In-mine evaluation of smart mine fire sensor

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Abstract

An evaluation of a nuisance-emissions-discriminating smart mine fire sensor system was made in an operating coal mine. These field evaluations were conducted to determine the sensor system's ability to discern nuisance emissions, such as diesel exhaust, emissions from flame cutting and welding operations, or hydrogen gas from a charging station, from real fires and to compare the number of falsely reported fire alarms generated between the sensor system and a standard carbon monoxide (CO) monitor. The sensor system's ability to operate successfully in the working environment of an operating coal mine was also evaluated. The smart mine fire sensor system consisted of four sensors whose data outputs were fused with the use of a neural-network-type computer program. Long-term trials were conducted in a haulageway, a belt entry, and a track entry. The system functioned successfully in the belt entry, in accordance with its developmental goals, where the sensor system even discriminated events not anticipated during development. It was only partially effective in the haulageway and track entry, though, due to a combination of significant diurnal air temperature variations, dust, and mechanically induced vibrations. Also, deteriorating rib conditions contributed to operational problems in the haulageway evaluation. In general, the smart mine fire sensor provided nuisance emissions discrimination and was shown to be an interesting new approach for mine atmospheric monitoring, and possibly a new method for enhancing miner safety. This paper describes the in-mine evaluation of the smart mine fire sensor system and discusses recommendations for improving the system.

Introduction

Typically, mines use fire protection monitoring systems that depend on carbon monoxide (CO) electrochemical cell sensors to detect fires. These devices have a cross sensitivity to a number of other gasses that are not necessarily from fires, such as hydrogen produced by lead acid battery charging, which when produced in sufficient quantities cause false responses in this type of sensor. Beltline drive assemblies have been known to produce large amounts of smoke from dangerous friction-producing stall conditions that generate very little CO and, therefore, are not detected by this type of sensor. Flame cutting and welding operations in coal mines have been registered by electrochemical CO sensors as a fire alarm, a key issue. Also, CO emissions from diesel engine exhaust from all types of diesel-powered underground mining equipment have generated false fire alarms. The only alternative would be to increase the ambient alarm level, which would be dangerous. These situations have lead to a need from the mining community for mine monitoring systems that will more precisely register the nature of the combustion event in question, that is, a fire signature.

Previous NIOSH research identified four sensors that, when used in conjunction with a neural-network (NN) software, could discriminate a mine fire from nuisance combustion emissions (Edwards et al., 2001). These sensors were a carbon monoxide (CO) sensor;[1] two metal oxide semiconductor sensors (MOS), both of which responded to hydrocarbons with a decreased sensor resistance,[2] but the second MOS sensor also responded to nitric oxide (NO) from diesel engine emissions with an increased sensor resistance;[3] and an infrared open-path smoke sensor (Beam[4]). (Reference to a specific product does not imply endorsement by NIOSH.)

The neural network program, NeuroSolutions, was acquired from NeuroDimension Inc. An MS Office Excel[5] spreadsheet was configured with a Visual Basic (VB) macro that implemented the NN algorithm to provide a real-time evaluation of fire probability. The NN algorithm classifies three outputs into probabilities that each outcome would occur. The output

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[1] Conspec Controls Inc. P2030KP Carbon Monoxide Monitor.

[2] Figaro USA TGS-2600 metal oxide semiconductor sensor.

[3] Figaro USA TGS-2105 metal oxide semiconductor sensor.

[4] Detection Systems, Inc Beam Smoke Detector, DS-240 (now, Bosch Security Systems model D-296).

[5] Microsoft Office 2003 Excel Spreadsheet with Visual Basic for Applications Macro Language from Microsoft, Redmond, Washington.

possibilities were clean air, only diesel engine exhaust in air and combustion products with or without diesel engine exhaust in air.

The neural network (calibration). This sensor system was evaluated in fire experiments in the presence of diesel emissions in the Safety Research Coal Mine (SRCM) at the National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Laboratory (PRL) (Edwards et al., 2003, 2004) to obtain fire signatures from various materials burned with and without the presence of diesel engine exhaust. The materials included coal, diesel fuel, electrical cable and conveyer belt. Flame cutting and welding experiments were also conducted at that time to evaluate the sensor system's response to these mining activities (Edwards et al., 2000). In addition, the smart fire sensor system was evaluated in an above-ground battery-powered mine locomotive charging building at PRL (Edwards et al., 2001) and at a battery-powered equipment charging station at the mine of Foundation Coal affiliate Emerald Coal Resources, LP in Greene County, Pennsylvania (Edwards et al., 2002). The system was then installed at the mine of Foundation Coal affiliate Cumberland Coal Resources, LP in Greene County, Pennsylvania, to determine the capability of the neural network for discriminating against false alarms in an operating underground coal mine environment and to evaluate its durability and the reliability of its operational systems. This paper discusses the results of this last evaluation and makes recommendations as to how the smart mine fire sensor system can be enhanced for optimum performance.

Smart mine fire sensor system installation at Cumberland Mine

The system was installed at the Cumberland Mine in Greene County, Pennsylvania, and operated from Sept. 17, 2004, until June 29, 2006, a total of more than 21 months. The system ran almost continuously except for short periods of shutdown for data collection, usually less than an hour, once every two weeks. The monitoring system interrogated the sensors once every minute, not too rapidly to inundate the system with large amounts of collected data in the long-term, and yet sufficiently rapid to keep up with sensor changes. A 30-minute daily average of the sensors' background signals was collected from 1:00 to 1:30 AM each day to account for daily changes in the mine's ambient environment.

