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REPORT OF INVESTIGATIONS/1992

Response of Underground Fire Sensors: An Evaluation

By Ronald S. Conti and Charles D. Litton

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	min	minute
cm	centimeter	mL	milliliter
hp	horsepower	m/s	meter per second
kg	kilogram	ppm	part per million
kW	kilowatt	s	second
m	meter	V	volt
m^2	square meter		

Factors for Conversion of Selected Units to U.S. Customary Units

Abbreviation	Unit of measure	To convert to—	Multiply by—
°C	degree Celsius	degrees Fahrenheit	1.8 and add 32
m	meter	feet	3.28
m/s	meter per second	feet per minute	196.85

RESPONSE OF UNDERGROUND FIRE SENSORS: AN EVALUATION

By Ronald S. Conti[1] and Charles D. Litton[2]

ABSTRACT

This U.S. Bureau of Mines report discusses the results of research conducted in the Bureau's experimental mine at Lake Lynn Laboratory on the response of fire sensors to simulated mine fires, which included (1) a slowly developing coal-conveyor belt fire, (2) a rapidly burning liquid fuel-belt fire, and (3) a liquid fuel-belt fire in the presence of diesel exhaust. During these tests, several mine fire sensors were evaluated with respect to sensor placement, spacing, and type. The data indicate that smoke sensors alarm several minutes before CO sensors do; and that, in the presence of diesel exhaust, a prototype diesel-discriminating smoke sensor can successfully function without being sensitive to the diesel contaminants. The vertical placement of sensors in the entry near the fire was also shown to be critical in terms of alarm times. Additional data showed that variations exist in response time and level of response for two brands of electrochemical CO sensor. Results also indicate that early detection of fires will improve the probability of miners' escape, because of reduced smoke concentrations during the incipient stages of the fire.

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INTRODUCTION

An underground mine fire not only is a serious threat to life, but also results in economic losses, such as losses of mining equipment, coal reserves, production, and jobs. Mine fires can spread rapidly and are both difficult and dangerous to extinguish. If they are not contained in the early stages, portions of a mine or the entire mine must often be sealed for long periods.

During the incipient stages of a fire, smoke and gaseous products including CO are produced and released into the mine atmosphere. If these products are not detected in the early stages of combustion, they can result in severe hazards to personnel in remote and confined areas. Many underground mine fires are discovered in their early stages by mine personnel who often must make a split-second decision to either fight the fire or escape. The success of safely controlling and extinguishing an incipient mine fire depends on several factors, such as awareness of the fire hazards, availability of effective fire fighting equipment, qualifications of the personnel, and amount of response time. If a coal mine fire cannot be contained by direct fire fighting methods within a few hours after discovery, the chances of successfully extinguishing the fire without sealing the mine are greatly diminished.

From 1983 to 1988, 86 underground coal mine fires were reported to the Mine Safety and Health Administration (MSHA) (*1*).[3] These fires caused 29 fatalities, numerous injuries, the sealing of several mines, and financial losses totaling tens of millions of dollars. To reduce the risks and severity of mine fires to an absolute minimum, the U.S. Bureau of Mines has an active research program to identify and eliminate mine fire hazards, develop and evaluate improved methods to detect and suppress mine fires, and help miners survive.

The successful detection of a developing fire in a mine entry using CO or smoke sensors requires that three events take place, each with an associated time frame. The first detection event that must occur is that the developing fire must be large enough or extensive enough to generate bulk average CO or smoke levels greater than, or equal to, the alarm threshold levels of the sensors. Bulk average levels are obtained when the fire-produced CO or smoke mixes with the ventilation airflow. The time it takes for sufficient CO or smoke to be produced depends upon the type of fire and the ventilation rate. For a liquid fuel fire, this time is short because the total surface area of the liquid fuel is involved very rapidly from the moment of ignition. For a more slowly developing coal fire, this time increases. If smoldering exists at a sufficient intensity, detection of the smoldering stage of a fire is possible. If the smoldering period is short and flames erupt before detection, then the coal fire must attain a sufficient intensity to generate the required CO or smoke levels for the alarm thresholds.

The second detection event that must occur is the transport of the CO or smoke from the fire to the sensor location. The transport time is computed by dividing the sensor spacing by the air velocity. At low air velocities this time can be long, resulting in a significant delay in the time to alarm. Increasing the airflow decreases the travel time, but also dilutes the CO and smoke levels.

The third detection event is the sensor response time. Although, in general, most sensors respond rapidly, the use of a sensor with a long response time can increase the time to alarm.

The combustion products leaving the fire are hotter than the ventilation air and, as a result, rise vertically toward the roof because of induced buoyancy forces. The greater the temperature difference between the fire products and the ambient air, the greater the buoyant velocity in the vertical direction is. This effect creates a layer of combustion products stratified near the roof downstream of the fire. Within this stratified layer, the levels of CO or smoke may be several times the bulk average levels. The point of formation of this layer downstream of the fire and the actual levels of CO and smoke that exist within the layer depend upon the relative values of imposed air velocity and buoyant gas velocity. As these hot gases move downstream, the layer dissipates because of cooling and turbulent mixing with the ventilation airflow.

Detectors located near the roof take advantage of this effect and provide earlier warning than detectors placed lower do, especially when located in close proximity to the developing fire. Detectors located along the vertical centerline of an entry may be too low and may fail to detect a fire occurring immediately upstream because all of the CO or smoke is layered near the roof.

This paper presents data on the detection of fires and addresses all of the above factors: travel time, sensor response time, and vertical sensor placement. The alarm times for CO versus smoke sensors are also compared. Of additional importance is the demonstration of a smoke sensor that can selectively detect a fire in the presence of diesel exhaust contaminants. Visual observations of smoke arriving downstream from the fire are also compared with sensor response and CO levels.

[3]Italic numbers in parentheses refer to items in the list of references at the end of this report.

ACKNOWLEDGMENTS

The authors wish to thank the following members of the Bureau's Pittsburgh Research Center for their important contributions: Robert Franks, electronics engineer, and John Opferman, electronics technician, for their assistance in calibrating the CO and smoke sensors; and Frank Nagy and Richard Pro, physical science technicians, for their assistance during experimental setup.

EXPERIMENTAL PROCEDURES

LAKE LYNN LABORATORY

The Bureau's Lake Lynn Laboratory, formerly a limestone mine (*2*), is now a multipurpose mining research facility for fire and explosion prevention research. Figure 1 shows the laboratory's underground layout and aboveground quarry area. The new entry dimensions of the underground mine range from 1.8 to 2.4 m high and from 5.3 to 6.7 m wide. The average dimensions are 2.1 m and 5.8 m, for an average cross-sectional area of 12 m^2.

