MINE FIRE DETECTION
UNDER ZERO AIRFLOW CONDITIONS

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ABSTRACT

A series of diesel fuel fire experiments were conducted in the Pittsburgh Research Center's Safety Research Coal Mine (SRCM) to determine products-of-combustion (POC) spread rates along a single entry under zero imposed airflow conditions. Six experiments with an average fire intensity of 330 kW and three experiments with an average fire intensity of 30 kW were conducted in a 180 m long entry which had an average 2 m height and 4 m width. POC spread rates were measured by the response time of diffusion type CO detectors, positioned at 30 m intervals, to CO concentrations 5 ppm above ambient. For the 330 kW fires, average POC spread rates of 0.22, 0.13, and 0.06 m/s were determined at 30, 60, and 90 m distances from the fire. For the 30 kW fires these average spread rates were reduced to 0.08, 0.04, and 0.04 m/s. The measured maximum roof layer temperature 30 m from two of the 330 kW fire was 30 and 36°C, which is less than the 57°C alarm point of a typical mine thermal sensor. It was determined that smoke detectors can be more effective for mine fire detection than CO detectors. The experimentally determined POC spread rates can be used to provide guidance for specification of sensor spacing to improve early fire detection at zero or very low air flows.

INTRODUCTION

Previously reported (Litton et al., 1991) recommendations for detector alarm thresholds for two detector spacings in a conveyor belt entry were based upon the assumption of forced convective transport of the fire products-of-combustion (POC) under positive ventilation conditions and an increasing fire intensity with associated POC production levels. Detector alarm thresholds were determined from the average time required, 14.25 min, for a small flaming coal fire to ignite a conveyor belt. In that work, the buoyancy induced flow of the POC was not significant, since forced convective airflow was dominant. This assumption was also used in previous studies (Friel et al., 1994, Edwards and Friel, 1996) which compared the effect of crosscuts on POC spread times along a single entry under positive ventilation. In a mine section with low airflow, the fire generated buoyancy forces become important. In the limiting case of zero airflow prior to the fire generated airflow, the POC are transported solely by the fire's buoyant forces.

To determine the buoyancy generated POC spread rates as a function of fire intensity, a series of nine experiments were conducted in the Pittsburgh Research Center's Safety Research Coal Mine (SRCM). Under zero airflow conditions in a horizontal airway, the time for POC spread was determined from the arrival of a CO concentration which was 5 ppm above ambient, at CO detectors positioned near the roof and spaced in either direction along an entry from the fire. The results of these experiments can be used to quantify the POC convective transport velocity in low airflow applications of the methodology previously developed (Litton et al., 1991) for specification of POC alarm levels. To provide a fire source of near uniform intensity and burning rate, the fuel source selected was diesel fuel. It has been demonstrated in laboratory smoldering and flaming coal combustion experiments at the Pittsburgh Research Center (Edwards and Morrow, 1995) that smoke detectors can be more effective for fire detection than CO detectors. These large scale mine experiments also provided the opportunity to make a relative comparison of six smoke detectors to each other based upon their alarm time, and the alarm time of a CO detector.

EXPERIMENTAL PROCEDURE

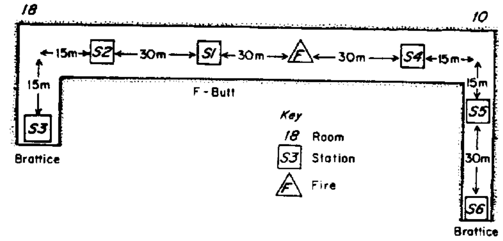

Figure 1. Plan view of mine section.