The 30-minute daily average processing consisted of the testing of a small group of data (30 one-minute samples) for statistical noisiness and, if acceptably quiet, used the group to calculate the group's mean and standard deviation (SD). The calibration was acceptable if no excursions in sensor response were found. If excursions were found, then a subsequent 30-minute calibration was automatically initiated. The mean and SD were then used to calculate a normalized sensor value from each subsequent sampled sensor value. This normalization of the data enabled trends from the mine's usual conditions to be more easily detected. The normal values were then condition tested before the NN calculation for such events as sensor electronic drift and equipment or people blocking the Beam sensor's IR path to avoid false alarms.

To implement the NN algorithm, two data functions derived from the four sensor inputs together with three of the sensor inputs were used as the five inputs into a trained, two-hidden-layer perceptron neural network. Twenty process elements (PEs) were in the first hidden layer and ten PEs were in the second hidden layer. The NN was trained over the default number of 1,000 iterations (epochs) of the training set consisting of seven sets of data from various materials burned in the SRCM with and without the presence of diesel engine exhaust. A total of 13,190 rows of data collected at two-second intervals and randomly sorted were present in the training data set. The NN training convergence criterion was the mean squared error. The momentum learning rule was used to determine the change of the weights in the NN after each row of input data (exemplar) was processed. The momentum constant used was the default value of 0.7. The weights were only changed after each epoch, and these changes were composed of the means of the calculated weight changes after each exemplar in the epoch. The activation function in each PE of the hidden layers was the hyperbolic tangent function. The activation function in each PE of the output layer was the SoftMax function. The SoftMax function classified three outputs into probabilities that each outcome would occur given a particular set of the five inputs. These outcomes are the output possibilities enumerated in the Introduction.

During the course of the evaluations, the sensors were maintained within operating specifications. The CO and CO-NO sensors were calibrated at 30-day intervals. Electrical resistances in the MOS sensors were adjusted to provide ambient output signals indicative of a fire products-of-combustion-free environment. The MOS sensors were replaced when needed as their surface elements lost sensitivity. The Beam sensor was reset to provide automatic calibration during each mine visit. At the conclusion of the evaluation of the smart sensor system in Cumberland Mine, electrical continuity checks were made on the signal and power lines from the PC to the sensors. No significant unwarranted resistance values in the lines were detected.

The Smart Mine Fire Sensor System was initially installed in the haulageway during this evaluation. The MOS sensor unit containing the two MOS sensors and the CO sensor unit along with a Conspec Diesel Discriminator[6] and a Becon Smoke Detector[7] were spread across the haulage entry and attached to the entry roof by a bar. These last two sensor units were used on the NIOSH mine monitoring system, but were not part of the Smart Sensor set. The Beam smoke sensor transmitter unit was located on the rib near the MOS sensor unit. The Beam receiver was located on the opposite rib 9 m (30 ft) down the haulageway from the transmitter unit. Signal transmission and power lines were connected between the sensors and a Conspec Senturion 500 mine monitoring system at a surface station via a Conspec mine trunk cable.[8] Linear airflow in the haulageway was usually about 1.8 m/s (350 fpm). There were significant temperature variations in the haulageway, ranging from 7° to 29°C (20° to 85°F), due to the proximity of the sensors' location to the intake air shaft. The evaluation of the system in the haulageway lasted for 14 months.

The equipment was then moved into the beltline entry, which was in an adjacent entry to the haulageway. The objective of the move was to place the sensors in an environment more representative of where their location would be for normal in-mine use. In the belt entry the linear air velocity in the vicinity of the sensors was approximately 1.2 m/s (230 fpm). The location was two miles from the intake, resulting in a fairly constant temperature of approximately 16°C (60°F). The ambient temperature was elevated due to the additional heat from the beltline equipment.

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[6] Conspec Controls Inc. P2512 Diesel Discriminating Monitor.

[7] Anglo American Electronics Laboratory C121B Becon Ionisation Smoke Detector.

[8] The mine monitoring system used was a Conspec Controls, Inc. S500 Senturion Super-system.

Lastly, the system was moved to a track entry in the mine's shaft-bottom area (the north track area) for two months. The track entry was the second entry toward the elevator shaft from the main haulageway. This area is where miners normally departed from at the beginning of shift work and returned to at the end of shift work by motorized equipment, mainly diesel man-trips. The track entry did not have the intensity of the vehicular traffic observed in the haulageway. The entry had approximately the same linear air velocity as in the haulageway, i.e., 1.8 m/s (350 fpm). The entry was about the same distance from the intake air as the haulageway, consequently having the same relative air temperature variations.