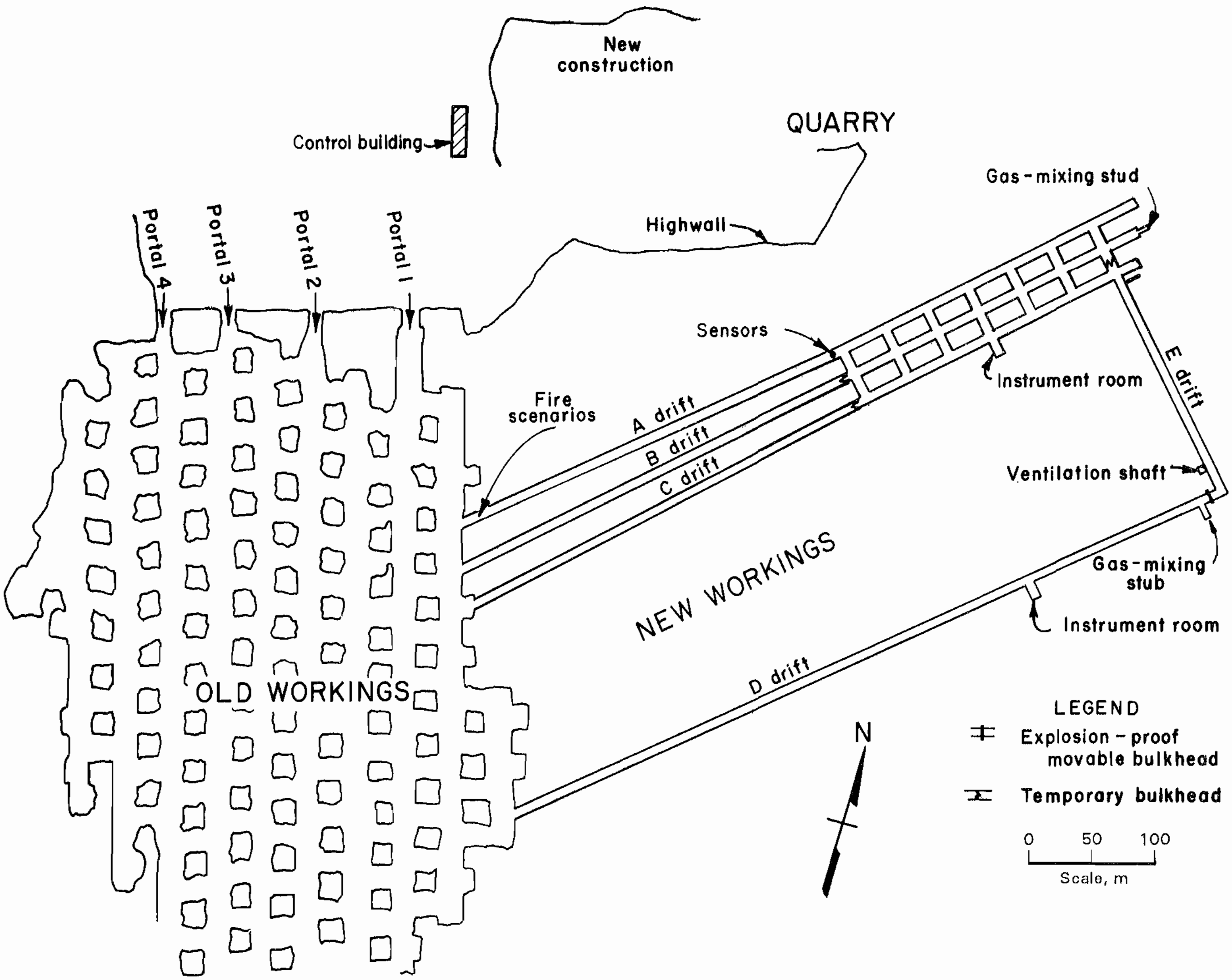

Figure 1.—Plan view of Lake Lynn underground mine and quarry area, showing configuration for fire scenarios in A drift.

SENSOR TYPE AND PLACEMENT

Fire detectors may be classified into three main categories according to their principles of operation: optical field of view, thermal, and products of combustion. The majority of optical sensors are designed to detect open fires or explosions where the combustion and radiance levels are high. Thermal sensors (thermal wire cables, thermistor cable, and thermocouples) respond to the increase in ambient temperatures that results from the high heating rates of a fire. A recent evaluation of a relatively new technology measuring distributed temperatures using fiber-optic cables (*3*) indicates that this approach may have considerable merit for temperature monitoring along mine entries, such as belt lines and trolley cables. Products of combustion detectors sense some product of the combustion process. These products, in the form of gas or smoke, are carried by the mine ventilation network to distances far removed from their point of generation, and may be detected by smoke or gas detectors. Smoke detectors can be classified into two types: those that use light extinction or scattering from the smoke to detect its presence, and those that sense the effect of smoke on the air-ionization current of a radioactive diode. Gas detectors can typically respond to CO, CO_2, or to other combustion products of a fire. A detailed study of detecting incipient combustion products can be found in reference 4 and a study of detecting fires in conveyor belt entries in reference 5.

The fire detection studies (*6*) reported here were conducted in A drift. A detailed layout of a typical underground fire and detection scenario is shown in the perspective view in figure 2. During the experiments the airflow of the mine was reversed, so that the combustion products were exhausted through the main fan. The moveable bulkhead door in D drift was closed, and the bulkhead door in E drift was in an open position. Temporary stoppings

