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# OVERVIEW OF MINE FIRE DETECTION

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Several experimental programs were conducted at the Pittsburgh Research Center to investigate the level of mine fire detection and alarm capability possible using state-of-the-art technology. These programs involved comparison of the response and alarm time of optical and ionization type smoke sensors to smoldering and flaming coal combustion in a smoke chamber. Coal combustion experiments conducted in the smoke chamber demonstrated that a CO concentration of 5 ppm above ambient corresponded to an optical density of $0.022m^{-1}$. For the four smoke sensors for which a continuous analog signal was available, a smoke sensor alarm was defined as the average background signal plus ten times the peak-to-peak noise. This alarm criterion resulted in the association of the alarm for three of the four sensors with a smoke optical density of $0.011m^{-1}$, and $0.033m^{-1}$ for the fourth smoke sensor. The smoke sensors used in the smoke chamber studies were incorporated into large scale diesel fuel fire experiments conducted under normal ventilation conditions in the Safety Research Coal Mine (SRCM) at the Pittsburgh Research Center. These experiments showed that a diffusion mode smoke sensor alarmed earlier than a diffusion mode CO sensor; and, based upon the measurement of the optical transmission at the location of a pump mode ionization type smoke sensor, that a pump mode ionization smoke sensor alarmed at an average smoke optical density of $0.021m^{-1}$ for the twelve experiments conducted. A series of 30 and 330 kW diesel fuel fire intensity experiments were conducted under zero airflow conditions in the SRCM. It was determined that :(1) thermal sensors are inadequate at 30 m from a 300 kW fire;(2) a diffusion mode ionization smoke sensor can be more effective for mine fire detection than a diffusion mode CO sensor;(3) recommendations can be made for sensor spacing in a mine entry based upon the measured CO buoyancy induced spread rates along the mine roof and the time for a developing coal fire to ignite a conveyor belt.

## INTRODUCTION

The safety of miners is dependent upon an atmospheric mine monitoring system which can provide early warning in the event of a fire in a mine. Common sensors used in a mine include CO, smoke, and thermal. NIOSH's Pittsburgh Research Center has evaluated (1) smoke sensors in a smoke chamber, as well as in a mine environment (2). Smoke sensors can be classified into two types based upon their operational principle-optical or ionization. Their sampling method will be either diffusion- or pump- controlled.

Ionization smoke sensors contain a radioactive source that ionizes the air. The oppositely charged ions form a current between two charged electrodes. Diffusion of smoke particulates into the path of the ion current reduces the ion current through attachment of the ions to the smoke particles. This process reduces the mobility of the ions, and thereby increases the ion's probability of recombination. The ion current reduction is amplified as a measurable signal.

Optical smoke sensors operate on the principle of scattering or absorption of light over an optical path through which the smoke particles migrate. For optical scattering, the sensor is located to the side of the optical path to measure the amount of light scattered by a smoke particle. In the case of optical absorption, the reduction of transmitted light due to absorption and scattering is measured.

The smoke sensors evaluated in the laboratory and under in-mine fire conditions as characterized by type and sampling mode are listed in Table 1. These are commercially available smoke sensors intended for mine or industrial use.

The smoke particle size is dependent upon the mode of combustion. Smoldering combustion produces relatively larger smoke particle sizes than flaming combustion of a given material. This is significant from smoke monitoring in terms of the use of an ionization or an optical type sensor. Ionization sensors are more sensitive to the smaller smoke particles associated with flaming combustion, whereas optical sensors are more sensitive to larger smoke particles associated with smoldering combustion (1,3).