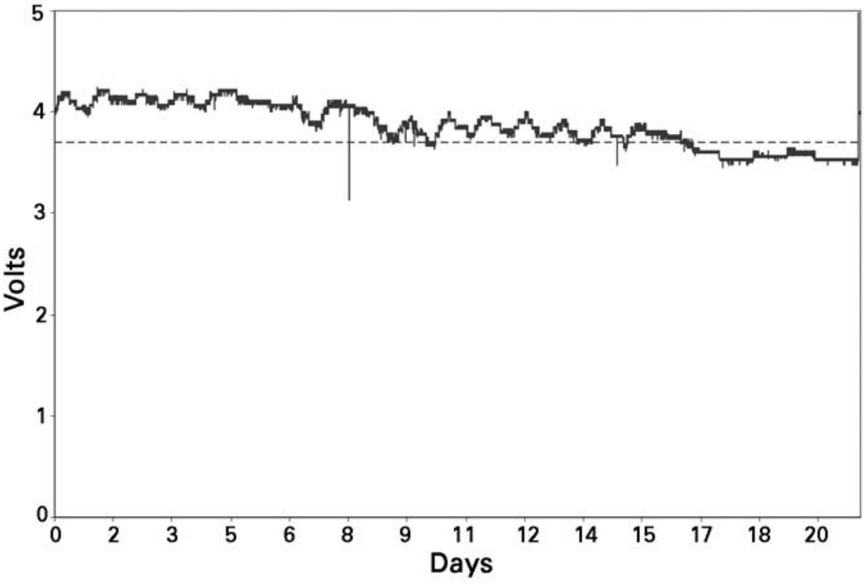

Figure 1 — Beam sensor response in the main haulageway.

Evaluation of durability, functionality and reliability

Drift. The Smart Fire Sensor System experienced significant drift problems with the Beam Smoke Sensor unit when the system was installed into the main haulageway at Cumberland mine. The drift was attributed to a combination of three or four persistent problems; loosening of screws in the Beam unit's interface assembly due to constant vibration from equipment moving in the haulageway, misalignment of the Beam transmitter unit due to the deterioration of the rib to which it was mounted, periodic build-up of dust on the lens assembly from the high air-flow and temperature fluctuations in the haulageway. No one specific cause was determined to be the reason for the drift. An example of the drift over a 20-day period is shown in Fig. 1.

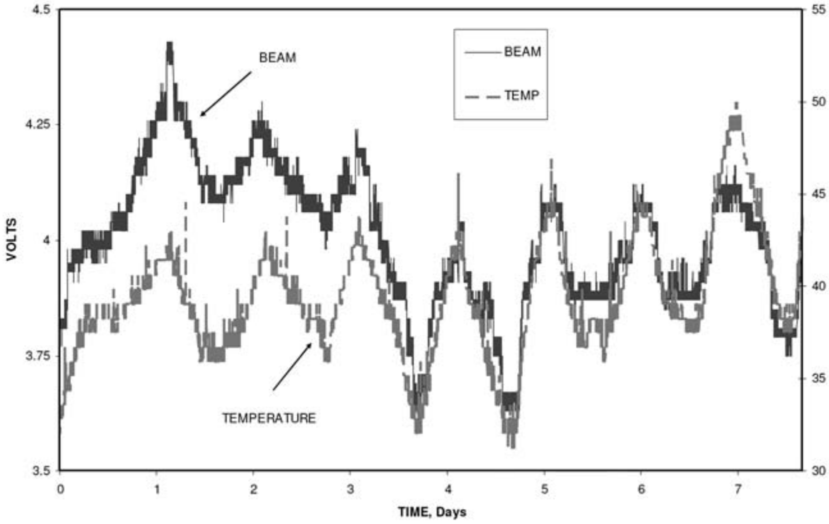

Figure 2 — Beam and temperature responses.

Temperature effects. Diurnal temperature effects on the Beam and MOS2105 sensors were observed in the haulageway. This temperature change was due to the proximity of the haulageway sensor station to the intake air. An example of the close correlation of the periodic fluctuations in signal level of the Beam sensor with a similar change in ambient air temperature in the haulageway is shown in Fig. 2 for a 7-day period. The maximum value occurred at about 6:00 PM and the minimum value occurred at about 7:00 AM on a recurring daily basis. These times corresponded to maximum and minimum outside air temperatures.

In an attempt to correct this temperature response problem, foam insulation was placed around the open perimeter of the Beam housing to isolate the electronics from the mine air and prevent convective cooling. However, this did not eliminate the problem. The MOS2105 sensor also showed a voltage drop due to severe winter temperatures, but recovered well whenever the low temperature conditions abated.

In the Emerald Mine charger entry, the Beam sensor's output temperature dependence did not manifest itself, as was also the case in all of the SRCM tests prior to the Cumberland evaluation, but this was under more stable temperature conditions. The sensors were located in a split from the mine's electric-vehicle charger entry. In this evaluation, the temperature was not recorded by the mine monitoring system as it was at Cumberland Mine. Also, at the sensors' location in the split the air velocity had a relatively low value of about 0.2 m/s (40 fpm).

An attempt was made to determine the exact dependence of the Beam's output upon ambient temperature by an evaluation of the correlation between the two parameters for a stable haulageway data set. For a 20-day period, the dependence of the measured Beam output signal on the temperature resulted in a fit of the Beam signal to a power of the air temperature measurement, as follows

$$PREDICTED\_BEAM = T^{0.329} \qquad (1)$$

where

T is the measured temperature in ºF and

PREDICTED_BEAM is the predicted Beam signal in volts.

