

## DISCRIMINATORY MINE FIRE SOURCE DETECTION

**J.C. Edwards**  
National Institute for Occupational Safety  
and Health P.O. Box 18070 Pittsburgh,  
PA 15236 (USA)

**R.A. Franks.**  
**G.F. Friel**  
**C.P. Lazzara**  
**J.J. Opferman**  
National Institute for Occupational Safety  
and Health P.O. Box 18070 Pittsburgh,  
PA 15236 (USA)

### ABSTRACT

Product-of-combustion sensors were used to discriminate mine fire sources of coal, diesel fuel, electrical cable insulation, conveyor belt, and nuisance emissions from acetylene torch cutting operations in experiments conducted in the National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Laboratory (PRL) Safety Research Coal Mine (SRCM). The sensors consisted of CO, ionization and optical smoke, and metal oxide semiconductor (MOS) sensors. Metal oxide semiconductor and smoke sensors demonstrated an earlier fire detection capability than a CO sensor. This capability was of particular significance for a smoldering conveyor-belt fire in which the optical visibility was reduced to 1.52 m with an increase in CO of less than 2 ppm at a distance of 148 m from the fire. An application of a neural-network program to the sensor responses from each type of fire source resulted in correct classifications of coal, diesel-fuel, cable insulation, belt, and metal-cutting combustion with a mean of 96% of the in-mine test data correctly classified. In a battery charging building, a fire sensor configuration consisting of an ionization type smoke sensor and a MOS, NO<sub>x</sub>-sensitive sensor was demonstrated to be capable of discriminating a coal fire from diesel equipment when H<sub>2</sub> from a battery charging operation saturated the CO chemical sensor cell.

### KEYWORDS

Mining, fire detection, mine fires, fire sensors

### INTRODUCTION

The early and reliable detection of underground coal mine fires enhances worker safety. Fire detection is aided by the in-mine ventilation which transports the products-of-combustion (POC) from the fire source to fire sensors, and it is impeded by the diluting effects of the ventilation which reduces the measurable signal. Early mine fire detection experiments in both normally ventilated and near-zero-airflow mine entries have been previously investigated [Edwards et al., 1999 and Edwards *et. al.*, 1997]. The results of that research showed the improved performance of ionization and optical smoke fire sensors over CO sensors. The next advancement beyond early detection, in addition to the designation of the fire location [Edwards 1990], is the determination of the material burning, the mode of combustion, and the extent of fire growth. This information can be applied to the selection of appropriate actions to be taken to initiate the evacuation and rescue of miners, and to extinguish a mine fire.

The selection of a fire sensor is significantly influenced by the thermal event which is to be detected. A persistent problem for early mine fire detection is the detection of conveyor belt frictional heating associated with belt slippage on drive pulleys which can produce copious amounts of smoke prior to emissions of detectable levels of CO associated with the transition from smoldering to flaming combustion.

In addition to the comparative advantage of some fire sensors with respect to early fire detection, the presence of nuisance alarms further limits the selection of mine fire sensors. One recurring nuisance alarm in mining operations is the cross-interference of a CO electrochemical cell to H<sub>2</sub> at a battery charging station. This results in a false CO reading which has two undesirable consequences: (1) the nuisance alarm interferes with the mining operation; or (2) the personnel learn to ignore alarms. State-of-the-art CO sensors which are insensitive to H<sub>2</sub> and hydrocarbons are not available in the low concentration range required for early detection. One solution is to monitor an alternative fire signature

such as smoke. An additional consideration is the POC from diesel equipment which could operate in the vicinity of the battery charging station. The particulates in the diesel exhaust can be interpreted by the smoke sensor to be a fire signature. A method to avoid this interpretation is to use a sensor which is selectively responsive to  $\text{NO}_x$  products from diesel emissions in combination with a smoke sensor which is responsive to POC. The  $\text{NO}_x$  responsive sensor should also discriminate acetylene cutting and welding emissions from fire POC.