Figure 1 shows a plan view of the mine entry, F Butt, and adjoining mine rooms, 10 and 18, which were used as the isolated airway for the zero airflow mine experiments conducted in the SRCM. The elevation change in the entry floor was less than one percent. Aside from undulations in the mine roof, this entry provided a region which was nearly free of elevation changes which would affect the buoyancy induced natural ventilation. F Butt has an average height of 2.0 m and 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. All crosscuts in the entry were isolated with brattices, and a brattice stopping was positioned in Room 18 for each of the nine experiments. For experiments 4-9, Room 10 was isolated by a brattice stopping. For experiment 1, the mine's exhaust fan moved air through the section of the mine used for the experiments, which resulted in a flow of 0.53 m^3/s in F Butt. For experiments 2-9, a door at the mine portal was opened to shunt air directly to the exhaust fan, and bypass the remainder of the mine. As a result, no detectable airflow was measured in F Butt. 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. The measurement station separation between adjacent stations other than S1 and S4, which are 60 m apart, was 30 m. To measure the POC advance from the fire, a pair of diffusion mode CO detectors were suspended from the roof at each of the stations, S1-S6. One detector of each pair was positioned with its inlet diffusion tube approximately 0.4 m from the airway roof, and the other detector was positioned midheight between the roof and floor. As a result of previous research (Edwards and Morrow, 1994), the detector's diffusion tube was mounted approximately 20° from the normal to the roof towards the expected airstream direction. A pump mode CO detector was also located at the stations most distant from the fire, S3 and S6.

To measure the smoke intensity, a light obscuration device was installed at station S2. The device consisted of a 6 volt lamp and a photoelectric cell separated by an optical path, L, of one meter. This device provided a direct measurement of the normalized optical transmission, T, through the smoke, and thereby of the smoke optical density OD, which is defined as,

$$OD = \frac{1}{L}\log_{10} T . \qquad (1)$$

To compare the alarm times of smoke detectors to a CO detector, smoke detectors specified in Table 1 were positioned at S2 for each experiment. For experiment 9, C detector was also positioned at station S4 and S6, and F detector was positioned at S2 and S4. The smoke detectors are divided into two type classifications - optical and ionization, and two sampling mode classifications - pump and diffusion. Optical type refers to the absorption or scattering of light by smoke particles as the operating principle of the detector, and ionization type refers to the adsorption of ionized-air molecules on the surface of the smoke particles and the reduction in the ionization current through electron-ion recombination. Pump sampling mode refers to point sampling of smoke laden air through a tube connected to a pump or a blower fan. Diffusion sampling refers to access to the detector through a combination of turbulent diffusion and forced convective air movement.

Detector F was available only for experiment 9. Its alarm response time was about 5 s. The response time of the detector E was about 15 s. For experiment nos. 1-8, the sampling line interior diameter for detector A was 6.35 mm, and resulted in an average 70 s sampling response time. For experiment 9 a sampling line with an interior diameter of 25 mm was used, and the average sample time was reduced to about 5 s. The measured alarm times for detector A for experiments 1-8 were compensated for the 65 s difference in sampling time from experiment 9. These sampling times were based upon striking a match near the sampling tube inlet and measuring alarm time.

Table 1. Smoke Detectors

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

Each of the smoke detectors, except for D, has a continuous analog output voltage which is a measure of the smoke intensity. Detectors D, E, and F have manufacturer defined alarms. For detectors A and B, the manufacturer provided a relationship between the analog voltage output and the optical obscuration per meter. The latter quantity can be related to the smoke optical density. A ten standard deviation change in the average background signal was used to define an alarm signal for smoke detectors A, B, and C. For the smoke detectors D, E, and F, the manufacturer set alarm was used. First detection of smoke by the light obscuration device was defined as a reduction in the average background signal by ten standard deviations of the background noise. CO detector alarm was defined as 5 ppm above background.

For experiment 5-9 a thermocouple was installed adjacent to the inlet of the CO detector near the roof at stations S1, S2, and S4. A thermocouple temperature transmitter was used to supply to the data acquisition system a 4-20 ma signal which is linear with the temperature measurement.

The detector analog output was acquired with a data acquisition system with a 2 s polling time interval between samples. Each detector was interfaced with an accessor card to convert the analog output signal to a digital signal.

Four pan sizes were used to contain the diesel fuel fires. Square pans of side lengths 0.46 m, 0.61 m, and 0.76 m were used, as well as a cylindrical pail with a diameter at the liquid surface of approximately 0.24 m. The pan depths were approximately 15 cm, and the pail depth was 28 cm. The quantity of diesel fuel used for these experiments ranged from 2 to 24 liters. For uniform ignition of the fuel with a propane torch, approximately 100 ml of gasoline was added to the fuel. A thermocouple was mounted above the pan to monitor the fuel burn time for experiments 2-5 and 7.

