Underground Fire Detection and Nuisance Alarm Discrimination

BY J.C. EDWARDS, R.A. FRANKS, G.F. FRIEL, C.P. LAZZARA, AND J.J. OPFERMAN

A fire detection research program conducted at the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Research Laboratory (PRL) recently demonstrated the advantage of multiple fire sensors for early fire detection and nuisance alarm discrimination in underground coal mines. As an example, research has shown that an appropriate combination of smoke, CO, and metal oxide semiconductor (MOS) sensors has the capability to detect a smoldering conveyor belt fire which produces low visibility due to smoke, but CO concentrations too low for an early fire alarm. Such a sensor combination has the additional advantage of being able to distinguish a nuisance alarm event such as those produced by diesel engines or acetylene torches from mine fire products-of-combustion (POC) produced by a real fire. Research has also shown that the problem of hydrogen (H_2) gas cross-interference with chemical CO sensors at battery-charging operations in diesel-emissions backgrounds can be resolved with a smoke sensor and a MOS sensor sensitive to NO_x associated with diesel emissions.

Other underground conditions, such as rock dust, exacerbate the problems with sensors. NIOSH has developed a neural network that takes many of these variables into account as it assesses real-time sensor data to discriminate nuisance alarms.

MINERS DEPEND ON FIRE PROTECTION

The early and reliable detection of underground coal mine fires enhances the safety of miners. Early fire detection in both well- and under-ventilated mine entries has been experimentally investigated [1,2] and the results showed that ionization and optical smoke fire sensors performed better than CO sensors for small fire detection. New detection devices, when deployed with more traditional mine fire sensors, can also determine the material burning and discriminate nuisance alarms from real ones. These sensors distinguish the POC from other gaseous and particulate emissions. Such information can be used to determine appropriate actions to evacuate and rescue miners, and to extinguish a mine fire. The selection of a base set of multiple sensors is a key decision for using a neural network program [3] to successfully discriminate between hazardous mine-fire combustion and normal mining POC that may result from sources such as battery-charging operations, diesel engine exhaust, and cutting and welding activities.

The selection of a fire sensor is significantly influenced by the thermal event to be detected. For example, a significant problem for mine fire safety is the early detection of conveyor belt frictional heating associated with belt slippage, which can produce considerable amounts of smoke prior to emissions of detectable levels of CO. But, the frictional heating event can easily be detected at an early stage with a smoke or MOS sensor. On the other hand, a diesel fuel fire produces detectable levels of CO and smoke rapidly. A diesel fuel fire could be detected equally early with a CO, smoke, or MOS sensor.

However, the performance of these individual fire sensors can be severely limited by nuisance alarms. One persistent nuisance alarm in mining operations is the cross-interference of a chemical CO sensor to H_2 near battery-charging operations. This results in a false CO reading which can have two undesirable consequences: the nuisance alarm interferes with the mining operation; and the mine workers learn to ignore alarms. Current state-of-the-art CO sensors which are insensitive to H_2 and hydrocarbons are unavailable for low-CO concentrations. One solution adopted by a number of mines is to use smoke sensors. However, an additional consideration is the POC from diesel equipment. Diesel emissions produce an additional nuisance signature for both CO and smoke sensors. One method to discriminate diesel emissions from the POC is to use a sensor responsive to NO_x. A NO_x responsive sensor, in conjunction with a smoke or CO fire sensor, will also discriminate a fire from POC produced by acetylene torch cutting and welding activities.

A smoke-sensor nuisance-alarm source, associated with normal coal mining operations, is rock dusting. Rock dust particulates can be as an effective source of ion recombination as smoke particulates, which can result in an ionization smoke-sensor false alarm. Similarly, an optical smoke-sensor false alarm will result from the change in transmitted or scattered optical intensity produced by dust particulates. One method to avoid a false fire alarm due to rock dusting is the use of a combination of POC sensors, such as a smoke sensor and a CO sensor.

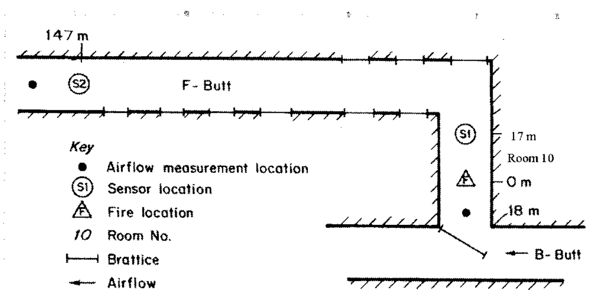

Figure 1—Plan view of the SRCM fire detection research station.