Novel candidate fire sensors have been evaluated. One type of sensor is an odor monitor which responds to $H_2S$, a product gas of combustion of sulfur containing coal. With respect to coal combustion it was determined that an odor monitor and a pump mode ionization type smoke sensor alarmed at nearly equivalent times for smoldering coal combustion, whereas for flaming coal combustion, the smoke sensor alarmed earlier than the odor monitor (1,4). A second novel candidate for mine fire detection is an ultrasonic ranging system. It was demonstrated (5,6) with diesel fuel fires and smoke candle experiments in the PRC's Safety Research Coal Mine (SRCM) that the acoustic sensor responded to both heat and smoke as the result of the refraction and absorption of ultrasonic waves transmitted through the heated air and smoke. In a fire research tunnel experiment it was shown that the acoustic sensor alarmed at an optical density of $0.025m^{-1}$ in response to smoke from a coal fire. This is slightly greater than the $0.022m^{-1}$ alarm associated with mine fire smoke detection.

The implementation of mine fire sensors as part of a mine fire detection strategy will depend upon the growth rate of the fire, and the mine ventilation conditions. Mine fire sensor spacings based upon known ventilation conditions can be specified to assure alarm settings to be consistent with fire growth rates. In the case of zero, or low, ventilation the buoyancy induced spread of products-of-combustion (POC) from the fire will determine the sensor spacings. Experimental programs at PRC have addressed the comparative response of CO and smoke sensors under normal and zero airflow conditions (2,8). This paper will discuss both the laboratory and in-mine evaluation of smoke sensors, and how recommendations can be made for fire sensors in zero airflow conditions.

## LABORATORY EVALUATION OF SMOKE SENSORS

A protocol was developed to evaluate the response of smoke sensors to smoldering and flaming coal combustion. Coal was selected because it is the most common fuel source in a mine. A smoke chamber was constructed according to UL268 specifications (9) and used for evaluation of five smoke sensors (1). The evaluation procedure led to reproducible rates of change in the optical density characteristic of smoldering and flaming coal combustion, as well as in the output signal from a standard ionization chamber. The optical density of the smoke was measured with a light obscuration device consisting of a light source and a photocell. For the laboratory experiments, an alarm was defined for sensors A, B, C, and E as an output signal change from the background equal to ten times the peak-to-peak noise. With this alarm criterion, sensors A, C, and E alarmed at a smoke optical density less than $0.011m^{-1}$ for smoldering and flaming coal combustion. Sensor B alarmed at $0.022m^{-1}$ for smoldering coal combustion, and at an optical density between $0.022m^{-1}$ and $0.033m^{-1}$ for flaming coal combustion. Sensor D did not have a continuous analog output signal, and the manufacturer's set alarm was used. For smoldering coal combustion sensor D's alarm occurred at an average optical density of $0.12m^{-1}$, and for flaming coal combustion the alarm occurred at an average optical density of $0.077m^{-1}$. For each of the sensors for which a continuous output signal was available, the sensor indicated a response to the smoke in the chamber coincident with the onset of smoke as measured by optical attenuation. This comparison showed the advantage of a continuous analog signal from a smoke sensor so that an alarm value can be readily identified to correspond with the smoke optical density.

The optical type smoke sensor A showed that at an optical density of $0.022m^{-1}$ the sensor's output signal was greater for smoldering coal combustion than for flaming coal combustion. The ionization type smoke sensor C showed the opposite effect. This is in agreement with previous research (3 ).

As an ancillary measurement, the CO in the chamber was monitored. This measurement established a correspondence between average CO concentration of 5ppm above ambient with an optical density of $0.022m^{-1}$. This is significant for establishing equivalent alarm levels for CO and smoke sensors.

Evaluation of the performance of smoke sensors must also account for the environment in which they are deployed. Mine environments can be humid, and temporarily have high dust concentrations when preventive rock dusting operations are in use. These features, as well as pressure and temperature effects, need to be incorporated into the sensor performance evaluation.

## IN-MINE COMPARISON OF CO AND SMOKE SENSORS

The development of a strategy for mine fire detection requires an evaluation of the relative response of CO and smoke sensors to an in-mine fire. An experimental study was conducted in the SRCM with a series of nine diesel fuel fires (2) under normal, linear airflow velocity between 0.8 and 1.2 m/s,and three reduced ventilation conditions, linear airflow velocity between 0.2 and 0.4 m/s, to compare the response of five types of commercially available smoke sensors with the more commonly used diffusion mode CO sensors. The sensors were located near the roof in a mine entry of average cross section 2.0 m high and 4.6 m wide. The fire source is about 360m before the first sensor. This provides for some dilution of the leading edge of the POC before they reach the sensor.