In addition to electrochemical CO and smoke fire sensors, there are MOS sensors which respond to oxidizable POC gases which include volatile organic compounds (VOCs). MOS sensors operate on the principle that oxygen ( $\text{O}_2$ ) adsorbed on a semiconductor surface increases the electrical resistance across the surface. The oxidation of POC gases removes  $\text{O}_2$  from the surface and reduces the electrical resistance across the surface. The measurable change in surface resistance is a measure of the POC concentration. These sensors are very responsive to, but not very selective of, the target gas. They are also temperature and humidity dependent. However, it is their extreme sensitivity to various hydrocarbons that increases their potential for use as mine fire sensors.

The types of fire products and their rate of change can indicate the combustion material, mode, and growth rate. One method which can be deployed to make these determinations is the use of multiple fire sensors to differentiate the POC. The analysis of fire products with a neural network program has been reported elsewhere [Ishii *et al.*, 1994 and Brinn and Bott, 1994]. Ishii [Ishii *et al.*, 1994] developed a neural network to characterize a fire based upon the rate of heat and smoke production, and temperature increase. Brinn [Brinn and Bott, 1994] developed a neural network to discriminate shot firing from a coal fire. The selection of a base set of multiple sensors is a key decision for a neural network program to successfully discriminate between hazardous mine-fire combustion and normal mining POC that may result from sources such as diesel engines and cutting and welding procedures. The sensors used in this research were both mining and commercially available fire sensors. This research addresses the use of multiple fire sensors and neural analysis as one method to accomplish the objective of mine fire source identification, and discrimination from nuisance events.

## EXPERIMENTAL METHOD

### In-Mine Fire Experiments

The plan view of the SRCM section, in which the mine fire experiments were conducted to obtain data for the neural analysis program, is shown in Figure 1. 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. The brattice at Room 10 and B-Butt was adjusted to regulate the airflow into Room 10 and F-Butt. Air quantity measurements were made near the fire zone and near the end of F-Butt, 7.6 m downwind from sensor station S2. For the experiments conducted, the air quantity at the fire zone was  $3.49 \text{ m}^3/\text{s}$  and at the end of F-Butt was  $5.17 \text{ m}^3/\text{s}$ . The increase in air quantity downwind of the fire zone was caused by air leakage into F-Butt around brattices, shown along the ribs in Figure 1, blocking crosscuts connecting F-Butt and parallel airways.

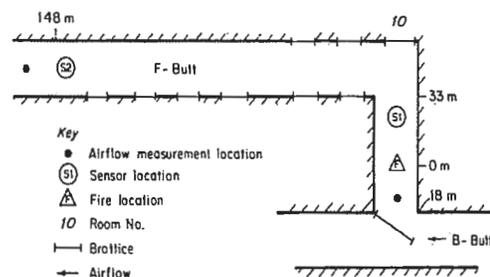


Figure 1. Plan View of SRCM Section

Table 1. Fire sensor types used

Sensor	Type
SA	Optical Smoke
SB	Ionization Smoke
CO	Electrochemical Carbon Monoxide
FA, FB, FC	Metal Oxide Semiconductor
HCl	Hydrogen Chloride

The fire sensors used for the experiments are listed in Table 1. Sensor SA is an optical path sensor which operates at an infrared wavelength with a transmitter-receiver separation path of 9.65 m. Sensors SB, CO, FA, FB, FC, and HCl are point-type sensors. CO and HCl are Mine Safety and Health Administration evaluated sensors. Sensors SA and SB are commercially available fire sensors. The MOS sensors FA and FB are similar in their responses to various POC gases, and sensor FC is responsive to  $\text{NO}_x$  in addition to POC. The surface element resistance of FC has a bimodal response which increases when exposed to  $\text{NO}_x$ , and decreases when exposed to POC. These sensors were located at station S2, 148 m downwind from the fire, as was an optical-path light obscuration monitor which operates in the