RESULTS

A compilation of the fuel quantity, fuel exposed surface area, fuel burn time, and heat release rate is listed in Table 2. The heat release rate is based upon a heat of combustion for diesel fuel of 42.3 kJ/g, and a combustion efficiency of 0.84 associated with high molecular weight hydrocarbons.

The fuel burning time is approximately proportional to the liquid fuel depth in the pan. This proportionality was used to estimate the fuel burn time for experiment 1 and experiment 2. For experiment 6, the roof temperature profile at stations S1 and S4 was used to estimate the fuel burn time. The burn time for experiment 8 was assumed to be the same as the measured burn time for experiment 7, and for experiment 9 the proportionality of burn time to liquid fuel depth was used based upon the measured burn time for experiment 7.

POC Spread Rate

The primary monitoring of POC spread in the mine entry was accomplished with the diffusion mode CO detectors.

The currently used mine fire alert value of 5 ppm above background was used to measure the POC advancement. This value is more definite than first arrival time of CO because of possible

Table 2. Diesel Fuel Fires

Fuel				
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

ambient fluctuations and CO sensor cell accuracy of ±1 ppm. For each experiment the POC advanced to stations S1, S2, and S3. Because the fire had extinguished before the POC reached S3 for experiments 1 and 2, their values were not included in the POC spread rate evaluation at S3. With the exception of experiment 7 in which the fire source was located midway between stations S1 and S2, the POC advanced to station S4. Station S5 was reached by the POC for experiments 4-6 and 8-9. For experiments 4-6 and 8-9, the POC advanced to station S6. However, for experiments 4 and 5 the POC reached S6 after the fire had extinguished, and their values were not included in the POC spread rate evaluation. The capability of experiments 6, 8, and 9 to produce POC which reached S6, in view of the considerably less intense fire for experiments 8 and 9 is probably due to the seasonal temperature effect. Experiments 6-9 were conducted in the winter months, October through February, with lower outside air temperatures than the months of May through July in which experiments 1-5 were conducted. The ambient air temperature near S2 in F Butt varied from 14 to 21°C for experiments 1-5, and from 10 to 14°C for experiments 6-9. Under fan driven ventilation conditions, the normal ventilation proceeds from S6 to S3. During the summer months the heat exchange with the strata will cool the air as it proceeds from S6 to S3, while in the winter months the opposite thermal effect occurs. The thermally induced air density gradient will favor one direction in the airway once the fire, the primary air pump, is ignited under zero airflow conditions.

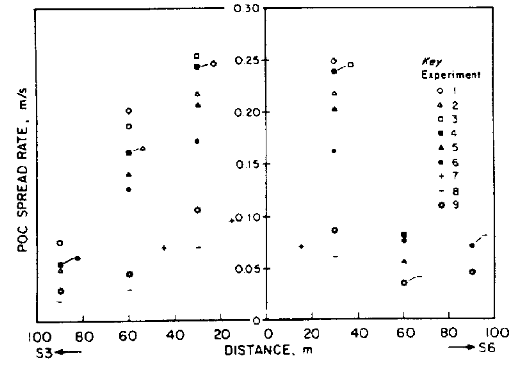

Figure 2. POC spread rate dependence upon distance from fire.

The POC spread rate was calculated from the sensor spacing and the measured POC travel time between adjacent CO sensors. This value represents an average over the distance between the two sensors, and because of the 15 and 30 m sensor spacings considered, is only an approximation.

Figure 2 shows the POC spread rates towards S3 and S6 for each experiment. It is apparent from Figure 2 that, as expected, the more intense fires of experiments 1-6 have a higher associated POC spread rate than the less intense fires of experiments 7-9. A comparison of the POC spread rate of the more intense fires and less fires can be made at 30 m, 60 m, and 90 m. Experiments 1-6 are in one group characterized by an average fire intensity of 330 kW, and experiments 7-9 are in a second group characterized by a fire intensity of 30 kW. Table 3 lists the average POC spread rate for these two average fire intensities at the three locations.