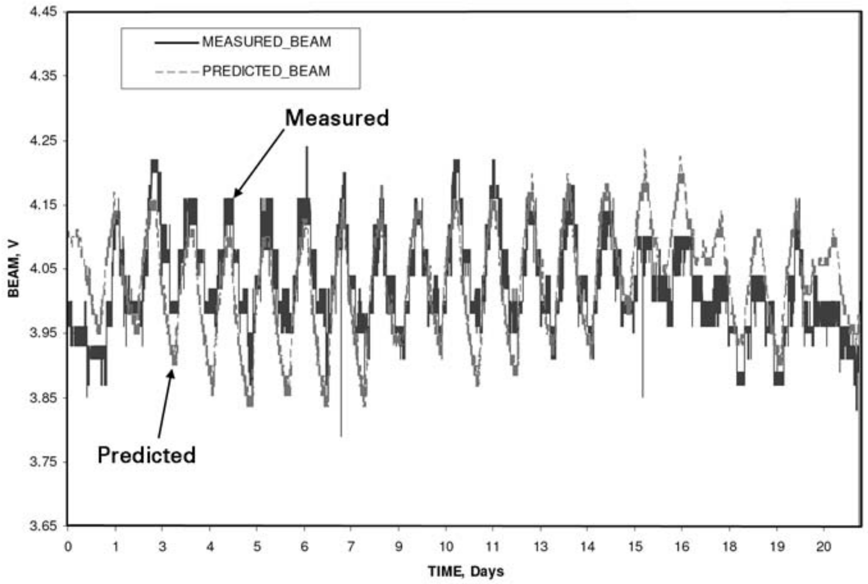

Figure 3 — Measured and predicted beam signals, based on ambient temperature.

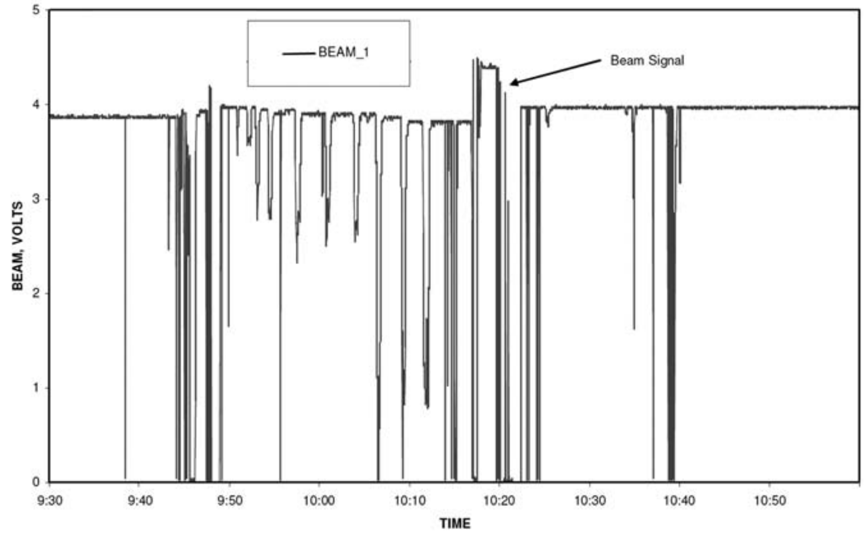

Figure 4 — The beam affected by rock dust in the SRCM.

The correlation coefficient is 0.62, which defines a moderate correlation. Figure 3 indicates that the period of the measured Beam oscillations is well represented by the *PREDICTED_BEAM* value, but the amplitudes are less well represented.

It should be noted that this correlation applies to this particular set of data and for which there was no long-term downward drift in the Beam output signal. Any modifications to the smart sensor unit as imposed temperature compensation would require the addition of a temperature measurement device to the smart fire sensor set and that a temperature compensation algorithm would need to be applied to the data normalization process.

Dust problems. Because the Beam smoke detector is an optical device, the Beam had a persistent problem with dust accumulation on its lens surfaces and the unit was indiscriminant in its response to the various types of particulate matter that were dispersed into its optical path. The effect of rock dust on the Beam sensor had been investigated in the SRCM. In the SRCM rock dust was hand-dispersed, at the entry's mid-height, upwind from the Beam sensor unit. The Beam sensor responses in the SRCM evaluations are shown in Fig. 4. The airflow was maintained at 1.3 m/s (250 fpm) during these evaluations.

It can be seen in Fig. 4 that the Beam recovered to its pre-rock-dusting value after the last intense injection of rock dust into the air stream. Two differences were possible from the perspective of rock-dust deposition between the SRCM and the in-mine evaluations. One possible difference was the rate of deposition of rock dust on the Beam lens cover. In the case of the in-mine evaluation, the deposition rate would be gradual. A gradual deposition rate might not be detectable by the logic inherent to the Beam sensor. Another possibility could be the presence of diesel combustion byproducts that could accumulate as a film on the Beam's plastic surface to which the dust could adhere. During the evaluation, it was also observed that rock dust periodically accumulated on the Beam lenses. The Beam lenses were cleaned and the unit reset to restore the Beam to its normal value of 4 volts.

In the north track area, dust and diesel particulate deposits built up on the Beam's transmitter unit causing the Beam's output to drift down over time by as much as 1 volt. The Beam's transmitter was well aligned with the end of the exhaust pipe on diesel man-trips when they parked in this area. This area would be subjected to diesel exhaust from these diesel-particulate-emitting vehicles during each shift change. The man-trips not only dispersed dust as they entered and exited the parking area, but the miners disembarking and entering the man-trips also contributed to dust dispersion. When the Beam was cleaned, the unit returned to its normal ambient output voltage without the necessity of resetting the unit.

In the main haulageway the Beam had some dust build up from heavily laden haulage trains and exposure to diesel exhaust because the location of this evaluation was at the entry switch to the mine bottom where the shops and crew parking areas were located. The difference between the main haulageway location and the north track location was that the Beam was mounted higher up on the rib in the haulageway and any man-trips entering or leaving the bottom never idled there for more than a minute or so before moving along the haulageway. These differences provided for a lighter rock-dust-laden buildup on the transmitter and receiver units of the Beam in the main haulageway than in the north track entry. However, even with a lighter dust build-up, the Beam unit in the haulageway would not return to its normal 4.0 volt clear air operation after a lens cleaning and always required a reset to return it to normal operation. This was a good indication that a gradual misalignment process was at work in the haulageway on the Beam mountings, and that vibrational loosening of the terminal-strip screws was occurring.