For the in-mine experiments, the manufacturer set alarm was used for sensors D and E. For sensors A, B, and C, the alarm value was defined as a ten standard deviation change in output signal from the ambient signal. Smoke sensors B, C, and E, consistently alarmed prior to the diffusion mode CO sensor located adjacent to it. For the normal ventilation airflow experiments, 3-9, with an average fire intensity of 330 kW, ionization type smoke sensors C and E alarmed an average 61 and 46s prior to the CO sensor, and the optical type smoke sensor B alarmed an average 63s prior to the CO sensor. Smoke sensor D alarmed an average 17 s before the CO sensor for those experiments for which the minimum optical density was greater than $0.15m^{-1}$. For the reduced ventilation airflow experiments, the smoke sensors alarmed at an average earlier alarm time with respect to the diffusion mode CO sensor than they did under normal airflow ventilation conditions. Smoke sensor A alarmed an average 17 s after the CO sensor for the normal ventilation experiments, but an average of 61 s before the CO sensor for the reduced ventilation experiments. At one location in the mine entry smoke sensor E and a diffusion mode CO sensor were positioned adjacent to a light obscuration device. The optical device consisted of a halogen lamp source and a photovoltaic cell separated by a distance of 1 m, and mounted horizontally and transverse to the airflow. The diffusion mode CO sensor alarmed at an average optical density of $0.085m^{-1}$, and smoke sensor E alarmed at an average optical density of $0.021m^{-1}$ for eight normal ventilation airflow experiments and three reduced ventilation airflow fire experiments. In this series of in-mine diesel fuel fire experiments, the smoke sensors were shown to be able to complement CO sensors when they are to be used as part of an atmospheric mine monitoring system.

## MINE FIRE DETECTION UNDER ZERO AIRFLOW CONDITIONS

The strategy for sensor deployment in a mine has been investigated (7) under the constraint of known ventilation conditions and expected growth rates of fires. The presence of mine entry crosscuts was shown (2) to increase the transport time of CO through entrainment established by vortex creation in the crosscut. The entrainment results in a dilution of the POC at their concentration profile front. This was quantified as an analytic relationship between measured transport time and calculated transport times based upon the inclusion and exclusion of crosscuts. In the absence of positive ventilation airflow, there is a need to understand the POC spread rates induced by buoyant flow induced by the fire.

To measure the buoyancy induced POC spread rates, six experiments with an average 330 kW and three experiments with a 30 kW diesel fuel fire were conducted in the SRCM (8). Fig. 1. shows a schematic of the mine entry in which the experiments were conducted. The mine section in which the experiments were conducted was nearly free of elevation changes. F Butt has an average height of 2.0 m and a width of 4.6 m. Room 10 has an average height of 2.2 m and width of 2.8 m. Room 18 has an average height of 1.7 m and width of 4.0 m. For each of the nine experiments, except 7, the fire was located as shown in figure 1 midway between stations S1 and S4. For experiment 7 the fire was located midway between stations S1 and S2. To measure the POC advance from the fire, a pair of diffusion mode CO sensors were suspended from the roof at each of the stations, S1-S6. One sensor inlet was 0.4 m from the roof, and the other's was at midheight in the entry. The measurement station separation between adjacent stations other than S1 and S4, which are 60 m apart, was 30 m.

At station S2 the light obscuration device was used to indirectly measure the smoke optical density. For comparison of alarm time response a diffusion mode CO sensor and smoke sensors A-E were positioned at S2.

Table 2. lists the experimental conditions for each diesel fuel fire in terms of the fuel quantity that underwent combustion; the surface area of the fuel fire; the burn time of the fuel; and the average heat release rate for the fire. For experiment 1 there was a small air quantity

leakage into F Butt which resulted in an average airflow velocity of 5.8 cm/s in F-Butt. This was eliminated in experiments 2-9, and there was no measurable airflow greater than 1.5 cm/s prior to the ignition of the fire.