Table 3 shows that within the first 60 m from the fire the smoke average spread rate is about three times greater for the fire which has the greater intensity. The results reported (Alpert, 1972) for a fire plume in a room show the maximum gas velocity outside the plume is proportional to the fire intensity to the 0.33 power. The results in Table 3 for the average spread rates at 30 m from the fire imply the smoke spread rate is proportional to the fire intensity to the 0.42 power. Alpert's result applies to a plume from which the gas can spread radially and relates to actual velocity. The experiments in the SRCM have ribs along the entry which confine the smoke spread.

At S3 the pump mode CO detector alarm occurred an average 5 s later than the diffusion mode CO detector alarm for experiments 1-8. At S6 the pump mode CO detector alarm occurred an average 82 s earlier than the diffusion mode CO detector alarm for experiments 4-6 and 9. The average standard deviation of the ambient background measured by the pump mode CO detector was 1.3 ppm, whereas the standard deviation of the ambient background measured by the diffusion mode CO detector was

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

less than 0.1 ppm. This intrinsic detector error, in addition to the difference in the detector's sampling mode and chemical sensor cell will produce expected differences in detector alarm times.

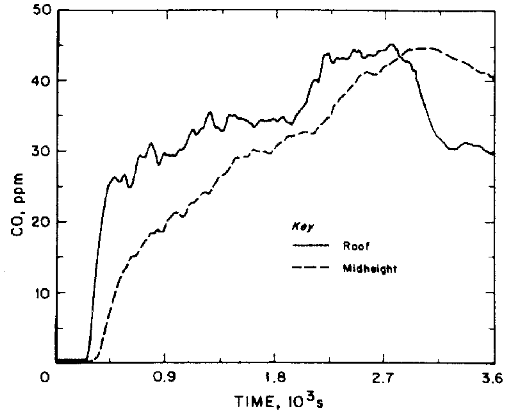

Figure 3. Measured CO at airway roof and midheight at station S1 for experiment 9.

The less intense fire presents an opportunity to clearly see the vertical mixing. Figure 3 shows the measured CO at the roof and entry midheight at station S1 for experiment 9, and figure 4 shows the measured CO at the roof and entry midheight at S2. A comparison of these figures shows the stratification of the POC which existed at S1 has all but disappeared at S2 above the entry midheight.

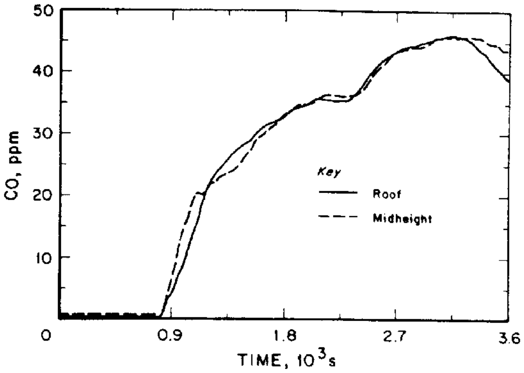

Figure 4. Measured CO at airway roof and midheight at station S2 for experiment 9.

Figure 2 showed a composite of average POC velocities at the sensor stations for the nine experiments. From the reference point of sensor spacing, it is useful to consider the CO alarm time at the various stations. Sensor spacing is defined to be twice the distance of the measurement station from the fire, since the POC can spread in two directions. The data in experiments 1-6 for an average fire intensity of 330 kW, and that in experiments 7-9 for a 30 kW fire are shown in figure 5 for the corresponding sensor spacings. Interpolation of the data in figure 5 for the 330 kW and 30 kW fires with the 14.25 min time required for a developing coal fire to ignite a conveyor belt implies minimum sensor spacing of 183 m and 105 m, respectively, would be necessary for fire detection at very low airflow conditions. Even though these results would not be strictly invariant with respect to airway dimensions, the results have wide applicability, since the SRCM is not atypical of coal mines.