visible wavelength and is used to measure the optical density and visibility of the smoke. A CO sensor and an ionization smoke sensor were also located at station S1, 18 m downwind from the fire. Table 2 lists the experiments, and the relative alarm times for those sensors used in all of the 12 experiments at S2, according to the combustion fuel source. BELT1, BELT2, and BELT3 refer to the conveyor belt types of styrene-butadiene rubber, neoprene, and polyvinyl chloride. For the belt experiment nos. 4, and 10-12 an HCl sensor was located at S1 and S2. The heating of the coal, cable insulation, and conveyor belt was conducted with electrical heaters to which power was gradually increased such that the smoldering combustion mode passed through a slow growth phase with the emanation of POC prior to flaming combustion in order to assess the early alarm sensitivity of the fire sensors in response to a slowly developing mine-fire event. Lumped coal with an average diameter less than 5 cm and pulverized Pittsburgh seam coal were heated in a 0.61 m square pan with 5 embedded electrical strip heaters for experiment nos. 1, 5, and 6. The coal depth was about 8 cm, and about 13 kg of lumped coal and 0.45 kg pulverized coal was used. In experiment nos. 3 and 9, electrical cable insulation was heated with a 0.46 m length of insulation attached to each of the five strip heaters. For the conveyor belt heating experiments, nos. 4 and 10-12, a 0.46 m by 0.53 m belt section was clamped to a steel plate heated from below by electrical strip heaters. The heating time prior to flaming combustion for the solid fuels varied between 42 and 109 min. The diesel fuel fires of experiment nos. 2, 7, and 8 were conducted with 1.0, 0.7, and 1.7 liters of diesel fuel in a 0.5 m square pan with the addition of about 0.2 liter of heptane to provide rapid ignition.

Table 2. Fire sensor relative alarm times at S2

Exp.	Fuel	FA, s	FB, s	CO, s	SA, s	SB, s	T <sub>f</sub> , s
1	Coal	80	0	3521	556	736	1579
2	Diesel	34	0	105	6	34	na <sub>1</sub> <sup>1</sup>
3	Cable	219	59	2614	0	149	2388
4	Belt1	178	98	1486	38	0	1307
5	Coal	218	204	1590	0	242	881
6	Coal	174	0	3690	1736	2166	3242
7	Diesel	na <sub>3</sub> <sup>3</sup>	55	83	0	29	na <sub>1</sub> <sup>1</sup>
8	Diesel	0	7	196	42	34	na <sub>1</sub> <sup>1</sup>
9	Cable	149	109	2746	0	191	2518
10	Belt1	952	892	2709	0	294	2572
11	Belt2	14	0	2853	156	92	na <sub>2</sub> <sup>2</sup>
12	Belt3	910	758	4735	406	0	4627

<sup>1</sup>Symbol na<sub>1</sub> - flame at initial heating time.

<sup>2</sup>Symbol na<sub>2</sub> - no flaming combustion.

<sup>3</sup>Symbol na<sub>3</sub> - alarm not achieved due to heptane vapors.  
na=not applicable

For evaluation of the sensors' response to diesel exhaust emissions, and metal cutting nuisance events, additional in-mine experiments which did not include fire sources were conducted. These experiments consisted of cutting a steel rail with an acetylene torch 23 m upwind from sensor station S2, as well as operating a diesel scoop 53 m upwind of S2. For these particular experiments, the response of the NO<sub>x</sub> sensitive sensor FC was compared with the CO sensor and smoke sensor SB.