Vibration effects. In an attempt to address the downward drift of the Beam's output signal in the environment of the main haulageway, the screw connections at the terminal strips in the Beam's interface box were tightened, and the unit was returned to service. The results of the evaluation for a 20-day period showing the stability of the Beam output signal are depicted in Fig. 5. This would indicate vibrations induced in the Beam's interface box was a significant factor in the long-term evaluation of the smart fire sensor in the haulageway.

It should be noted that Fig. 5 shows an isolated fire probability of 0.8 that occurred on Day 7. However, during that time only a small decrease in the Beam output voltage occurred, so the NN does not indicate an alarm event.

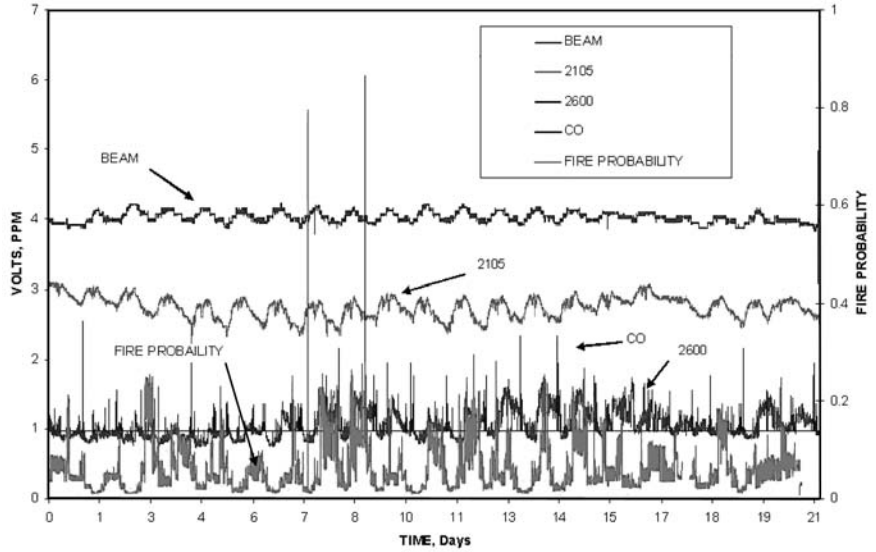

Figure 5 — Sensor responses and predicted fire probability in the haulageway.

Ground movement effects. Spalling of the haulageway rib to which the Beam's transmitter unit was attached also caused alignment problems with the Beam detector. In a simple lab experiment, with the Beam set up along an approximate 1.8-m (6-ft) path, the unit showed a significant voltage loss in the receiver output with slight lateral movement of one corner of the receiver's mounting-plate in a direction perpendicular to the optical path. Although the same displacement on the 9-m (30-ft) path-length in the mine would require five times the movement, the results indicated that a continual slow movement of the rib mounting caused by the working rib would produce a continual voltage drop in the Beam. The Beam transmitter mounting supports on the main haulageway rib eventually collapsed at some point in time after the Beam unit had been removed from the haulageway.

Evaluation of sensor ability to discern false alarms

The sampled data at Cumberland Mine were recorded every minute on the surface mine-site monitoring system PC and the fire probability was calculated with the NN software in real time using the algorithm derived from data collected from previous experiments in the SRCM. After initial mine-site installation, site-specific modifications were required to the algorithm related to the calculation of the daily averages of the sensor ambient values and the criterion for an alarm.

To be acceptable data for a daily average calculation:

- the Beam sensor output voltage was required to be greater than 3.7 volts and less than 4.3 volts;
- the CO sensor output deviation from its mean had to be less than 1.5 times its standard deviation; and
- for the MOS sensors and Beam sensor, the ratio of the signal (mean) to noise (standard deviation) had to be greater than 5.

If any set of sensor values did not conform to the above constraints, another set of 30 one-minute scans would be collected and tested until the constraints were satisfied. Once the daily averages were determined, all data were normalized by dividing each value by its associated daily average. A very high probability fire alarm (HH) required that the NN predicted fire probability be greater than 0.9 and the normalized Beam data be less than 0.8. Blockage of the Beam sensor optical path by an object occurs often. To exclude a blockage as a fire event by the NN program required the provisional evaluation of the Beam, the CO sensor, and the MOS2105 sensor. If the normalized Beam deviation was greater than ten standard deviations (SD), the normalized CO deviation was less than one and one half SD and the normalized MOS2105 increase was less than ten SD, then the event was considered to be a blockage of the Beam path by an object and not a fire event. If the event met the conditions for a blockage, then the fire probability was not calculated.

In-mine verification of the NN program modifications — rail burn. For validation purposes, the new modifications of the NN program were applied to the data from the in-mine rail-cutting operation performed at the Emerald Mine as a flame cutting experiment. The sensor measurements are shown in Fig. 6. No HH alarms resulted. Figure 6 shows that there were CO values greater than the 10-ppm alarm level. Although the fire probability exceeded 0.9 during the burn, the normalized Beam values were greater than 0.8. As noted above, the criterion for an HH alarm required both the fire probability to exceed 0.9 and the normalized Beam values to be less than 0.8. This demonstrated the nuisance discrimination capability of the smart sensor system.