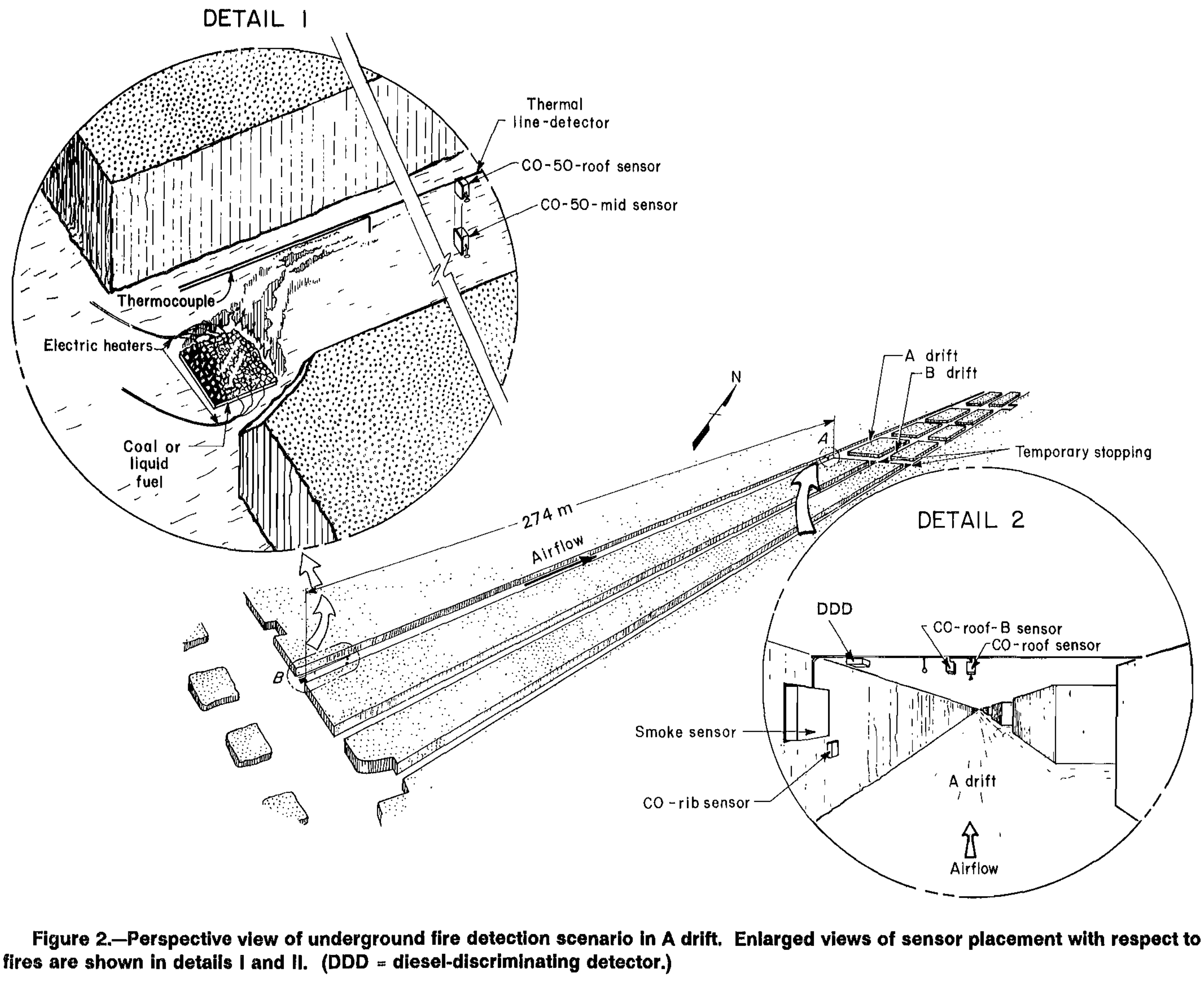

Figure 2.—Perspective view of underground fire detection scenario in A drift. Enlarged views of sensor placement with respect to fires are shown in details I and II. (DDD = diesel-discriminating detector.)

were installed at the last cross cuts of B and C drifts. The airflows were adjusted with one of the four positions of the main fan and a 0.61-m butterfly valve located in the bulkhead door of D drift. The airflow was measured with a vane-type anemometer 15.2 m inby the fire zone.

Two thermal sensors were located near the fire source. A type-K thermocouple was placed at the roof 0.3 m inby the fire zone, and a continuous length of a thermal line-type fire detector (heat-sensitive cable) was mounted at the roof from the portal of A drift and extended 30.5 m over and past the fire zone. This line-type fire detector is a twisted pair of insulated wires that short circuit when exposed to temperatures in excess of 68° C.

Products of combustion detectors were used at two positions along the mine entry. Two pump-operated, electrochemical CO sensors (see figure 2, detail I) were mounted 15.2 m inby the fire zone in the middle of the entry. One CO sensor was mounted near the roof and was labeled CO-50-roof. The other CO sensor was mounted directly below, 0.66 m from the floor, and was labeled CO-50-mid. Figure 3 shows the placement of the two CO sensors mounted in the entry, 15.2 m inby the fire zone.

Five fire sensors were mounted as shown in detail II of figure 2, in the entry cross section at a point 274 m inby the fire zone. Three diffusion-type electrochemical CO sensors were used. Two were mounted at the roof, labeled CO-roof and CO-roof-B, and represented two brands of CO sensor. The other CO sensor was mounted 0.66 m from the floor on the rib, identified as CO-rib, and was the same brand as the CO-roof sensor. A commercially available ionization-type smoke sensor, labeled Smoke, was mounted on the rib, with the intake sampling point located beside the CO-roof-B sensor at the 274-m location. A prototype diesel-discriminating smoke detector, labeled DDD, was mounted beside the intake sampling point of the Smoke and CO-roof-B sensors at the 274-m location. Figure 4 is a photograph of these sensors mounted in the entry. CO and smoke sensors were calibrated before each test.

The diesel-discriminating detector (7) is a novel device that can be used to discriminate between smoke produced

