IN-MINE EVALUATION OF SMART MINE FIRE SENSOR

R. A. Franks, NIOSH, Pittsburgh, PA
G. F. Friel, NIOSH, Pittsburgh, PA
J. C. Edwards, NIOSH, Pittsburgh, PA
A. C. Smith, NIOSH, Pittsburgh, PA

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 haulage way, 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 not totally effective in the haulage way 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 haulage way evaluation. In general, the smart mine fire sensor provided nuisance emissions discrimination and was shown to be a viable new approach for mine atmospheric monitoring, 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 event in question, or a fire signature.

Previous NIOSH research identified four sensors that when used in conjunction with a neural-network-type computer program could discriminate a mine fire from nuisance diesel engine emissions, hydrogen gas emissions from battery charging stations, emissions from flame cutting and welding, and other contaminants (Edwards et al., 2001). These mine fire sensors were configured into a discriminating mine-fire sensor system by integrating them with neural network (NN) software. These sensors were a carbon monoxide (CO[1]) sensor, two metal oxide semiconductor sensors (mos), one which responded to hydrocarbons with a decreased sensor element resistance[2], and the other which responded to hydrocarbons with a decreased sensor element resistance and to nitric oxide (NO) from diesel engine emissions with an increased sensor element resistance[3], and an infrared open-path optical 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 Excel[5] data storage application was configured with a Visual Basic (VB) macro that implemented the NN algorithm to provide a real-time evaluation of fire probability.

The mine fire sensor system was evaluated in fire experiments in the presence of nuisance diesel emissions in the Safety Research Coal Mine (SRCM) at the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Research Laboratory (PRL) (1, 2). Flame cutting and welding experiments were also conducted at that time to evaluate the sensor system's response to these mining activities (3). In addition, the smart fire sensor system was evaluated in an above-ground battery powered mine locomotive charging building at PRL (4), and at a battery-powered equipment charging station at the mine of Foundation Coal affiliate Emerald Coal Resources, LP in Greene County, PA (5). The system was then installed at the mine of Foundation Coal affiliate Cumberland Coal Resources, LP in Greene County, PA 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 evaluation and makes recommendations as to how the mine fire smart sensor system can be enhanced for optimum performance.

The Neural Network (Calibration)

To develop the smart sensor capability, the NN was subjected to fire experiments in the SRCM at the Pittsburgh Research Lab 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. The NN was also subjected to flame cutting and welding experiments in the presence of battery-powered mine-locomotive charging stations both at PRL and at the Emerald Mine in Greene County, PA. The NN algorithm then classified three outputs into probabilities that each outcome would occur. The

[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

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

Smart Mine Fire Sensor System Installation At Cumberland Mine

The system was installed at the Cumberland Mine in Greene County, PA to determine the capability of the neural network for discriminating against false alarms and to evaluate the component durability and reliability in an operating underground coal mine environment. The system operated from September 17th, 2004 until June 29th, 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 rows of samples) for statistical noisiness and, if acceptably quiet, using the group to calculate the group's mean and standard deviation (SD). 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 neural network algorithm for the smart fire sensor system, two functions of the data from four of the sensors used in the system together with the inputs from three of the four sensors used in the smart fire sensor system were used as the five inputs into a trained, two-hidden-layer perceptron neural network (NN). Twenty process elements (PE's) were in the first hidden layer and ten PE's were in the second hidden layer. The NN was trained over the default number of 1000 iterations or epochs of the training set consisting of 7 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 criterion of convergence of the training of the NN 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 or exemplar was processed. The momentum constant used was the default value of 0.7. The weights were only changed after each epoch and those 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. The output possibilities were clean air, only diesel engine exhaust in air, and combustion products with or without diesel engine exhaust in air.

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.

Figure 1 shows the MOS sensor unit (the unit on the right end) and the CO sensor unit (the unit on the left end) installation in the haulage way during the evaluation. The MOS sensor unit contains the two MOS sensors. Also shown in the figure are a Conspec Diesel Discriminator[6] (left center unit) and a Becon Smoke Detector[7] (right center unit) used on the NIOSH mine monitoring system but not part of the Smart Sensor set. The Beam smoke sensor transmitter unit is not shown, but is located on the rib near the MOS sensor unit. The Beam receiver is located on the opposite rib 30 feet down the haulage way from the transmitter unit. Signal transmission and power lines were connected between the sensors and a Conspec Senturion 500[8] mine monitoring system at a surface station via a Conspec mine trunk cable. Linear airflow in the haulage way was usually about 350 feet per minute. There were significant temperature variations in the haulage way, ranging from 20 to 85 ºF, due to the proximity of the sensors' location to the intake air shaft. The evaluation of the system in the haulage way lasted for fourteen months.