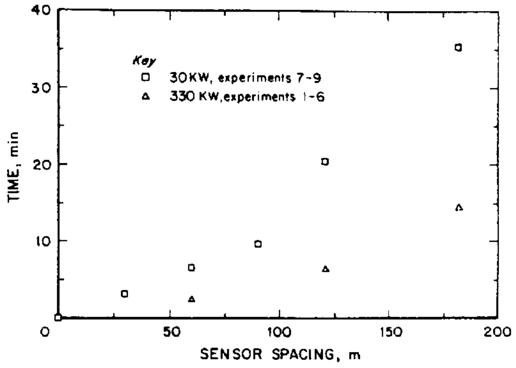

Figure 5. CO alarm time dependence upon detector spacing for average 330 kW and 30 kW fires.

Thermal Sensor

One type of fire detector used as part of an atmospheric mine monitoring system is a thermal detector. It is considered to be in alarm when the temperature reaches 57°C (Custer and Bright, 1974). In order to determine the POC temperature which developed in the SRCM diesel fire experiments at the CO measurement location nearest to the fire, a thermocouple was installed near the entrance inlet to the roof CO detector at stations S1 and S4. Experiments 5 and 6 are representative of the high intensity fire experiments. The maximum temperature during experiment 5 at S1 and S4 was 36 and 34°C, respectively. The ambient air temperature was 15°C. For experiment 6, the maximum values were 30 and 26°C, and the ambient temperature was 10°C. These values are considerably less than the 57°C alarm temperature of a thermal detector. If an alarm is defined for the thermal detection in an analogous manner to the definition of a smoke

Table 4. Alarm time of smoke and CO detectors at station S2 relative to first arrival of smoke

Detector alarm lag time, s							
Experiment	CO	A	B	C	D	E	F
1	37	-1	39	18	17	25	NA
2	42	8	54	30	45	NA	NA
3	40	23	66	26	37	22	NA
4	48	32	101	39	NA	30	NA
5	57	32	NA	43	55	NA	NA
6	46	47	>4 min	34	46	20	NA
7	6	NA	-10	-8	70	-39	NA
8	102	108	>4 min	107	>4 min	51	NA
9	162	74	>4 min	125	>4 min	70	34

NA = Not Available

detector alarm, as the mean ambient temperature plus ten standard deviations of the signal noise, then a comparison can be made of a thermal and CO alarm time. For experiment 5 the thermal detection lags the CO alarm by 14.7 min and 14.2 min at stations S1 and S4, and for experiment 6 the lag times are 5.2 and 10.3 min. For the less intense 30 kW fires, there was no significant temperature rise 30 m from the fire. At a distance of 15 m from the 30 kW fire in experiment 7, there was a significantly smaller temperature rise than there was 30 m from the 296 and 264 kW fire in experiments 5 and 6. During the fire of experiment 7, the thermocouple 15 m from the fire at S2 measured a temperature increase from an ambient value of 6°C to a maximum temperature of 17°C, although the measured CO exceeded 45 ppm at the same location.

Smoke Sensors

A relative comparison was made of the response of the smoke detectors listed in Table 1 with the first detection of smoke by the light obscuration device at station S2. The minimum measured light transmission at S2 was between 5 and 15 pct for the more intense fires of experiments 1-6, whereas for the relatively lower intensity fires of experiments 7-9, the minimum optical transmission varied between 53 and 58 pct. The relationship between visibility and optical density (Rasbach, 1971), based upon visibility studies using placards, implies that the minimum visibility for experiments 1-6 varied between 0.6 and 1.0 m, and for experiments 7-9 the minimum visibility varied between 2.9 and 3.4 m. Each of these values is less than the 4 m visibility required for escape from a building for someone familiar with the surroundings (Jin, 1981).

If only the results in the experiments for those smoke detectors and the CO detector at S2 which alarmed within 4 min of the first detection of smoke as measured by the light obscuration device are considered, then the lag or lead time of the detector relative to the first detection of smoke are within 92 s of each other, as shown in Table 4. Table 4 shows that smoke detectors A, C, and E and the CO detector are consistent indicators of the diesel fuel fire within a 92 s time span of each other for the nine experiments conducted.

A comparison was made of the alarm time of each smoke detector and the diffusion CO detector 5 ppm alarm times.