Figure 7 shows the identification of a typical nuisance emission in the haulageway during the evaluation that shows the MOS2105 sensor responded simultaneously with the NO and CO sensors. The responses by the CO and NO sensors were less than 2 ppm. However, the absence of the Beam sensor's response is indicative of an absence of optical obscuration. The predicted fire probability from the NN algorithm was less than 0.11. Although the emission source was not known, it most likely was a diesel engine that produced insignificant smoke obscuration compared to a fire.

An example of the Smart Sensor's ability to discern a false alarm in a belt entry is shown in Fig. 8. In this case, given the

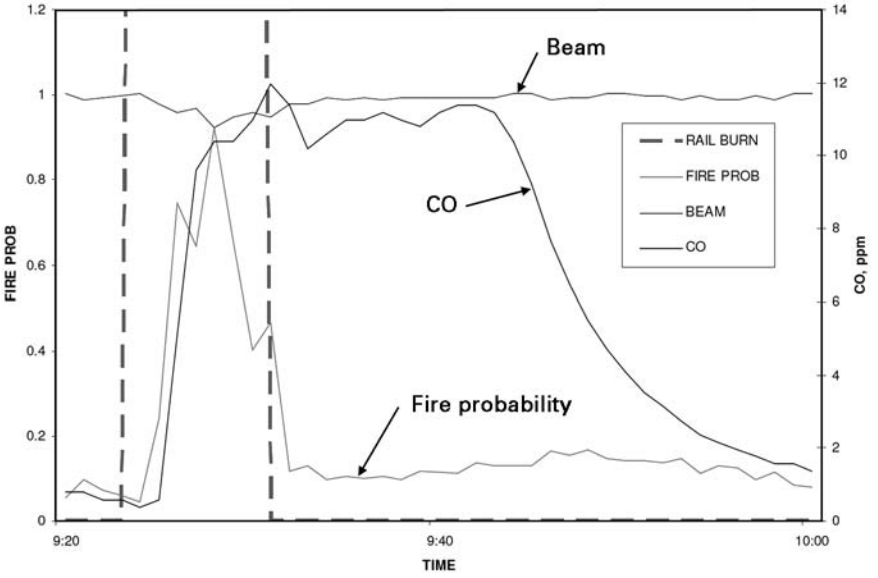

Figure 6 — CO and beam responses, and predicted fire probability

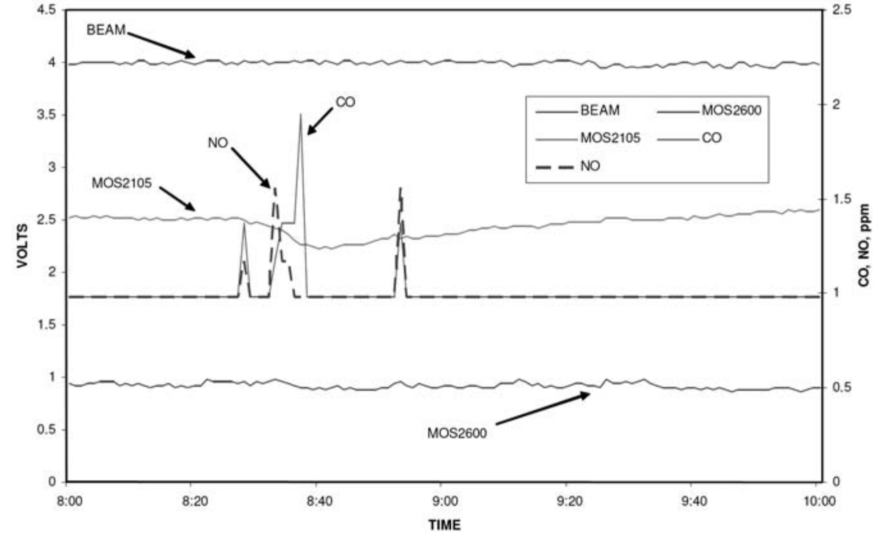

Figure 7 — Sensor responses in the haulage way at Cumberland.

response of the MOS2105 to NO and a small response of the NO chemical cell sensor to this event, the speculation was that a diesel-powered scoop operation was in progress in the belt entry to remove coal spillage upwind from the sensors, which resulted in dust-laden airflow. Another event of the type depicted in Fig. 8 occurred in the belt entry later in the evaluation. Figure 9 shows the sensors' outputs. This resulted in one HH alarm. Figure 9 also shows a small increase in the CO at the time of the HH alarm. The broken fire probability curve in Figs. 8 and 9 is a consequence of the Beam sensor response being more than ten standard deviations below its mean value and the MOS2105 sensor response increase being less than ten standard deviations above its mean value. In this case there is a source other than smoke, such as optical path blockage by equipment or dust, which induces the Beam sensor response. When this occurs, the fire probability is not calculated and no alarm is given.

Another case for which the fire probability cannot be calculated is when a sensor or communication link fails. In these cases, the mine monitoring system produces textual error statements. The algorithm does not process these textual errors.

The Smart Sensor's discriminating capability was compared to that of a diesel discriminating monitor currently in use in mines during the evaluation in the track entry, shown in Fig. 10. During this event, the CO response from the CO-NO sensor (ACO) was 11 ppm for the measured CO concentration. The NO sensor response was 20 ppm. In this figure, ACO refers to the actual CO response of the CO-NO sensor. CCO refers to the corrected CO response read by the CO-NO sensor based upon the CO and NO historical record. The CO-NO sensor identified this event as a non-alarm with a base line CCO value equal to 0.98 ppm. The fire probability identified with the NN evaluation from the smart fire sensors was 0.14, and the diesel emissions probability identified with the NN evaluation was 0.24. This demonstrates a consistency of the smart fire sensor system with the diesel discriminator unit's evaluation.