Figure 1. The smart mine fire sensors in the main haulage way, from left to right: Conspec CO Monitor, Conspec Diesel Discriminator, Becon Smoke Detector, and NIOSH MOS unit.

The equipment was then moved into the belt line entry, which was in an adjacent entry to the haulage way. 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 230 fpm. The location was two miles from the intake, resulting in a fairly constant temperature of approximately sixty degrees Fahrenheit. The ambient temperature was elevated due to the additional heat from the beltline equipment.

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 haulage way. 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 haulage way. The entry had approximately the same linear air velocity as in the haulage way, 350 feet per minute. The entry was about the same distance from the intake air as the haulage way, consequently having the same relative air temperature variations.

[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

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 haulage way 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 haulage way, 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 haulage way. 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 figure 2.

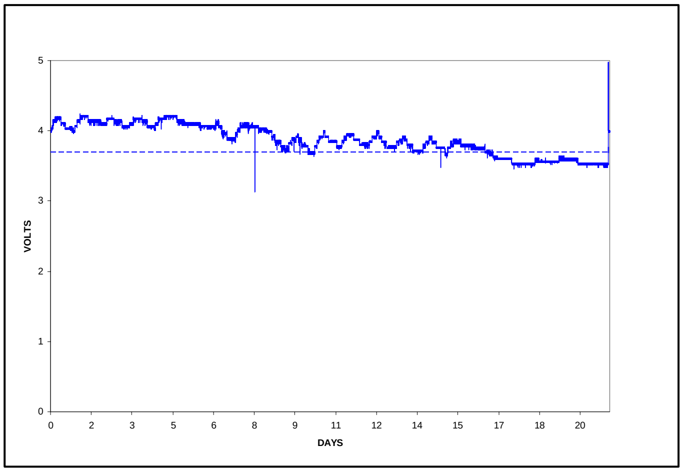

Figure 2. Beam sensor response in the main haulage way.

Temperature Effects

Diurnal temperature effects on the Beam and MOS2105 sensors were observed in the haulage way. This temperature change was due to the proximity of the haulage way 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 haulage way is shown in figure 3 for a seven-day period. The maximum value occurred about 6:00 PM and the minimum value about 7:00 AM on a recurring daily basis. These times corresponded to maximum and minimum outside air temperatures.

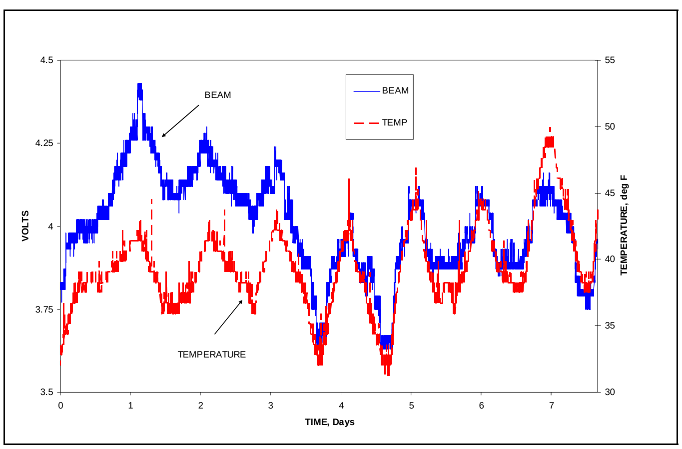

Figure 3. Beam and Temperature responses.

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.

An evaluation of the Beam sensor's output temperature dependence under more stable temperature conditions in the Emerald Mine charger entry is shown in figure 4. 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 40 fpm.