SENSOR RESEARCH

Sensors used in the mine fire research detection project include both Mine Safety and Health Administration, evaluated for intrinsic safety fire sensors, and commercially available fire sensors. The latter sensors provide an opportunity to examine a wide range of sensors with potential for mine application. These sensors include an infrared optical sensor which can operate over a distance from 9 to 107 meters (m) between the transmitter and receiver, and MOS point type sensors which have applications in environmental monitoring. The optical sensor can probe a path across a mine entry to assure the entry is smoke free, whereas an ionization type smoke sensor is a point measurement device which may not detect a channeled flow of smoke. An optical smoke sensor is more responsive to the larger diameter particulates produced by smoldering combustion, and an ionization smoke sensor is more responsive to the numerous small-diameter particulates produced by flaming combustion.

MOS sensors operate on the principle that oxygen adsorbed on a semiconductor surface increases the electrical resistance across the surface. The oxidation of POC gases removes oxygen from the sensor surface and reduces the measurable electrical resistance across the surface. The measurable change in surface resistance is a measure of the POC concentration. These sensors are responsive to, but not selective of the target gases, and they are also temperature and humidity dependent. However, it is their extreme sensitivity to various gases that increases their potential for use as mine fire sensors. A light obscuration monitor which operates in the visible spectrum is used to determine the visibilty in smoke-filled entries coincident with the fire sensor response.

EXPERIMENTAL MINE FACILITY

The Safety Research Coal Mine (SRCM) at PRL provides a research laboratory to conduct controlled mine fire detection experiments. Figure 1 shows a plan view of the mine section in which the fire detection experiments are conducted. The average height and width of room No. 10 in which the fire is located are 2 m and 3.9 m, and the average height and width of F-Butt are 1.9 m and 4.5 m, respectively. Two sensor stations were used in the experimental program. Sensor station S1 is in room No. 10, located 17 m downwind from the fire, and sensor station S2 is in F-Butt, 147 m downwind from the fire source.

At the fire location in room No. 10, three coal, two electrical cable-insulation, four conveyor-belt, and three diesel-fuel fire experiments were conducted. The solid materials, which were confined to a 0.6 m square area, were heated with electrical heaters to which power was supplied at a low rate such that the smoldering combustion mode passed through a slow growth phase with the generation of POC prior to flaming combustion. This was done in order to validate the early alarm sensitivity of the fire sensors in response to a slowly developing thermal event. The heating time prior to flaming combustion for the solid fuels varied between 42 and 109 minutes. Rapid flaming combustion resulted from the diesel fuel fires confined to a 0.5 m square pan. The average air quantity at the fire zone was 3.5 m^3/s (7,400 cubic feet per minute (cfm)).

For evaluation of the sensors' response to diesel engine and torch-cutting emissions, in-mine experiments were conducted which consisted of cutting a piece of 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_x-sensitive sensor, MOS2, was compared with the CO sensor and an ionization smoke sensor, ION.

FIRE SENSOR RESPONSE

The fire sensor response was measured by the alarm time. The CO sensor alarm was defined to be a CO concentration increase of 5 parts per million (ppm) above ambient, and the smoke and MOS fire sensors' alarm was defined to be a 10 standard deviation signal change from the sensor's ambient value. This fire alarm definition for a non-CO sensor assures that the measured sensor signal is sufficiently removed from the environment to assure its validity as representing a thermal event.

For the 12 in-mine experiments, the smoke and MOS sensors alarmed before the CO sensor. For the coal, electrical cable insulation, and conveyor belt fires, the MOS sensors, as well as ION and the optical smoke sensor, OPTICAL, on average alarmed between 38 and 45 minutes before the CO sensor at station S2, 147 m from the fire. Because of the quick ignition time of the diesel-fuel fire, the MOS, ION, and OPTICAL sensors alarmed two minutes prior to the CO sensor.

For the heating of a conveyor-belt material, which simulated conveyor-belt slippage, a visibility-obscuring dense white smoke with very low CO was produced. This resulted in the alarm times at S2 for sensors ION, OPTICAL, and MOS2 occurring 40, 45, and 35 minutes prior to the CO alarm time for one of the belt-heating experiments. Thirteen minutes prior to the 5- ppm CO concentration, the visibility was reduced to 1.52 m for this experiment. Figure 2 shows the thick white smoke produced by the heating of a conveyor-belt sample. This experiment demonstrates the early fire warning capability of smoke and MOS sensors for a low CO-producing thermal event.