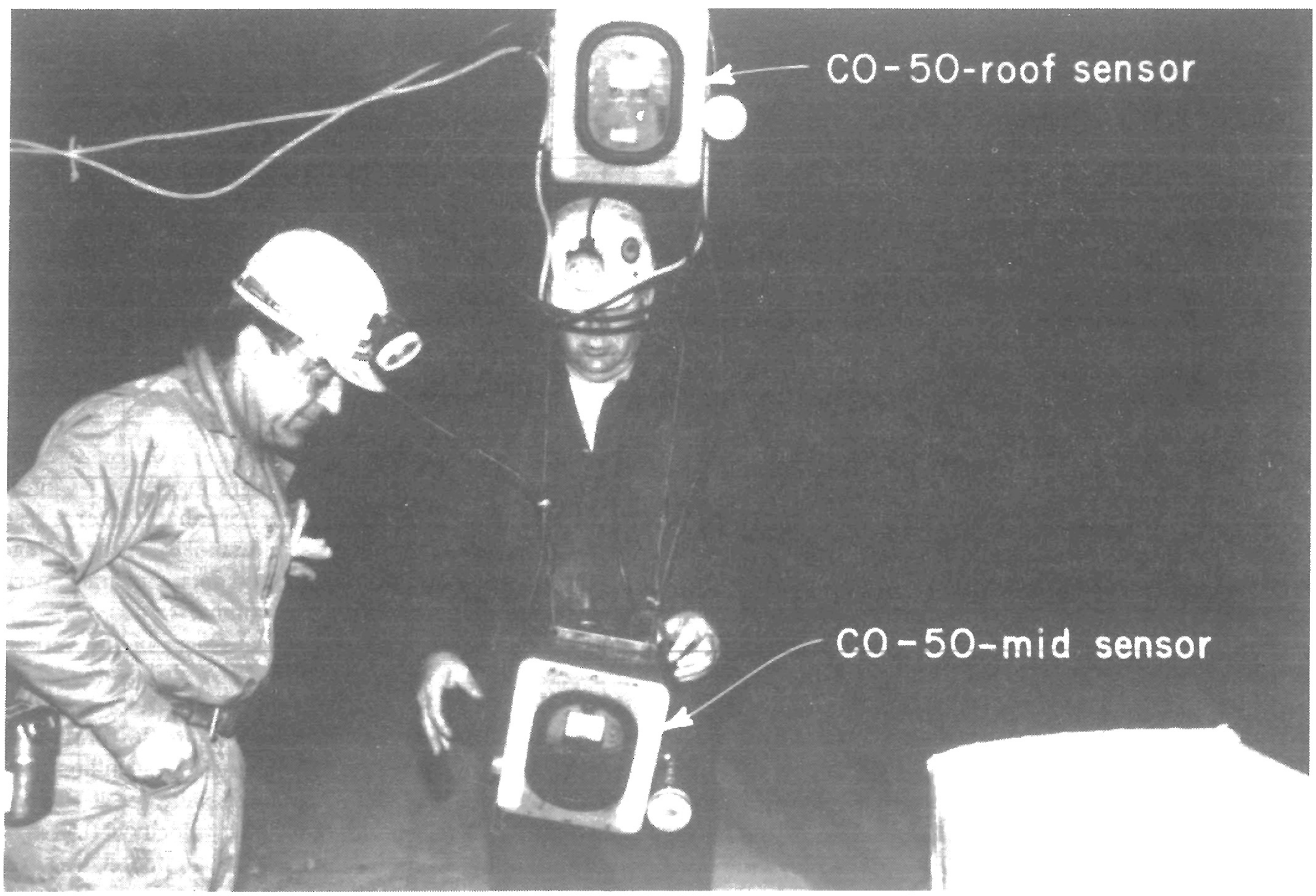

Figure 3.—Vertical placement of CO sensors, 15.2 m inby fire zone.

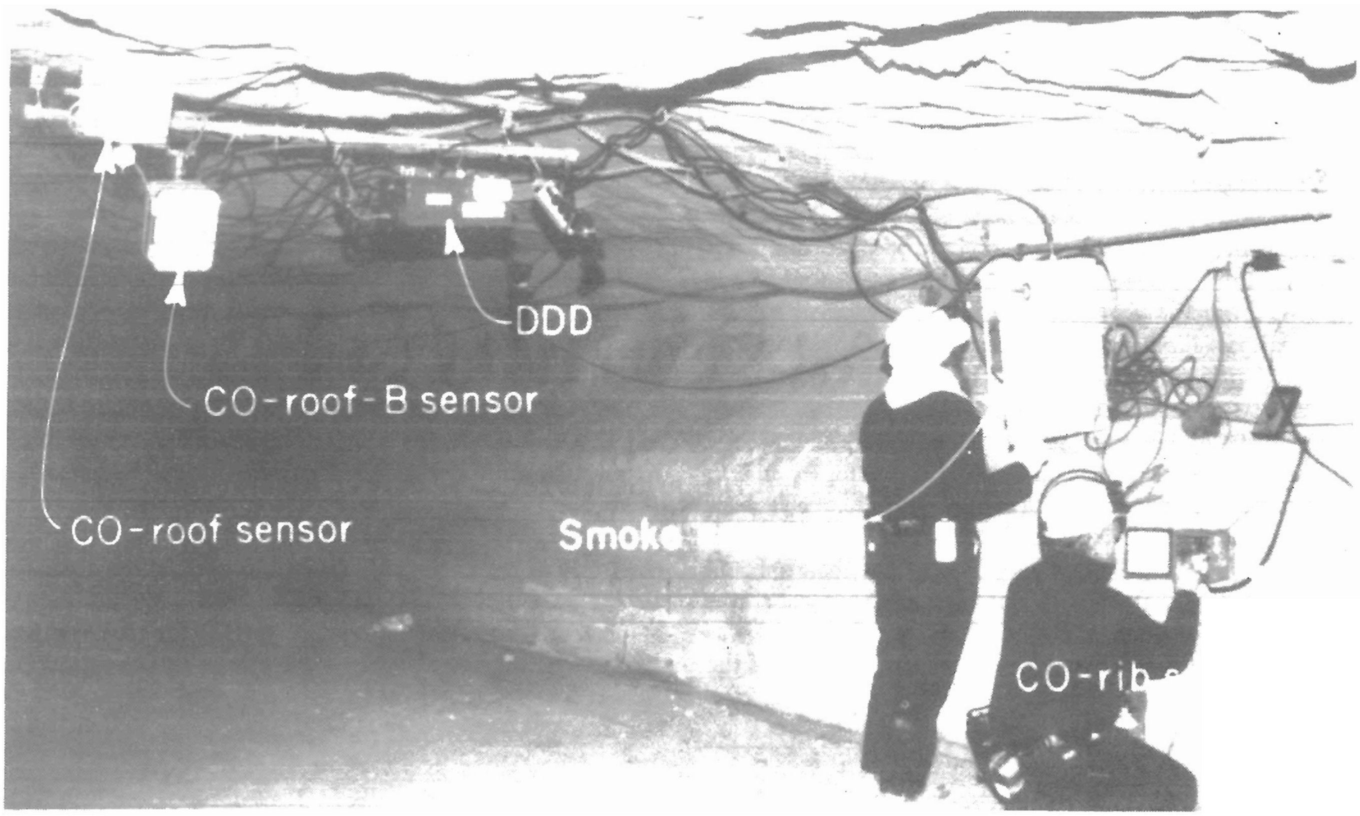

Figure 4.—Fire sensors, 274 m inby fire zone. (DDD = diesel-discriminating detector.)

by a fire and smoke produced by a diesel engine. The detector uses a pyrolysis technique whereby a sample of smoke-laden gas passes through a short, heated tube. Within this tube, fire smoke particles pyrolyze, increase in number concentration, and decrease in average size; diesel smoke particles are unaffected. The diesel-discriminating detector was developed to reduce the numerous false alarms in mines that utilize diesel equipment, which makes detection of fires complicated because of the background levels of diesel emissions.

EXPERIMENTAL RESULTS

SENSOR RESPONSE TO COAL-BELT FIRES

One of the scenarios studied was a slow-developing coal-conveyor belt fire. Seven 220-V electric strip heaters with a combined power rating of 9.5 kW were embedded into a 1.2- by 1.2-m coal pile and used to ignite 75 kg of Pittsburgh coal. Six 10.2- by 22.8-cm strips of rubber conveyor belting were evenly distributed in the coal pile and then the pile was seeded with approximately 0.75 kg of pulverized Pittsburgh coal dust. Full electrical power was applied to the heating elements. Visible smoke from the coal pile was usually observed in 3 to 4 min, with flames emitting from the coal 9 min later, as shown in figure 5.