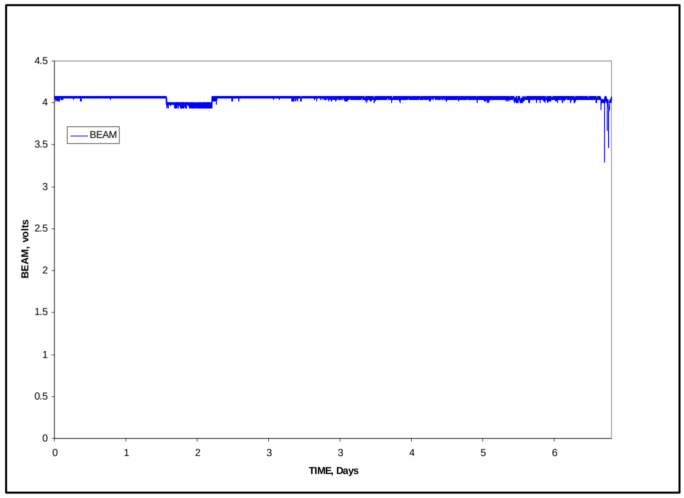

Figure 4. Beam response in Emerald Mine.

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 haulage way data set. For a 20 day period, the dependence of the measured Beam output signal upon temperature resulted in a fit of the Beam signal to a power of the air temperature measurement.

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

where T is the measured temperature in ºF, and PREDICTED_BEAM is the predicted Beam signal in volts. The correlation coefficient is 0.62, which defines a moderate correlation. Figure 5 indicates that the period of the measured Beam oscillations is well represented by the PREDICTED_BEAM value, but the amplitudes are less well represented.

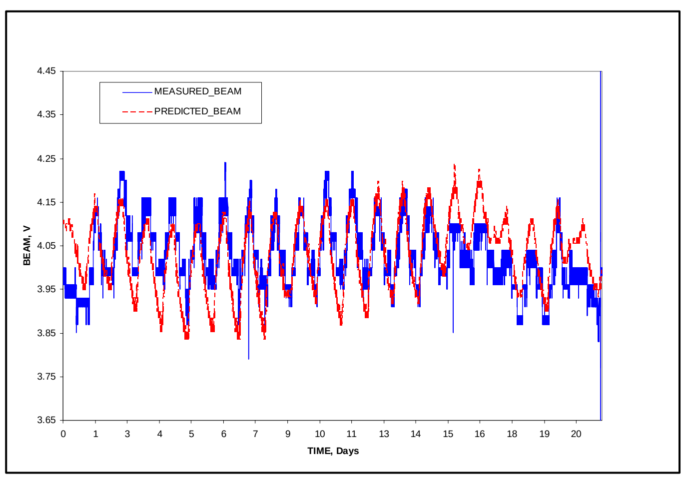

Figure 5. Measured and predicted Beam signals, based on ambient temperature.

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 be applied to the data normalization process.

Dust Problems

Since the Beam smoke detector is an optical smoke sensor, 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 entry mid-height upwind from the Beam sensor unit. The Beam sensor responses in the SRCM evaluations are shown in figure 6. The airflow was maintained at 250 fpm during these evaluations.

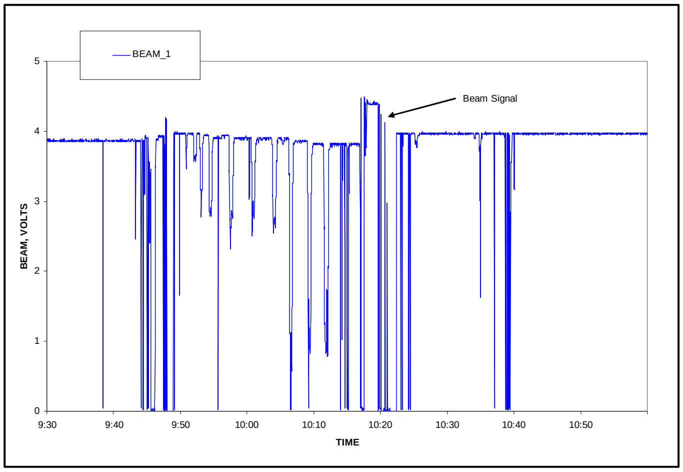

Figure 6. The Beam affected by Rock Dust in the SRCM.