In response to acetylene-torch cutting and diesel-equipment emissions, sensor MOS2 responded with a decreasing voltage, in direct contrast to an increasing voltage signal for fire POC, indicative of a semiconductor increased surface resistance due to oxygen adsorption. This sensor's bimodal response could be a useful discriminatory feature for filtering a nuisance NO_x-producing event from a mine fire. It is the sensor's characteristic response to various combustibles and nuisance signatures which forms the basis for the application of a neural analysis to identify the fire source.

NEURAL NETWORK ANALYSIS

A commercially available neural network analysis computer program was applied to the classification of the fire sensors' response to differentiate between possible fire sources. A neural analysis is one method to determine classification of events based upon a number of known different events which can be used to train the network to recognize classifications of unknown events from measurements of variables characterizing the events.

The training of the neural network was accomplished with five sets of sensor data from coal, diesel fuel, electrical-cable insulation, and conveyor-belt fires, and an acetylene-torch, metal-cutting experiment. For testing the neural network, sensor data from seven mine combustion experiments were presented to the trained network. Over the time period of each test in which the fire sen-

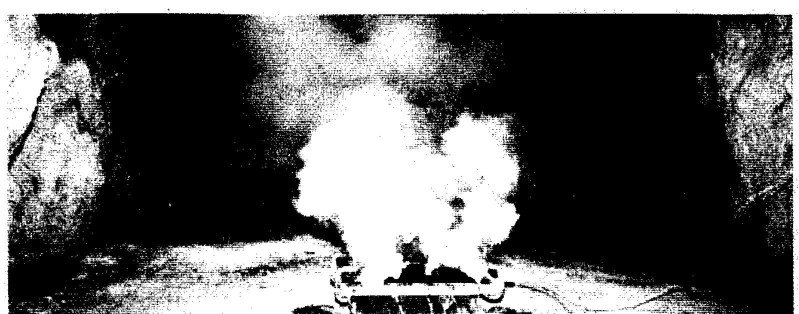

Figure 2—This is an example of the thick white smoke associated with a heated conveyor-belt sample.

sors were responsive, the average correct classification of the combustion source for the seven experiments was 96%. The minimum value for a single experiment was 86%. This validates the concept of a neural network program as a practical method to classify a thermal event in a mine by the combustion source. The incorporation of a trained neural network for an associated set of multiple sensors as part of a mine-monitoring system would enhance mine-fire identification.

HYDROGEN CROSS INTERFERENCE

The discriminatory capability of multiple mine fire sensors with respect to a battery-charging operation was evaluated in a non-ventilated building 6.1-m square with a 4.6-m height. While a battery-operated locomotive was being charged, air in the building above the locomotive was monitored with a CO sensor, ION, and MOS2. During the battery-charging operation, the CO sensor indicated 50 ppm, which is the top of the sensor's calibrated scale. However, air samples analyzed by gas chromatography contained an average CO concentration of 3 ppm, and an average H_2 concentration of 560 ppm. The false CO reading is due to the cross interference from the H_2. After a constant level of H_2 was established in the building, pulverized coal in a 15-centimeter diameter container was heated to a smoldering state. Diesel engine exhaust was then introduced into the building. The response of sensors ION and MOS2 to these events is shown in Figure 3, where MOS2 responded at time 9:05 to the H_2 from the battery-charging operation which was initiated at 9:00. Smoke sensor ION indicated the absence of fire POC. Following the initial heating of the coal at 10:11, the smoke sensor signal decreased at a constant rate and the MOS2 signal moved into saturation at 5 volts in response to POC from the smoldering coal. Introduction of the diesel exhaust into the battery-charging room at 11:23 resulted in a rapid decrease in the signals from both sensors. The diesel engine was turned off, and the fresh air recovery of the building commenced at 11:33.

Without the MOS sensor, the response of the smoke sensor could lead to the erroneous conclusion that the fire had transitioned to a flaming combustion stage or that the intensity of a flaming combustion stage had increased. This experiment shows the value of a smoke sensor for eliminating the nuisance alarm associated with a CO sensor's cross interference from H_2, and the advantage of a MOS sensor to discriminate diesel emissions.