#### Battery Charging Nuisance Alarms

The discriminatory capability of the multiple mine fire sensors with respect to a battery charging operation was evaluated in an unventilated building approximately 6.1 m square and 4.6 m in height. While a battery operated locomotive was being charged, the air in the building above the locomotive was monitored with a CO sensor and POC sensors, FC and SB. After the establishment of an equilibrium concentration of H<sub>2</sub> in the building, which produced cross-interference with the CO sensor to register a false CO reading, a small smoldering coal fire was initiated to determine the response of the POC sensors. This was followed by the introduction of diesel engine exhaust into the building for the purpose of evaluating multiple POC sensors for discrimination of the three events.

#### NEURAL NETWORK ANALYSIS

A neural network analysis was applied to the classification of fire sensor responses to differentiate between possible fire sources. In this neural network program, the time dependent fire sensor data were compared to the nonlinear approximations generated by the neural network until adequate approximations for correct classifications were obtained through corrective iterations. The input layer of neurons contained the experimental sensor data. The output layer of neurons contained the fire source classifications generated by the neural network. Between the input and output layers were two hidden layers of neurons or process elements (PEs). The inputs to the hidden layers of neurons were multiplied by weights, summed, and processed through a bounded, nonlinear activation function. In the training phase of the neural network, the output classifications were subtracted from the correct classifications and the differences, or errors, were used by a back propagation method, which was a modification of the gradient-descent search technique, to adjust the values of the weights until a sum of the errors was adequately reduced over a reasonable time interval. For the sensor data analysis considered here, the neural network software package entitled NeuroSolutions for Excel<sup>1</sup> from NeuroDimension, Inc. was used.

<sup>1</sup> Reference to a specific product does not imply endorsement by NIOSH

## RESULTS AND DISCUSSION

In-Mine Fire Experiments

Table 2 lists the in-mine fire experiments conducted with reference to fuel type and the relative alarm times of the fire sensors at station S2 with respect to the sensor which alarmed first (indicated by 0 s). The estimated arrival time of the POC at station S2 from the flaming-stage, solid fuels, relative to the first sensor alarm time, is listed as  $T_f$  and is based upon the measured average ventilation flow rate and the observed onset of flaming combustion. The alarm time for CO is based upon a 5-ppm rise above the ambient concentration. For the smoke and MOS sensors, the alarm time is defined to be a ten-standard-deviation change from the sensor ambient signal. The diesel fuel experiments required the calculation of a background value for sensors FA and FB which excluded vapors from heptane used to enhance ignition of the fuel. In the case of experiment no. 7, the background concentration was too high to define an alarm for FA. Table 2 shows that the smoke and MOS fire sensors always alarmed before the solid fuel flaming-stage POC reached the sensor station at time  $T_f$ , which occurred before the CO sensor alarm time. As was the case for the solid fuel fires, the smoke and MOS fire sensors alarmed prior to the CO sensor for the diesel fuel fires.

Measurements were made of HCl at S1 for belt experiment nos. 4 and 10-12. The HCl sensor reached 5 ppm above ambient after the CO sensor for each experiment. In BELT1 fires of experiment nos. 4 and 10, the HCl reached 5 ppm at time lapses of 5.8 and 1.6 min after the CO, whereas for BELT3 in experiment no. 12, the HCl sensor lagged the CO sensor by 48.8 min. For experiment no. 11 the HCl did not reach 5ppm. The maximum HCl concentration was achieved shortly after the material reached flaming combustion, except for experiment no. 11 which did not transition to flaming combustion. At station S2 the HCl was too dilute to signal a 5ppm alarm value for each of the four experiments. Although HCl is a discriminating signal for belts, it has no advantage as an early warning fire signature when compared to other POC sensors.