The outputs of the fire sensors were connected to a 24-channel A/D converter that transmitted the data to a computer for storage. The data were logged at 1-s intervals and displayed on a computer terminal. After a test, time-CO concentration traces and smoke sensor voltage plots were generated from the stored data. Several experiments were also recorded on videotape.

Figures 6 through 12 are typical traces of the various fire sensors that were mounted in A drift for a slow-developing coal-conveyor belt fire. The data collected from the CO sensors are shown in figures 6 through 10 and indicate the level of CO in parts per million with respect to time. The CO alarm levels were set at 10 ppm, and the tests were conducted at an air velocity of 0.58 m/s.

The output signal, in volts, of the commercially available ionization-type Smoke sensor is shown in figure 11. The Smoke sensor was set to alarm when the threshold voltage reached 0.5 V. Figure 12 is an output trace for the

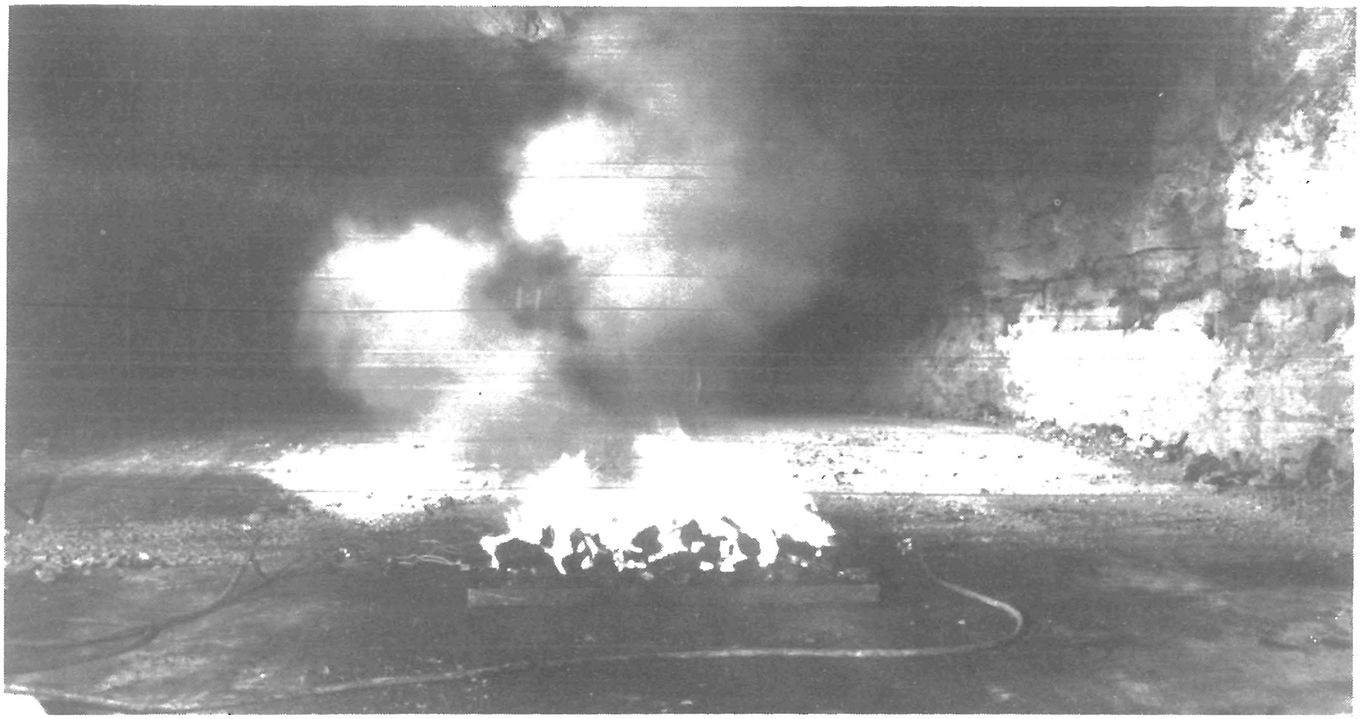

Figure 5.—Flames from coal-conveyor belt pile.

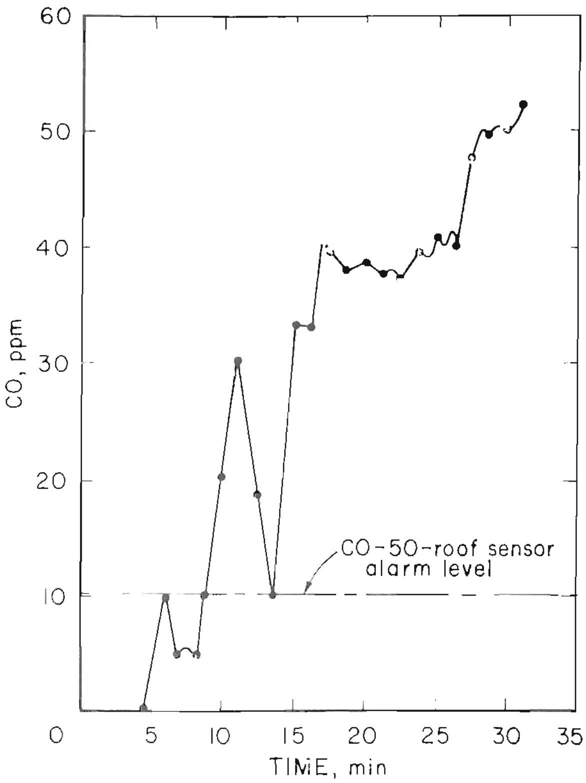

Figure 6.—CO concentration at 15.2-m roof station as function of time.

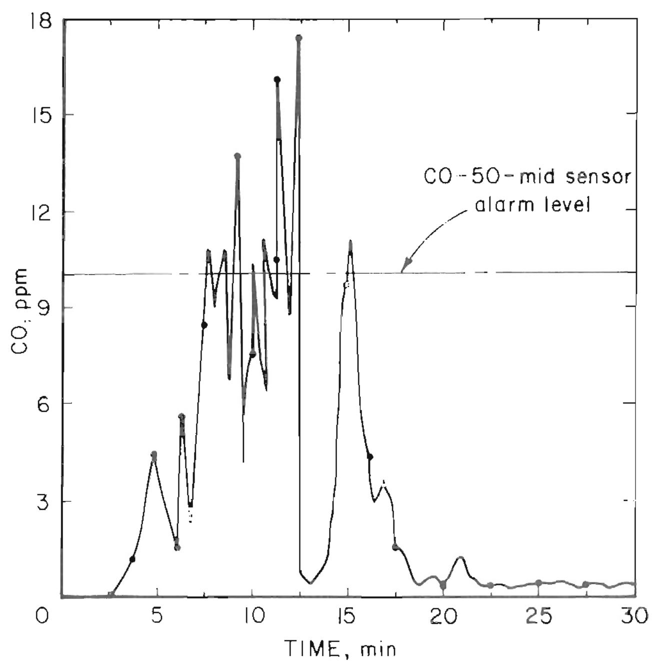

Figure 7.—CO concentration at 15.2-m mid-entry station as function of time.