A comparison was made of the response of the Smart Fire Sensor system with CO alert and alarm signals at the measurement sites. During the 21-month evaluation period of the Smart Mine Fire Sensor system in the Cumberland mine there were 47 CO alert or alarm events that were unrelated to a fire as summarized in Table 1. The most likely CO sources were operating diesel equipment. Eighteen of these events occurred in the haulageway, and 29 of these events occurred in the north track area. There were no CO alerts or alarms in the belt entry. The Smart Mine Fire Sensor system correctly identified five of the CO events in the haulageway as non-fire events. The other thirteen events could not be identified due to sensor system malfunction. In the north track area, 27 CO events were correctly identified by the Smart Mine Fire Sensor system as non-fire events. Two additional CO events in the north track area occurred during the system setup period and consequently were not amenable to analysis.

It should be noted that the stability of the Beam over many of the two-week sampling periods in the belt entry, as demonstrated by the stability of the collected data from the belt evaluation, was due to the stable belt entry air conditions with the exceptions of the coal cleanup activities. This indicates a single average of the sensor values during one 30-minute period at the beginning of the two-week sensor evaluation in the belt entry could be sufficient. By way of example, an evaluation with the NN program with a single 30-minute average was made for the belt entry data from the time period March 9, 2006, to March 23, 2006. As with the previous daily average evaluations, there were no HH alarms. The maximum fire probability for the single average NN calculation for the sensors was 0.42. This is to be contrasted with the maximum fire probability of 0.49 when a daily average was computed.

However, the aforementioned temperature, vibration and ground movement effects, which occurred in the haulageway, resulted in a significant loss of data acceptable for application of the NN system. The primary interference effect in the north track area was dust. The loss of the NN system evaluation capability occurred both as a consequence of the sensor drift beyond its normal acceptable reporting range during the automated data collection and in the determination of sensor ambient background values. In both the haulageway and the north track area excessive 30-minute time periods were required for the sensors to reach an acceptable low level of statistical noisiness to be accepted by the NN system as ambient background values. This effect screened out considerable sensor data from NN evaluation, and made the NN system ineffective for application during those periods. Except for one period of time, the determination of the ambient background values was a minimal problem in the belt entry evaluation.

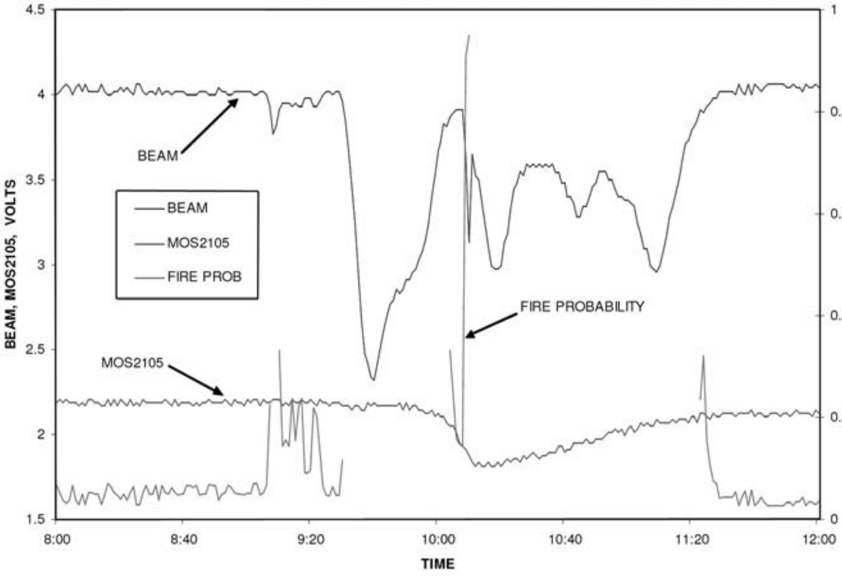

Figure 8 — Sensor responses and predicted fire probability in belt entry.

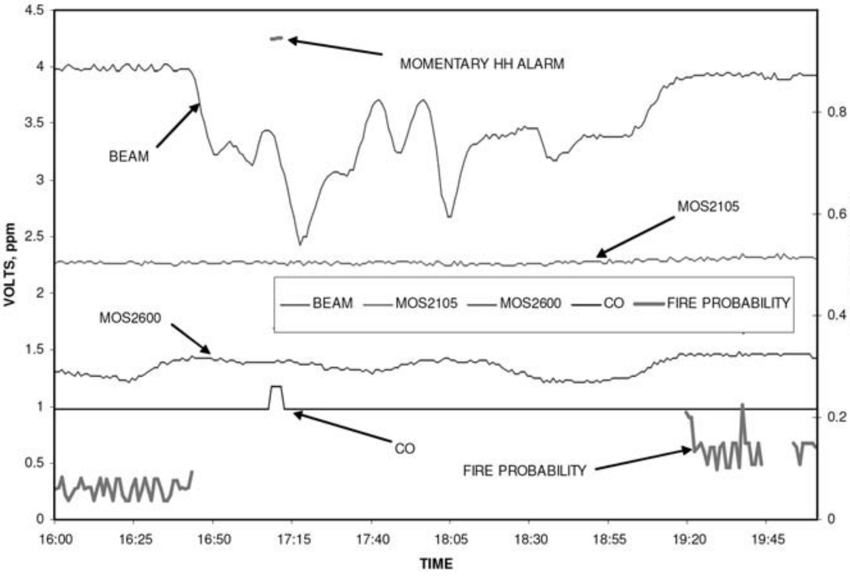

Figure 9 — Sensor responses and fire probability in the belt entry.