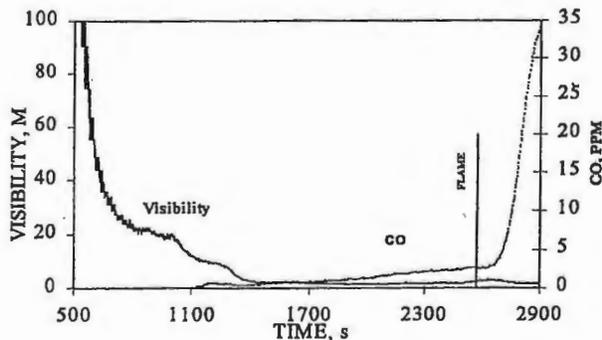


Figure 2. Visibility and CO Concentration at S2 for belt experiment no. 10

A comparison of the visibilities measured with the optical obscuration monitor for the slowly heated solid fuels, which is calculated from the optical density [Rasbash 1975] measured by the light obscuration monitor at S2, 15 min prior to the CO sensor reaching 5 ppm, showed that the POC from BELT1 produced a visibility reduction to 15.2 m and 1.8 m for experiment nos. 4 and 10. The other solid fuels produced smoke visibility obscuration no less than 56.7 m fifteen min prior to the CO sensor reaching 5 ppm, except for coal experiment no. 5, which produced a visibility restriction of 25.6 m. It can be determined from figure 2 for belt experiment No. 10 that the measured visibility decreased to 1.52 m while the CO concentration increased to 1.1 ppm above ambient concentration 1,900 s after the first alarm by SA and, based upon table 2 data, 948 s after sensor FA, the last of the non-CO fire-sensor alarms. The times shown in figures 2 and 3 are from the first alarm time. Figure 3 shows the early response to the belt POC at S2 of sensors SB and FC compared with the CO sensor. The values of FC in figure 3 were reduced by 4 volts for clarity. The flaming mode POC did not reach the sensor station until 2,572 s after the first sensor alarmed. This flaming event is coincidental with the significant increase in measurable CO seen in figures 2 and 3. The in-mine hazard of severely reduced visibility without a CO alarm as shown for BELT1, but with an alarm for each smoke sensor, reinforces the importance of fire smoke sensors.

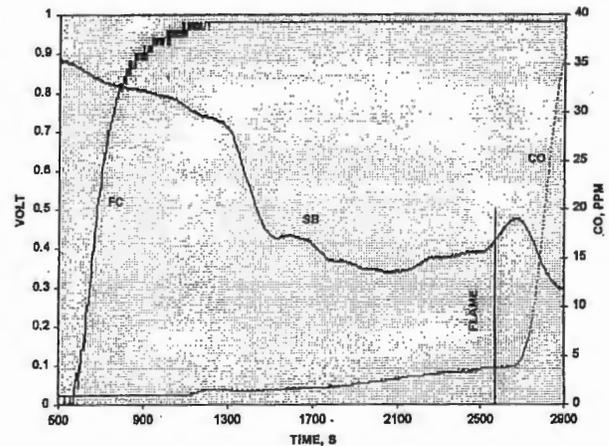


Figure 3. Response of sensors SB and FC at S2 for belt experiment no. 10

A comparison of the ionization smoke sensor SB alarm time and the CO alarm time at S1, 18 m downwind from the fire, showed a marked contrast for the conveyor belt fire experiments which involved BELT1 and BELT3 compared with BELT2. SB alarmed 25 and 30 min before CO for experiment nos. 4 and 10 with BELT1, and for BELT3 the lead time was 33 min. BELT2, which did not transition to flaming combustion, had a smoke sensor SB lead time of 4 min relative to

CO. These comparisons are all made within the time period prior to flaming combustion.

Figures 4 and 5 show the response of sensors SB, FC, and CO to diesel scoop exhaust and acetylene torch cutting of a steel rail. Smoke sensor SB and the CO sensor respond in a manner similar to their response to belt fire combustion as shown in Figure 3. Sensor FC responds with a decreasing voltage to the NO<sub>x</sub> products of the diesel engine exhaust and the acetylene cutting, which is opposite to the response to the belt POC in Figure 3. Sensor FC initially responded with a slight increase in signal for about 45 s to the diesel scoop exhaust POC while sensor SB's signal decreased. This could initially be interpreted as a fire signal. This response is specific to starting a diesel engine, and not a diesel engine passing a sensor station. This demonstrates that sensor FC is applicable to discrimination of nuisance alarms from NO<sub>x</sub> producing events in conjunction with other mine fire sensors.