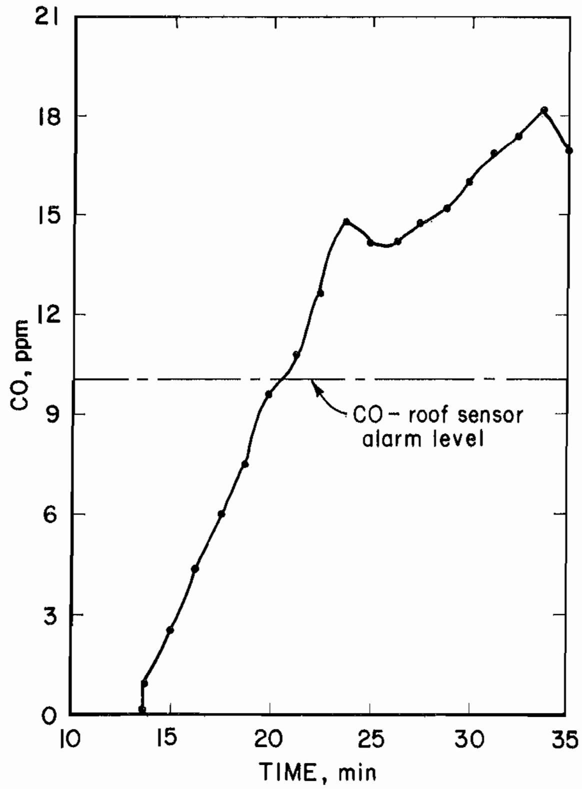

Figure 8.—CO concentration at 274-m roof station as function of time.

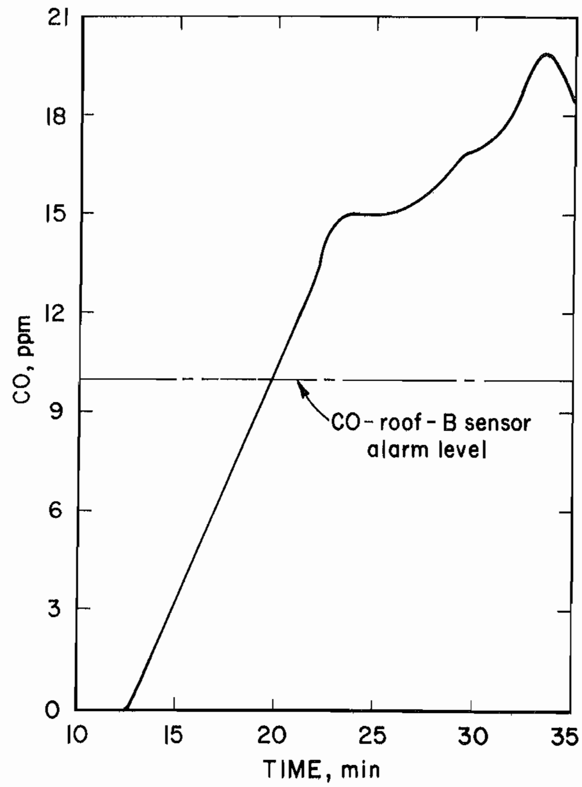

Figure 9.—CO concentration at 274-m roof station of another brand of sensor as function of time.

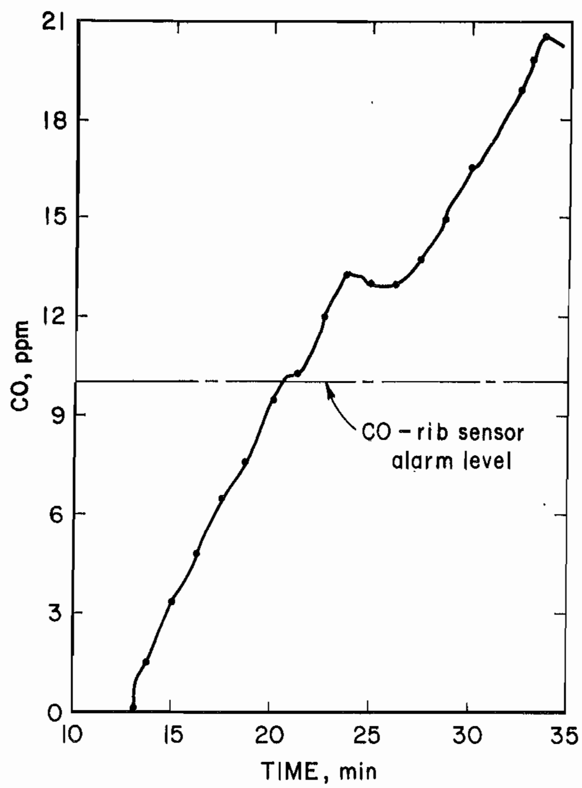

Figure 10.—CO concentration at 274-m rib station as function of time.

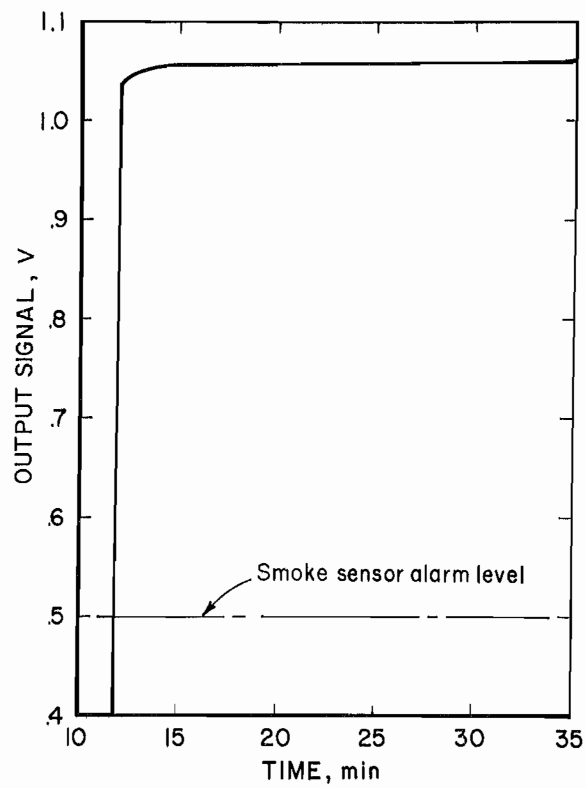

Figure 11.—Typical response of downstream Smoke sensor as function of time.