ROCK DUSTING

Three rock dusting experiments were conducted in the SRCM to determine the effect of rock dusting on the diffusion mode ionization smoke sensor, ION. An air hose was used to disperse the dust in the entry which had an average ventilation of 4.41 m^3/s (9,340 cfm) across the entry cross section. The smoke sensor and the optical obscuration monitor output showed a rapid and simultaneous response to the airborne dust. Each rock-dusting operation lasted 5 minutes, and visibility reductions to 4.6, 2.9, and 1.7 m occurred in the experiments.

Although the smoke sensor went into an alarm with reductions in signal voltage of 12, 29, and 59 standard deviations for the three experiments, the output signal voltage recovered to within 0.8, 1.4, and 2.6 standard deviations of their pre-rock dusting values. This shows that a smoke sensor must be supplemented by another sensor, such as a CO sensor, to exclude rock dusting false alarms. The recoverbility of the ionization smoke sensor after the rock-dusting event is encouraging for its inclusion in a mine monitoring system.

Recent fire detection research conducted in the SRCM at the PRL has demonstrated the potential for mine fire combustible discrimination based upon the selective use of multiple fire sensors. A judiciously selected combination of sensors has the capability to discriminate nuisance alarms due to diesel operations, cutting and welding operations, and rock-dusting operations from hazardous mine fires. A neural network analysis method was shown to have application to combustion source and nuisance emissions identification. In the absence of diesel equipment, a smoke sensor would provide discrimination of hydrogen gas interference with a battery-charging station. The mine fire detection results, using sensors currently existing in other industrial applications, are encouraging for realizing the expansion of mine-fire detection and discrimination capability. CA

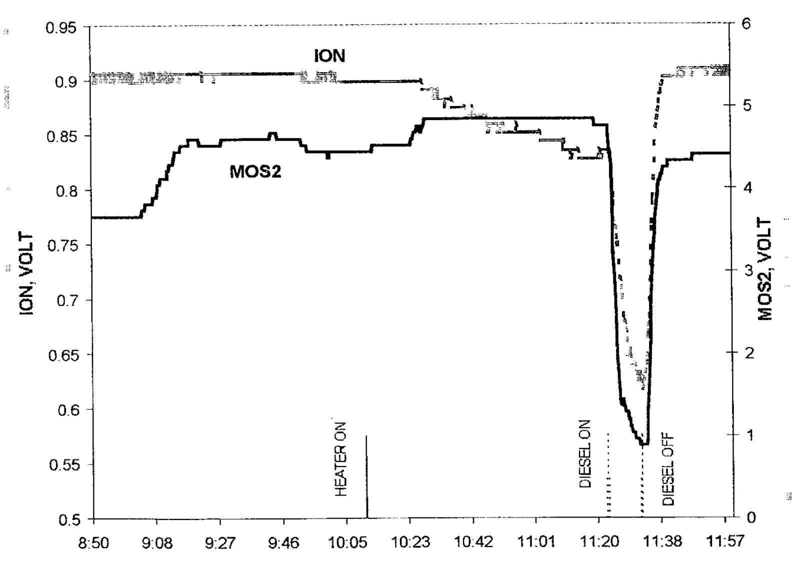

Figure 3—This graph illustrates the sensors response to a smoldering coal fire and diesel exhaust at a battery-charging station.

Edwards is a research physicist, Franks is an electronics engineer, Friel is a chemical engineer, Lazzara is a research chemist, and Opferman is an electronics technician at NIOSH/PRL.

REFERENCES

1. Edwards, J.C., Franks, R.A., Friel, G.F., Lazzara, C.P., and Opferman, J.J. *Mine Fire Detection in the Presence of Diesel Emissions.* 8th U.S. Mine Ventilation Symposium, pp. 295-301, (June 1999).

2. Edwards, J.C., Franks, R.A., Friel, G.F., and Opferman, J.J. *Mine Fire Detection Under Zero Airflow Conditions.* 6th International Mine Ventilation Congress, (May,1997) pp. 331-336.

3. Edwards, J.C., Franks, R.A., Friel, G.F., Lazzara, C.P., and Opferman, J.J. *Mine Fire Source Discrimination Using Fire Sensors and Neural Network Analysis.* 2000 Technical Meeting of Central States Section of The Combustion Institute. April 16-18, 2000, pp. 207-211.