The POC spread rate in each experiment was determined from the alarm time of the CO sensors along the mine entry roof. The CO alarm time is the time at which the CO concentration achieves 5ppm above ambient. The calculated POC spread rate is an average over the 15 and 30 m spacing between sensors. Figure 2 shows the POC spread rates towards stations S3 and S6 for each experiment. It is apparent from Figure 2 that the more intense fires of experiments 1-6, average fire intensity of 330 kW, have a higher associated POC spread rate than the less intense fires of experiments 7-9, average fire intensity of 30 kW. Table 3 lists the average POC spread rate for these two average fire intensities at the three locations. Based upon the limited data in Table 3, the POC spread rate is proportional to the fire intensity to the 0.36 power.

The less intense fires resulted in slower mixing over the cross section of the mine entry. This was confirmed from a comparison of the measured CO concentration near the roof and at midheight. Figure 3 shows the measured CO concentration at entry roof and midheight at S1, 30 m from the fire, for experiment 9. Figure 4 shows the disappearance in the roof layer stratification at S2, 60 m from the fire, for experiment 9.

The average of the CO alarm times at the sensor stations can be used to determine the alarm times for CO sensors at fixed sensor spacings for the two average intensity fires considered. Sensor spacing is equal to twice the distance of the measurement station from the fire, since POC can spread in two directions. The results for experiments 1-6 for an average fire intensity of 330 kW, and for experiments 7-9 for an average fire intensity of 30 kW are shown in figure 5. Interpolation of the data in figure 5 for the 330 kW and 30 kW fires with the 14.25 min time rquired for a developing coal fire to ignite a conveyor belt (7) implies maximum sensor spacings of 183m and 105m, respectively, would be necessary for fire detection at very low airflow conditions. Although these results are not strictly invariant with respect to airway dimensions, the results have wide applicability, since the SRCM is not atypical of coal mines.

### Thermal Sensor

One type of fire sensor used as part of an atmospheric mine monitoring system is a thermal sensor. The minimum alarm temperature for a fixed-temperature sensor is 57° C (10). The effectiveness of this type of fire sensor for early fire detection was investigated as part of the low flow experiments. For experiments 5 and 6 a thermocouple was placed at S1 and S4, and for experiment 7 a thermocouple was placed at S2. The thermocouples, which simulate thermal fire sensors, were positioned near the roof. For the high intensity fire experiments, 5 and 6, the maximum temperature rise above ambient was 21 and 20° C at the station 30 m from the fire. The specific maximum temperatures were 36 and 30° C at the stations. These values are considerably less than the minimum 57° C alarm temperature. If a thermal sensor alarm is defined in an analogous manner to the definition for a smoke sensor as the ambient value plus ten standard deviations of the signal noise, then a comparison of thermal and CO sensor alarm times can be made. The thermal detection lags the CO alarm time by 14.7 min and 14.2 min at stations S1 and S4 for the 296 kW fire of experiment 5, and by 5.2 and 10.3

min for the 264 kW fire of experiement 6. For the low intensity 30 kW fire of experiment 7, the temperature rise 15 m from the fire was 11° C to a maximum of 17° C, although the measured CO exceeded 45 ppm. These results show that thermal sensors are limited in their applicability to mine fire protection.

### Smoke Sensors

A relative comparison was made of optical and ionization type smoke sensors which operate in a diffusion mode or a pump mode with the first detection of smoke by a light obscuration device at station S2 under zero airflow conditions. For smoke sensors A-C the alarm was defined as a ten standard deviation change in the signal from its ambient value. The manufacturer set alarm was used for sensors D and E. It was determined that smoke sensors A, C, and E and a diffusion mode CO sensor consistently detected a diesel fuel fire within a 88 s time span of each other. Because of the lack of dilution from ventilation air, the maximum optical density was between 0.82 and 1.30 $m^{-1}$ for the 330 kW average fire intensity experiments 1-6, and between 0.24 and 0.28$m^{-1}$ for the 30 kW fire intensity experiments 7-9. The equivalent visibility is between 0.6 and 1.0 m for experiments 1-6, and between 2.9 and 3.3 m for experiments 7-9. The visiblity is calculated from the optical density based upon visibility studies (11) . These values are less than the 4 m visibility required for escape from a building for someone familiar with the surroundings (12).