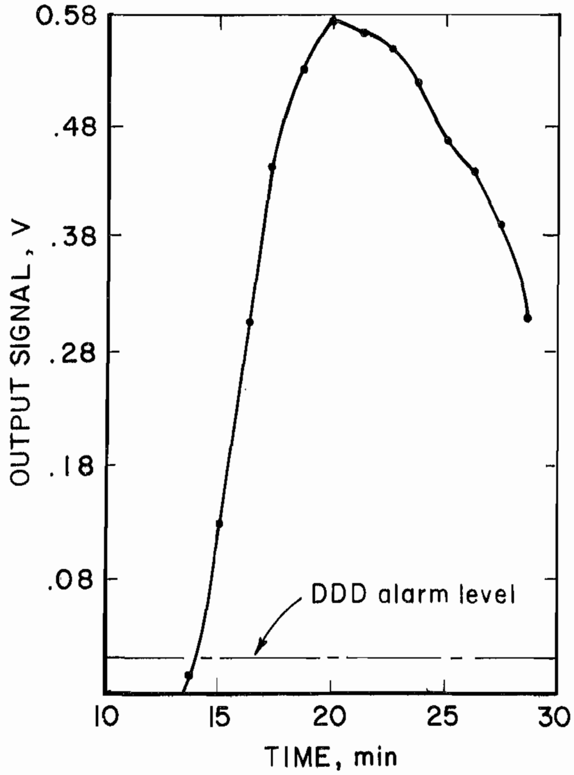

Figure 12.—Response of downstream diesel-discriminating detector (DDD) as function of time.

prototype DDD. The alarm level of the DDD was arbitrarily set for 0.025 V.

Table 1 lists the response time (T_A) of the various sensors for a test conducted at an air velocity (V_o) of 0.56 m/s. In this test visible smoke was first observed from the coal pile 2.5 min after power was supplied to the strip heaters, and flaming was observed 12 min into the test. For this test the smoke and CO travel time from the fire to the 274-m station was 8.2 min. The earliest observed response was from the CO-50-roof sensor. This is to be expected, since the combustion products rise to the roof. Both the Smoke sensor and DDD responded to smoke that was actually produced from the smoldering fire. In other words, the smoke levels at alarm were actually produced about 5 min into the test, and it took an additional 8.2 min for this smoke to reach the sensors. Only the CO-roof-B sensor at the 5-ppm level actually detected CO produced from the smoldering coal prior to flaming. These delayed alarm times clearly show the impact of travel time on fire detection.

The effects of the 10-ppm alarm threshold levels were also dramatic, especially when the alarm times between 5 and 10 ppm are compared. For the CO-roof-B sensor it took about 5.5 min longer to reach 10 ppm than it took to reach 5 ppm. For the CO-roof and CO-rib sensors, an additional 10 min was required to reach 10 ppm. At the 15-ppm CO level, the average time for CO sensors at the 274-m station to respond was 31 min, almost 17.5 min longer than that of the Smoke sensor. It is also worth noting that by subtracting the travel time from this response time (31 min minus 8.2 min), the 15-ppm CO response did not occur until 11 min after flaming was first observed.

The other point to note from the data is that the two CO sensors of the same brand, CO-roof and CO-rib, responded at almost the same time, even though one was located near the roof while the other was located on the rib, approximately 1.4 m from the roof. These results indicate that by the time the CO reached the 274-m station essentially complete mixing of the fire-produced CO with the ventilation airflow had occurred.

All of the times discussed above are significant, especially when it is realized that rapid response and warning may mean the difference between life and death of underground personnel.

Table 1.—Response times of underground fire sensors to coal-belt fire

Sensor	Distance from fire, m	Alarm time,[1] min:s	T_A: 5 ppm CO, min:s	T_A: 10 ppm CO, min:s	T_A: 15 ppm CO, min:s
CO-50-roof . . .	15.2	NAp	4:20	5:40	7:17
CO-50-mid . . .	15.2	NAp	6:11	[2]6:22	[2]8:49
CO-roof	274	NAp	19:03	29:11	31:51
CO-roof-B . . .	274	NAp	16:43	22:05	29:40
CO-rib	274	NAp	19:03	29:31	31:23
Smoke	274	13:50	NAp	NAp	NAp
DDD	274	13:20	NAp	NAp	NAp

DDD Diesel-discriminating detector.
NAp Not applicable.
T_A Response time.
[1]Alarm time of Smoke sensor and DDD is the amount of time before sensors reached the preset threshold voltage.
[2]Fire sensor oscillating in and out of alarm.

COMPARISON OF ALARM TIMES OF SMOKE SENSORS AND CO SENSORS AT FOUR AIRFLOWS FOR SLOW-DEVELOPING COAL-BELT FIRES

The superiority of smoke sensors over CO sensors is quite evident from data presented in table 2. This table shows the alarm times of the smoke sensors at four airflows for slow-developing coal-belt fires and the corresponding CO level at the time of the smoke alarm. The Smoke and CO sensors were located 274 m inby the fire. At the average CO level of only 1 ppm, the Smoke detector had already reached the alarm threshold. For the DDD alarm, the average CO was 2.5 ppm. These data are consistent with previous data (*8*), which show that, on the average, at a smoke optical density of 0.44 m^{-1} (alarm level), the CO is 1.8 ppm for smoldering coal fires.

Table 2.—CO levels at smoke alarm times for coal-belt fires

V_o, m/s	Time to Smoke alarm, min:s	CO at Smoke alarm, ppm	Time to DDD alarm, min:s	CO at DDD alarm, ppm
0.48 . . .	11:15	1	13:16	4
0.61 . . .	14:15	1	16:02	2
0.76 . . .	13:15	1	13:20	2
1.09 . . .	11:05	1	12:21	2

DDD Diesel-discriminating detector.
V_o Air velocity.

Figure 13 plots the bulk average CO produced by the fire and the ratio of the roof CO at the 15.2-m location to the bulk average CO versus time for a slowly developing coal-belt fire at an air velocity of 1.09 m/s. For these data, the average CO levels of three CO sensors at the 274-m station are used, subtracting the travel time (4.2 min) from the fire to the sensors. It is obvious that location of a sensor near the roof immediately downstream from the fire takes advantage of the buoyancy-induced stratification that occurs. For instance, at 7 min into the test, the bulk average CO was only 4 ppm, yet the CO-50-roof sensor measured almost 17 ppm because of the stratification.