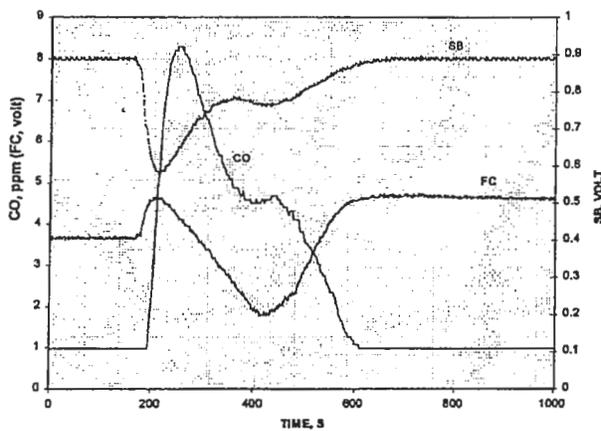


Figure 4. Sensor SB, FC, and CO response to diesel scoop exhaust

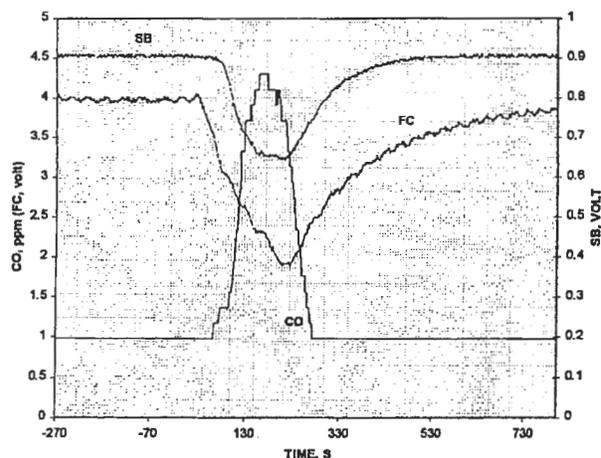


Figure 5. Sensor SB, FC, and CO response to acetylene torch cutting of steel rail

Battery Charging and Coal Fire Discrimination

Smoke sensor SB and a NO<sub>x</sub> sensor, FC, were used with a chemical cell CO sensor to discriminate a battery charging operation from a smoldering coal fire and diesel engine exhaust. During the battery charging operation, the CO sensor indicated 50 ppm, which is the top scale of the calibrated sensor. Air samples analyzed by gas chromatography showed an average CO concentration of 3 ppm, and an average H<sub>2</sub> concentration of 560 ppm. Figure 6 shows the response of sensors SB and FC to the heating of pulverized coal in a 15 cm diameter container placed on a hot plate and to diesel engine emissions in a battery charging background. Sensor FC responded at 9:05 to the H<sub>2</sub> from the battery charging operation which was initiated at 9:00. Following the initial heating of the coal at 10:11, sensor SB decreased at a constant rate and sensor FC moved into near saturation at 5 volts in response to POC from the smoldering coal. Introduction of the diesel exhaust into the battery charging building at 11:23 resulted in a rapid decrease in SB's signal and a reversal in FC's signal. Without sensor FC, the response of SB alone would lead to the erroneous conclusion that the smoldering coal fire had transitioned to a flaming combustion stage in this particular scenario. This result suggests that multiple sensors consisting of a smoke sensor and a NO<sub>x</sub> sensor can be used to discriminate a coal fire from a battery charging operation and from diesel engine exhaust.