The comparison of alarm times at S2 can be made with smoke detectors by type - ionization and optical. With regard to the ionization type, E alarmed an average 36 s before the CO detector for seven of the nine experiments. For experiments 2 and 5, E was not operational. Detector C alarmed an average 16 s prior to the CO detector, except in experiment 8 in which it alarmed 5 s after the CO detector. For experiment 9 the alarm time of detector F occurred 2.1 min before the CO detector.

For the high intensity fire experiments 1-3 and 5-6, smoke detector D alarm time occurred within 20 s of the CO detector. It was not operational for experiment 4. For the low fire intensity, experiment 7, detector D's alarm was 1.1 min after the CO alarm, and it was 9.9 and 9.0 min after the CO alarm for low fire intensity experiments 8 and 9. The difference between experiments 7, 8, and 9 is attributable to the 15 m spacing between the fire and S2 for experiment 7, and 30 m spacing for experiments 8 and 9. Although detector D has a manufacturer defined alarm, as does detectors E and F, it operates in a diffusion mode, which, as expected in a zero or low airflow condition, would be at a disadvantage with respect to a pump mode detector. Smoke detector C, which operates in a diffusion mode, was more effective than detector D for the less intense fires of experiments 7-9 because of its continuous analog output signal with a user specified alarm.

With regard to the optical detectors, detector A's alarm occurred an average 27 s prior to the CO detector alarm. Detector B showed more variation in its alarm time with respect to the CO alarm time. B's alarm time occurred on the average 42 s after the CO detector alarm for the high intensity fire experiments 1-4 and 6 for which data were available. For the low intensity fire experiment, experiment 7 with a 15 m detector-fire separation, the detector B's alarm time was comparable to the CO alarm time. At the 30 m detector-fire separation in the low intensity fire experiments 8 and 9, detector B's alarm time occurred 2.6 and 2.2 min after the CO detector alarm. In this regard, Detector B's response characteristic was similar to that of smoke detector D.

At station S3, detector C's alarm occurred an average 17 s after the diffusion mode CO detector alarm for experiments 1-7. Detector C's alarm time was earlier than the CO alarm time for two of the experiments, and later than the CO alarm time for the other five experiments. For experiment 8, detector C alarmed 4.8 min earlier than the CO detector. This greater alarm time difference for experiment 8 at S3 in comparison to the measurements at S2 is possibly a result of the slower increase in POC farther from the less intense 30 kW fires. A similar effect was measured at S6 for experiment 9 for which detector C's alarm time occurred 4.6 min earlier than the diffusion mode CO detector alarm time.

At S4, for experiment 9, a comparison was made of smoke detector C's and F's and the CO alarm times. Smoke detectors C and F alarmed 1.0 and 2.0 min earlier than the CO detector respectively.

This comparison of smoke detector's alarm time with CO alarm time shows that detectors A, C, E, and F are more consistent early mine fire warning smoke detectors than are B and D.

CONCLUSIONS

The results of the diesel fuel fire experiments conducted under zero imposed air flow conditions resulted in the following conclusions.

1. Average POC spread rates of 0.22, 0.13, and 0.06 m/s were determined for 330 kW average intensity fires at 30, 60, and 90 m distances from the fire. For 30 kW average intensity fires these average POC spread rates were reduced to 0.08, 0.04, and 0.04 m/s.
2. Thermal detectors with an alarm value of 57_ C would not be adequate for fire detection even at 30 m from an average 330 kW fire.
3. A diffusion mode and a pump mode ionization type smoke detector, and a pump mode optical type smoke detector, and a diffusion mode CO detector, were consistent indicators of a fire within 4 min after the first optical detection of smoke. These detectors alarmed within 92 s of each other.
4. A less restrictive comparison of the smoke detectors' alarm time with that of a diffusion mode CO detector within 30 m distance of the fire demonstrated that a smoke detector can be more effective for mine fire detection if the continuous analog output signal from the smoke detector is used to identify an alarm.

The results of this research can be used to make recommendations for sensor spacings in a zero or low air low section of a mine. Interpolation of fire sizes between 30 and 330 kW could be used to estimate detector spacing as part of an atmospheric mine monitoring system in a mine section in which low airflow is expected. The recommended detectors would be CO, or smoke detectors with alarm values identifiable from a continuous analog output signal. Implementation of these measures can be expected to improve miners' safety.

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