It can be seen in figure 6 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 which 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 haulage way 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 haulage way location and the north track location was that the Beam was mounted higher up on the rib in the haulage way and any man-trips entering or leaving the bottom never idled there for more than a minute or so before moving along the haulage way. These differences provided for a lighter rock-dust laden buildup on the transmitter and receiver units of the Beam in the main haulage way than in the north track entry. However, even with a lighter dust build-up, the Beam unit in the haulage way 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 haulage way 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 haulage way, 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 figure 7. 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 haulage way.

It should be noted that figure 7 shows an isolated fire probability of 0.8 that occurred on day 6. However, during that time only a small decrease in the Beam output voltage occurred, so the NN does not indicate an alarm event.

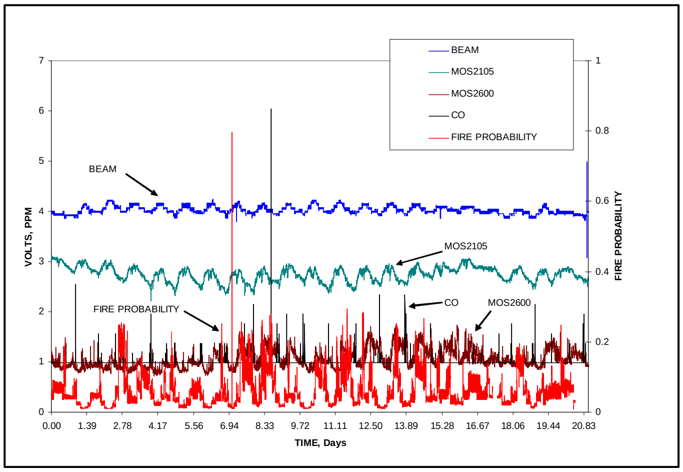

Figure 7. Sensor responses and predicted fire probability in the haulage way.

Ground Movement Effects

Spalling of the haulage way rib to which the Beam's transmitter unit was attached also caused alignment problems with the Beam detector. Figure 8 shows the Beam transmitter unit mounted on the rib in the haulage way. In a simple lab experiment, with the Beam set up along an approximate 6 foot 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 30 foot 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 haulage way rib eventually collapsed at some point in time after the Beam unit had been removed from the haulage way.

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.

Figure 8. The Beam transmitter mounted on the rib in the haulage way.

To be acceptable data for a daily average calculation: (1) the Beam sensor output voltage was required to be greater than 3.7 volts and less than 4.3 volts; (2) the CO sensor output deviation from its mean had to be less than 1.5 times its standard deviation; and (3) 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 the data was 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 requires 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 depicted in a photograph of the flame cutting experiment (figure 10). The sensor measurements are shown in figure 9. No HH alarms resulted. Figure 9 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 earlier, 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.

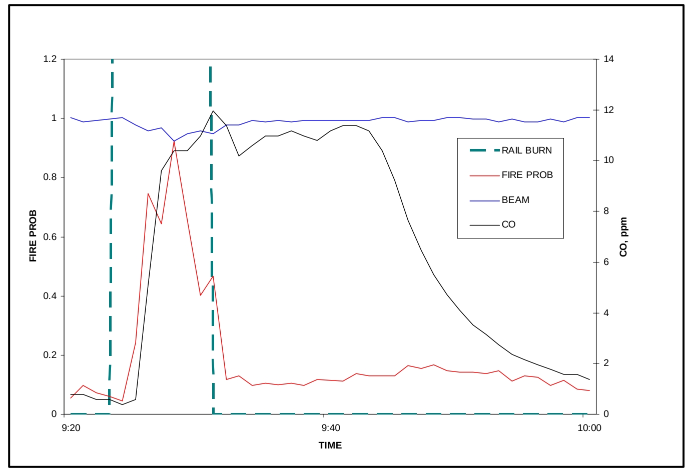

Figure 9. CO and Beam responses, and predicted fire probability.

Figure 10. Flame cutting of a piece of rail.

Figure 11 shows the identification of a typical nuisance emission in the haulage way 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 which produced insignificant smoke obscuration compared to a fire.

Another example is shown in figure 12. In this case, given the 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 air flow. The broken probability curve in figure 12 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, textual error statements are produced by the mine monitoring system. These textual errors are not processed by the algorithm.