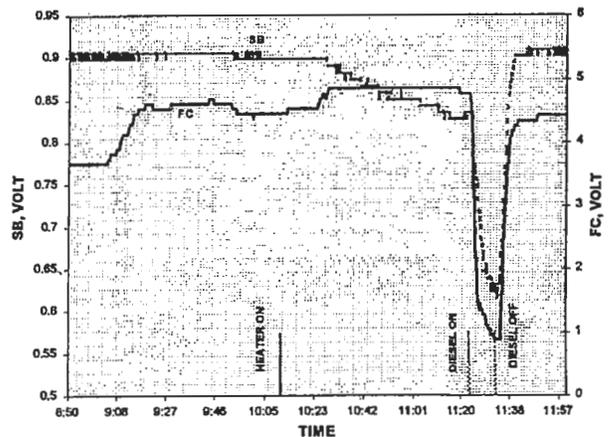


Figure 6. Response of sensors SB and FC to battery charging, coal POC, and diesel engine emissions

Neural Analysis

The neural network application was restricted to the in-mine experiments listed in Table 2 and an acetylene cutting experiment. The complete set of sensors for which measurements were available for the fire experiments listed in Table 2 were CO, FA, FB, SA, and SB. In order to use the neural network program, the data for each experiment were prepared in files with the fire sensor signals normalized to their ambient background

signals. The responses of FA and FB were nearly identical. The training of the neural network was accomplished with the five sets of sensor data from coal, diesel-fuel, electrical-cable insulation, and conveyor-belt fires, which are the fires of experiment nos. 1 to 4 in Table 2, and an acetylene-torch, metal-cutting experiment. Seven data inputs were processed from the sensor data to classify the five fire types. The inputs, which include time and multiplicative combinations of the data from four of the sensors but excluding sensor SB, were determined by trial-and-error to be the most suitable inputs for accurate classifications. The size of the training data sets ranged from 85 to 991 exemplars, or time samples, of the four sensor inputs and two functions of the sensor inputs with the total size of the training set being 2,988 exemplars. The two functions of the sensor inputs were the product of CO and the average of FA and FB, and the product of CO and SA. This was determined by trial and error. Time zero at the beginning of each data set corresponded to the first sensor alarm for each type of fire. Sampling by the sensors occurred at two-second intervals.

Various neural network programs provided in the package by the vendor were applied to the data in attempts to successfully classify the fire types. A two-hidden-layered perceptron network with momentum-back propagation-of-error algorithm produced reproducible results. The first hidden layer consisted of twenty neurons, or process elements (PE), and the second hidden layer consisted of ten PEs. It was discovered that the testing results were reproducible even though the initial weights between the PEs were assigned randomly before each training calculation. The activation function used in the hidden layers was the hyperbolic tangent function with the output layer using a softmax classification function. One thousand epochs, or iterations, through the samples were performed with error correction after every epoch. The minimum squared error achieved after one thousand epochs was 0.0012.

For testing the neural network, seven data files were presented to the trained network. These files included experiment nos. 5 to 10 in Table 2 and one acetylene torch metal-cutting experiment. The number of testing exemplars in each file ranged from 121 to 1,854 with the total size of the testing set being 4,255 exemplars. Two coal and two diesel-fuel fires were included in the set of testing files. The percentage of exemplars predicted correctly in each of the seven testing data files is presented in Table 3.

Table 3. Percentages of testing files predicted correctly

Exp.	5, Coal	6, Coal	7, Diesel Fuel	8, Diesel Fuel	9, Cable Insulation	10, BELT1	Acetylene Torch Cutting
% Correct	100	86	90	99	94	100	100

The average correct classification of the fire sensor data for the seven tests in table 3 is 96%. The minimum value of 86% for a single experiment is not unreasonable. Evaluation of experiments 11 and 12 could not be made with the neural network program because experiments using materials similar to those of BELT2 and BELT3 were not available to include in the training set.