A comparison was made of the alarm time of each smoke sensor and the diffusion CO sensor 5ppm alarm times. Table 4 shows the average time interval by which the smoke sensor alarm leads the diffusion mode CO alarm time at S2. A minus sign in Table 4 denotes a time lag. The 330 kW average fire intensity experiments 1-6 are in one group, and the 30 kW fire experiments 7 and 8-9 are in separate groupings. For experiment 7 the fire is 15m from S2, whereas the separation is 60 m for the other experiments.The results in Table 4 show that a smoke sensor, in the case of sensors A, C, and E, is a viable candidate for a mine fire sensor in place of a CO sensor. Diffusion mode smoke sensor C alarmed earlier than the diffusion mode CO sensor at S2 in eight of the nine experiments, and can be more effective for mine fire detection than a diffusion mode CO sensor if the alarm time for the smoke sensor is defined as a ten standard deviation change of the analog signal from its ambient value.

## CONCLUSION

Early mine fire detection can be best accomplished with CO or smoke sensors. The equivalency of CO concentration of 5 ppm above ambient to a smoke optical density of 0.022$m^{-1}$ was demonstrated for smoldering and flaming coal combustion. It was determined that smoke sensors can be reliable indicators of smoldering and flaming coal combustion for an optical density less than 0.011$m^{-1}$. From an operational point of view in terms of sensor alarm definition, smoke sensors with a continuous analog output have an advantage over those with preset alarm levels. For diesel fuel mine fire experiments it was demonstrated that a diffusion mode ionization type smoke sensor alarmed earlier than a diffusion mode CO sensor under normal ventilation conditions. A similar result was found for 30 and 330 kW average intensity diesel fuel fire experiments under zero airflow conditions. Thermal detection was shown to be inadequate at a 30 m distance from a 300 kW fire under zero airflow conditions. For imposed mine fire ventilation conditions, sensor spacing in a mine fire detection system can be evaluated from the known ventilation conditions. In the absence of imposed mine ventilation, the buoyancy generated flow produced by the fire defines the sensor spacing criteria. It was determined that for the 14.25 min required for a developing coal fire to ignite a conveyor belt, a sensor spacing of 183 m and 105 m would be required for average 330 kW and 30 kW fires respectively under zero airflow conditions.

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Table 1. Smoke Sensors

| Smoke Detector | Type | Sampling Mode |
|---|---|---|
| A | optical | pump |
| B | optical | diffusion |
| C | ionization | diffusion |
| D | ionization | diffusion |
| E | ionization | pump |

Table 2. Diesel Fuel Fires

| Experiment | Fuel, L | Area, sq. m | Burn Time, s | Heat Release Rate, kW |
|---|---|---|---|---|
| 1 | 4 | 0.58 | 250 | 495 |
| 2 | 6 | 0.37 | 589 | 315 |
| 3 | 12 | 0.37 | 1,222 | 303 |
| 4 | 18 | 0.37 | 1,910 | 291 |
| 5 | 24 | 0.37 | 2,506 | 296 |
| 6 | 24 | 0.21 | 2,816 | 264 |
| 7 | 2 | 0.047 | 2,024 | 30 |
| 8 | 2 | 0.047 | 2,024 | 30 |
| 9 | 3 | 0.047 | 3,036 | 30 |

Table 3. POC Spread Rates

| Average Fire Intensity, kW | POC average spread rate, m/s at 30 m | 60 m | 90 m |
|---|---|---|---|
| 330 | 0.22 ±0.03 | 0.13 ± 0.05 | 0.06 ± 0.01 |
| 30 | 0.08 ±0.02 | 0.04 ±0.006 | 0.04 ± 0.02 |