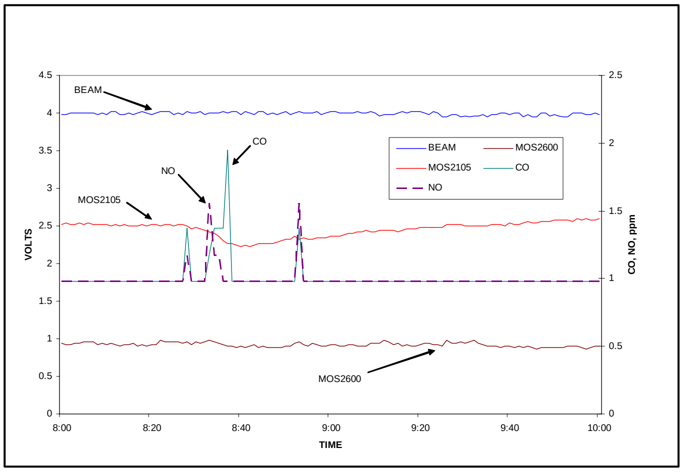

Figure 11. Sensor responses in the haulage way at Cumberland.

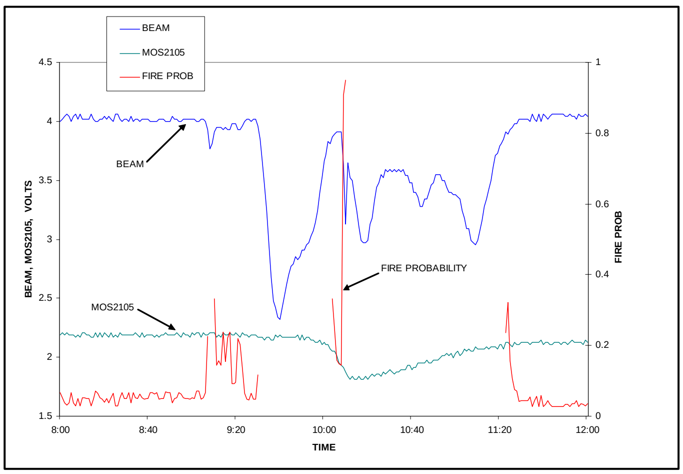

Figure 12. Sensor responses and predicted fire probability in belt entry.

Another event of the type depicted in figure 12 occurred in the belt entry later in the evaluation. Figure 13 shows the sensors' outputs. This resulted in one HH alarm. It should be noted that breaks in the red Fire Probability curve in figure 13 indicates that the fire probability was indeterminate at that point in time as it was just prior to and just after the momentary HH alarm. Figure 13 also shows a small increase in the CO at the time of the HH alarm.

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 figure 14. 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.

During the 21-month evaluation period of the Smart Mine Fire Sensor system in the Cumberland mine there were forty-seven CO alert or alarm events which were unrelated to a fire. The most likely CO sources were operating diesel equipment. Eighteen of these events occurred in the haulage way, and twenty-nine 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 haulage way as non-fire events. The other thirteen events could not be identified due to sensor system malfunction. In the north track area, twenty-seven 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.

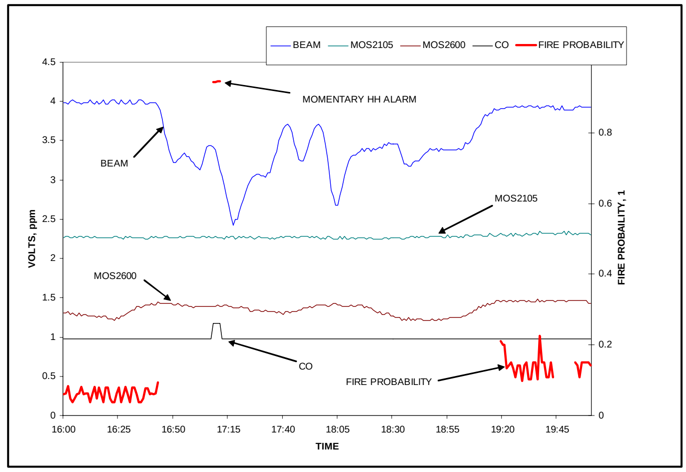

Figure 13. Sensor responses and fire probability in the belt entry.