## CONCLUSIONS

The mine fire detection study has shown that the use of multiple fire sensors with a neural network program as part of an atmospheric mine monitoring system can lead to improved early mine fire detection and discrimination. Specific conclusions derived from the analysis of the experimental data are:

1. It was determined that smoke and MOS fire sensors, with an alarm value set to be a ten standard deviation change in the signal from its ambient value, always alarmed before the solid fuel, flaming-stage POC reached the sensor station, which occurred before the CO sensor measured a 5 ppm increase in CO. This provides new guidance for setting an alarm value for a non CO fire sensor.
2. Although HCl is a discriminating signal for conveyor belts, it has no advantage as a fire early warning signature when compared to other POC fire sensors.
3. It was demonstrated for a smoldering conveyor belt fire with obscuring visibility prior to detectable CO emissions that smoke and MOS sensors can provide early fire warning. This reinforces the significance of fire sensors other than CO sensors as part of an atmospheric mine monitoring system.
4. The bimodal response of a NO<sub>x</sub>-sensitive MOS sensor to NO<sub>x</sub> emissions from a diesel scoop and acetylene torch metal cutting operation, and to POC from coal fires, demonstrated how a MOS sensor could be used for discriminating a coal fire from in-mine nuisance emissions.
5. The cross-interference of CO chemical cells to H<sub>2</sub> at a battery charging station demonstrated the need for smoke sensors for the detection of battery station fires. In this particular case a NO<sub>x</sub> sensitive MOS sensor could further differentiate diesel exhaust from a fire at the battery charging station.
6. Application of a trained neural analysis program to in-mine coal, diesel fuel, electrical cable insulation, conveyor belt fires, and acetylene torch cutting was able to successfully classify an average of 96 pct of the fire sensor data from seven experiments. The neural network approach demonstrated the capability of multiple types of fire sensors to classify a mine fire by its combustion event by fuel source.

Future research will evaluate the response of multiple sensors to mine fire sources in the presence of diesel

emissions, and include the results in a neural analysis for mine fire nuisance alarm discrimination.

#### REFERENCES

- Brinn, M., and Bott, B., 1994, „A Fresh Approach to Mine Fire Detection,” Mining Engineer, Vol. 154, No. 396, Sept., pp. 71-74
- Edwards, J.C. 1990, „Fire Location Model”, U.S. Bureau of Mines Information Circular 9261, 14 pp
- Edwards, J.C., Franks, R.A., Friel, G.F., Lazzara, C.P., and Opferman, J.J., 1999, „Mine Fire Detection in the Presence of Diesel Emissions,” Proceedings, 8th U.S. Mine Ventilation Symposium, J.C. Tien, ed., University of Missouri-Rolla, Rolla, MO, pp. 295-301
- Edwards, J.C., Friel, G.F., Franks, R.A., and Opferman, J.J., 1997, „Mine Fire Detection Under Zero Airflow Conditions,” Proceedings, 6th International Mine Ventilation Congress, R.V. Ramani, ed., SME, Littleton, CO, pp. 331-336
- Ishii, H., Ono, T., Yamauchi, Y., and Ohtani, S., 1994, „Fire Detection by Multi-Layered Neural Network with Delay Circuit,” Proceedings, Fire Safety Science-4th International Symposium, T. Kashiwagi, ed., International Association for Fire Safety Science, Ottawa, pp. 761-772
- Rashbash, D.J., 1975, „Sensitivity Criteria for Detectors Used to Protect Life,” Fire International, Vol. 5, No. 40, pp. 30-49

#### ACKNOWLEDGEMENTS

The authors acknowledge the miners who maintain the Safety Research Coal Mine at the Pittsburgh Research Laboratory for their assistance in preparation of the experiments.

0000256378 - 7/2/02 - COVER BOOK RES. - \$100.00

**Proceedings**  
**of the**  
**7th International Mine Ventilation Congress**

*Editor*  
Stanisław Wasilewski  
Research and Development Center EMAG

TN 301  
.I6  
2001

June 17-22, 2001, Cracow, Poland