Conclusions and recommendations

As with any initial in-mine evaluation of new technology, several issues were brought to light. The in-mine, smart mine fire sensor evaluation identified significant problems with the Beam sensor due to temperature variations, mounting instability and mechanical vibrations in the haulageway area. In the track entry, only dust was a persistent problem. It should be noted, except for one event during an extended period of malfunction, that during the CO Alert or Alarm events, the Smart Mine Sensor System did not register any HH Alarms that would have indicated a false alarm by the system. Either the system was not processing data properly or if processing data properly, it did not indicate an alarm during any of the CO events.

In the belt entry with a less variable ambient temperature, the performance of the smart mine-fire sensors showed significant improvement and demonstrated an important method for mine fire detection with diesel emissions, dust and fire discrimination. The in-mine evaluations with iterative improvements in the NN software have provided guidance for future improvements in the hardware and software and demonstrated that the Smart Mine Fire Sensor System could possibly provide a viable method for preventing nuisance alarms, thereby, increasing mine safety. The multi-sensor mine fire detection system with a trained neural network program to provide fire source discrimination could be a viable approach for enhancing miner safety.

The following specific recommendations were derived from the in-mine evaluation for improvement in the next

Table 1 — Alert and alarm summary during evaluation.

Entry location	Correctly identified diesel event	Malfunction	Total events
Haulage	5	13	18
Belt	0	0	0
Track	27	2	29
Total	32	15	47

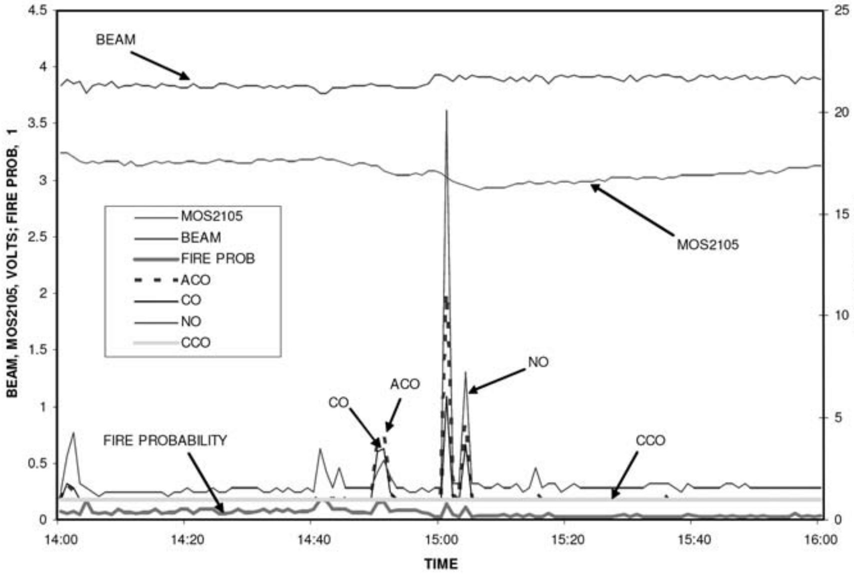

Figure 10 — Sensor responses and predicted fire probability.

generation Smart Mine Fire System:

- The connections within the electronics interfaces should be mechanically hardened to exclude vibration-induced mechanical loosening.
- A correlation needs to be developed between Beam sensor output and ambient air temperature. Temperature compensation should be introduced into the NN program. This would be useful for field evaluation. For long-term in-mine use, the device temperature could be stabilized with a heated enclosure. Such a hardware modification would directly correct the signal uncertainty.
- The MOS sensors should be temperature compensated.
- Site evaluation should be made specifically for mounting stability of the Beam optical units.
- A mechanical design that would reduce the deposition of dust on the lens of the Beam should be determined. The dust shield design could be simplified and exclude the need for the optical path to pass through the shield by configuring the Beam with the optical path perpendicular to the axis of the mine entry. In simple lab tests, the Beam has worked with optical path lengths as short as 1.8 m (6 ft), although the unit has never been subjected to smoke at these path lengths. Using the Beam with a perpendicular optical path in most mine entries would reduce the path length to less than two-third the minimum path length recommended by the manufacturer. This would affect the unit's sensitivity to smoke because the optical attenuation is a function of the product of the optical path length and the smoke concentration. As an alternative, a reflector could be mounted on one rib. The Beam transmitter and receiver would be located on the opposite rib. This would double the optical path, and thereby maintain the sensitivity of the Beam to small smoke concentrations. It would be possible to maintain the receiver and transmitter nearly perpendicular to the rib. An extended shroud around the transmitter and receiver would prevent airborne dust accumulations.
- The sensors should be packaged into a compact unit.
- The daily averaging of the sensor ambient values could be replaced by a biweekly, or longer, averaging if the sensors are used in a belt entry or mine area with relatively stable temperature conditions.
- The software should be modified to report the presence of significant airborne dust concentration, as a counterpoint to smoke particulates, in a belt entry through an interpretation of the sensors' outputs.

The first five recommendations above are in response to problems encountered in entries with significantly changing air temperature, mining equipment induced vibrations and spalling of the mine ribs.

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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