samples were drawn by an observer at the CO sensor location. Analysis of the gas samples determined ambient CO less than 3 ppm, and H_2 concentrations of 155 and 192 ppm. The in-mine indicated CO sensor value was 18 ppm. This demonstrates the cross-interference effect of the CO on the chemical cell.

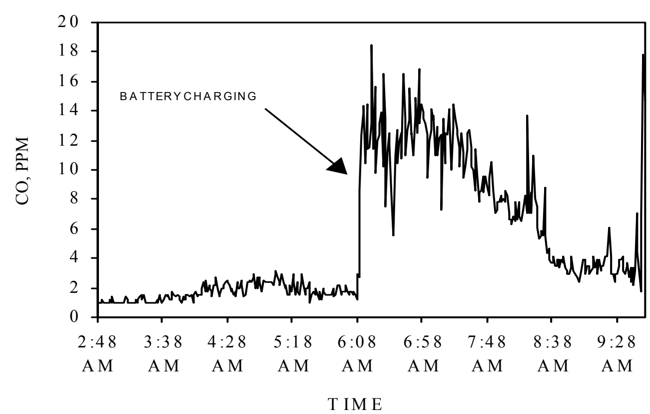

Figure 9. CO sensor response to battery charging operation.

4 CONCLUSIONS

1. No false alarms occurred when MOS sensor MC was used to determine smoldering coal or mine belt section fires in diesel emissions background.
2. Use of the ionization smoke sensor would result in false alarms at both sensor stations for the six experiments conducted.
3. The ionization smoke sensor was more responsive than optical smoke sensor in diesel emissions regime than in smoldering combustion regime.
4. It is not practical to increase the smoke sensor alarm to accommodate diesel emissions,

since the diesel emissions concentration is variable.

5. Neither an individual CO alarm nor an individual smoke sensor alarm can distinguish open combustion from diesel emissions.
6. Ratio of normalized ionization smoke sensor signal to optical smoke sensor signal was less than unity for diesel emissions, and greater than unity for smoldering combustion.

Combination of an MOS NO_x sensitive sensor and the ratio of normalized ionization smoke sensor signal to optical smoke sensor signal seems to be a possible method to not only discriminate open combustion from diesel emissions, but also to discriminate diesel emissions from H_2 produced by battery charging which cannot be determined by a chemical CO sensor due to cross-interference.

This research shows the significance of multiple fire sensors for mine fire nuisance event discrimination. The mission of NIOSH to protect the health and safety of mine workers is furthered by the exclusion of false fire alarms associated with in-mine nuisance emissions events, and the recognition of a fire signature in the presence of diesel emissions. Although some sensor combinations may be redundant for one type of open fire nuisance emissions discrimination, they will be significant for another scenario of open fire nuisance emissions discrimination. The analysis of the sensor response characteristics demonstrates the need to develop a systematic approach based upon a set of algorithms to process the sensor data. One such methodology would be the use of neural analysis.

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