Table 4. Low Flow Experiments Smoke Sensor Alarm Average Lead Time Relative to CO Sensor Alarm Times

| Experiments | A | B | C | D | E |
|---|---|---|---|---|---|
| 1-6 | 21 | -23 | 13 | 4 | 18 |
| 7 | NA | 16 | 14 | -64 | 45 |
| 8-9 | 41 | -130 | 16 | -566 | 67 |

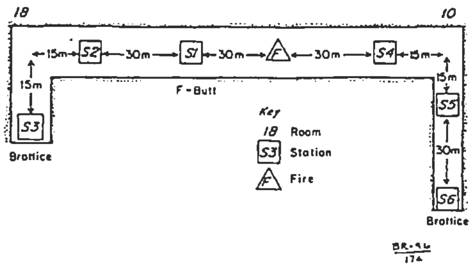


Fig. 1 Plan view of mine section

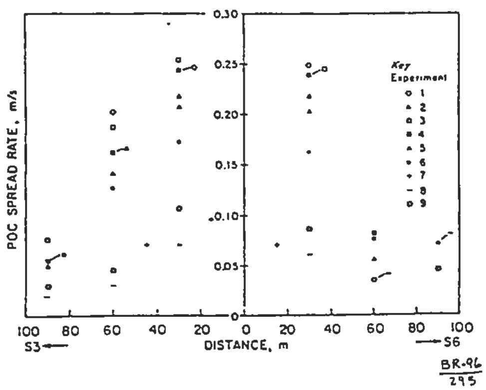


Fig. 2 POC spread rate dependence upon distance from fire

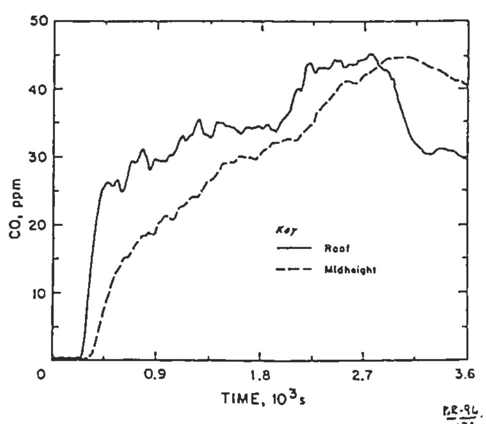


Fig. 3 Measured CO at airway roof and midheight at station S1 for experiment 9

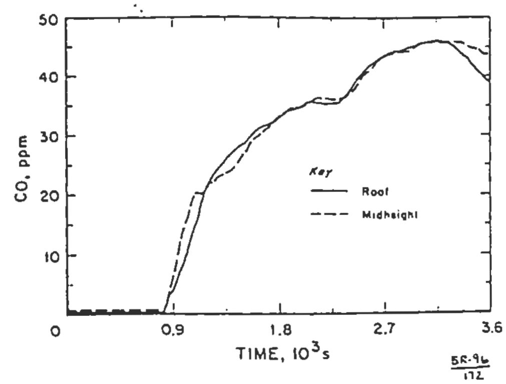


Fig. 4 Measured CO at airway roof and midheight at station S2 for experiment 9

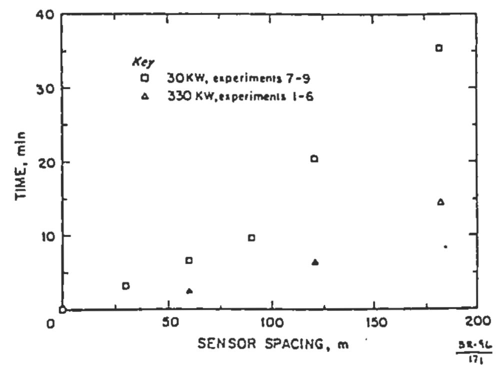


Fig. 5 CO alarm time dependence upon sensor spacing for average 330kW and 30kW fires