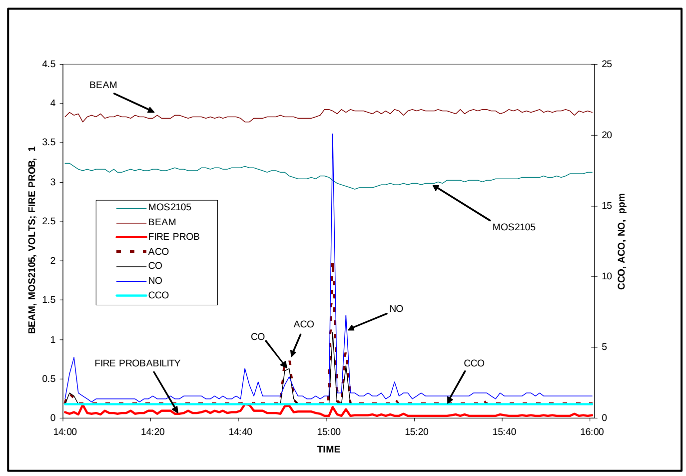

Figure 14. Sensor responses and predicted fire probability.

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 in the haulage way and track entry, and mounting instability and mechanical vibrations in the haulage way area. Only in the track entry was dust a persistent problem.

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 provides 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 is a viable approach for enhancing miner safety.

The following specific recommendations were derived from the in-mine evaluation for improvement in the next generation Smart Mine Fire System:

1. The connections within the electronics interfaces should be mechanically hardened to exclude vibration-induced mechanical loosening.
2. A correlation needs to be developed between Beam sensor output and ambient air temperature. Temperature compensation should be introduced into the NN program.
3. The MOS sensors should be temperature compensated.
4. Site evaluation should be made specifically for mounting stability of the Beam optical units.
5. A mechanical design should be determined which would reduce the deposition of dust on the lens of the Beam. 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 6 feet 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 since 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.
6. The sensors should be packaged into a compact unit.
7. 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.
8. 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.

Recommendations 1 – 5 are in response to problems encountered in entries with significantly changing air temperature, mining equipment induced vibrations, and spalling mine ribs.

Acknowledgements

The authors wish to acknowledge the Foundation Coal Corporation and its affiliates for providing access to their mine and personnel for assistance without which the sensor evaluations could not have been conducted. Particular thanks are extended to John Gallick, Robert Bohach, Joseph Culp, and Grant Colbert, who facilitated the project and the miners who assisted us with the in-mine experimental setup. Additional support was provided by Conspec Controls, Inc. with the loan of a Conspec Senturion 500 mine monitoring system for data acquisition.

References

1. Edwards, J.C., Franks, R.A., Friel, G.F., Lazzara, C.P., and Opferman, J.J. "Multiple Type Discriminating Mine Fire Sensors" SME Transactions, vol. 314, pp. 166-171, 2003.

2. Edwards, J.C., Franks, R.A., Friel, G.F., Lazzara, C.P., and Opferman, J.J. "Real-Time Neural Network Application to Mine Fires --- Nuisance Emissions Discrimination", proceedings 10th US / North American Mine Ventilation Symposium, (eds. R. Ganguli and S. Bandopadhyay, University of Alaska, Fairbanks, A.A. Balkema publishers, New York) Anchorage, AK, 16-19 May, 2004, pp. 425- 431.

3. Edwards, J.C., Friel, G.F., Franks, R.A., Lazzara, C.P. and Opferman, J.J., Mine Fire Source Discrimination Using Fire Sensors and Neural Network Analysis, Combustion Fundamentals and Applications; 2000 Technical Meeting of the Central States Section of the Combustion Institute; Proc., pp. 207-211, April 17-18, 2000, Indianapolis, IN.

4. Edwards, J.C., Franks, R.A., Friel, G.F., Lazzara, C.P. and Opferman J.J., Discriminatory mine fire source detection. In S. Wasilewski (ed.), Seventh International Mine Ventilation Congress; Proc., Cracow, Poland, Ch. 91, pp. 649-655, June 17-22, 2001, Research and Development Center EMAG.

5. Edwards, J.C., Franks, R.A., Friel, G.F., Lazzara, C.P., and Opferman, J.J., In-Mine Evaluation of Discriminating Mine Fire Sensors. In E. DeSouza(ed.), North American / 9th U.S. Mine Ventilation Symposium; Proc., Queen's University, Kingston, Ontario, Canada, A.A. Balkema publisher, Lisse, pp. 527-532, June 8-12, 2002.