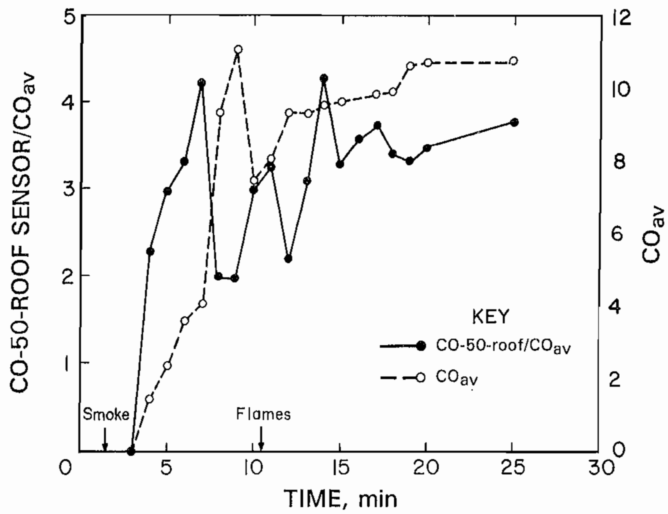

Figure 13.—Comparison of bulk average CO (CO_{av}) produced at fire with ratio of roof CO to average CO versus time for coal-belt fire.

SENSOR RESPONSE TO LIQUID FUEL-BELT FIRES

The effects of air velocity on alarm times (10-ppm CO alarm level) of fire sensors for rapid-burning liquid fuel-belt fires are shown in table 3. The experiments were conducted at four airflows of 0.48 to 1.09 m/s. Two strips of rubber conveyor belting (0.143 m^2) were placed over a 0.26-m^2 metal pan filled with 400 mL of No. 2 diesel fuel. The belting strips were allowed to overlap the metal pan, forming a cross. The pan fire was ignited, producing a rapid-burning fuel fire. The alarm times of the CO sensors 274 m downstream did not significantly change with increased airflows, because the reduced time for the CO to reach the sensor location at the higher airflows was offset by greater dilution. The alarm times for the Smoke sensor decreased with higher airflows, varying inversely with the air velocity, because of its greater sensitivity compared with CO sensors.

Table 3.—Alarm times of fire sensors at four airflows for liquid fuel-belt fires, minutes

Airflow rate . . . . . m/s . .	0.48	0.61	0.76	1.09
CO-roof	13.8	13.3	13.6	12.3
CO-roof-B	11.5	11.0	11.8	11.0
CO-rib	12.5	12.8	13.7	12.3
Smoke	9.2	8.0	7.2	5.9

SENSOR RESPONSE TO DIESEL EXHAUST AND TO FIRE

A scenario was developed simulating the numerous false alarms experienced by many mines utilizing diesel equipment. During the tests, a small 65-hp diesel engine (fig. 14) was positioned near the portal of A drift and allowed to operate until downstream smoke sensors alarmed. Then a liquid fuel-conveyor belt fire was allowed

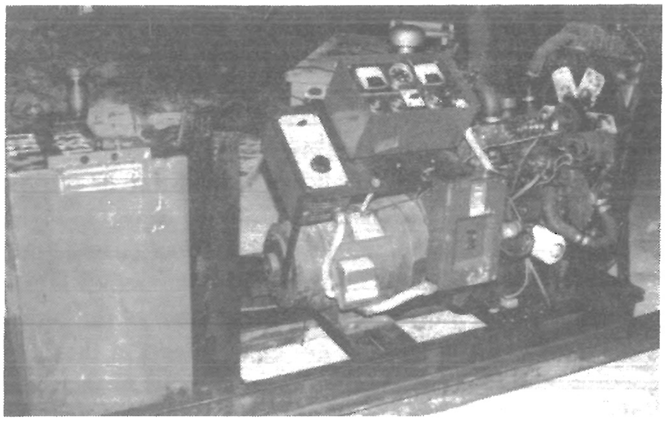

Figure 14.—65-hp diesel engine used to generate diesel background.

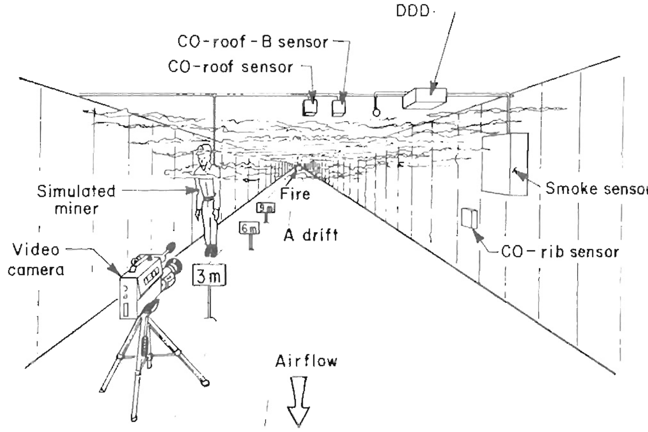

Figure 15.—Perspective view of underground fire detection scenario in A drift to compare smoke arrival with sensor response at 274-m station. (DDD = diesel-discriminating detector.)

to develop in a diesel background. Two strips of rubber conveyor belting (0.143 m^2) were placed over a 0.26-m^2 metal pan filled with 400 mL of No. 2 diesel fuel. The belting strips were allowed to overlap the metal pan, forming a cross. After a steady-state diesel level was established, the pan fire was ignited by an extended propane torch, producing a rapid-burning fuel fire.

Table 4 shows the alarm times of CO sensors, the Smoke sensor, and the DDD to the diesel exhaust products at an airflow of 0.56 m/s. All sensors but the DDD responded to the diesel products. Three CO sensors alarmed at 10 ppm, along with the Smoke sensor, while two CO sensors indicated 9- and 7-ppm maximum CO levels. For this test, the fuel-belt fire was ignited about 18.7 min into the test. Subtracting the travel time (8.2 min), the DDD took about 4.6 min to respond to the fuel-belt fire. For a typical liquid fuel-belt fire without the diesel exhaust products, the DDD typically responded in about 5 to 6 min. These results indicate that not only does the DDD remain insensitive to diesel smoke, but also that the presence of diesel smoke does not affect the alarm time of this detector to an actual fire.

SENSOR RESPONSE COMPARED WITH VISIBLE SMOKE

Figure 15 illustrates an underground fire detection scenario that was conducted in A drift to compare visual smoke arrival with fire sensor response and CO concentration at the 274-m station. Three placards were placed in the center of the entry 3, 6, and 9 m upstream from a video camera. A simulated miner was also positioned 4.5 m from the camera and in the same plane as the fire sensors. The airflow was 0.3 m/s and the ambient temperature was 13° C. The data in figure 16 depict the relationship between visibility and CO concentration 274 m downstream with respect to time and sensor alarms. The time was measured from the moment when the heating elements in the coal pile were energized. The test fire was a slow-developing coal-belt fire with added conveyor belting. Eight 10.2- by 22.8-cm strips of rubber conveyor belting were evenly distributed in the coal pile, and then the pile was seeded with approximately 0.75 kg of pulverized coal dust. Increased CO and smoke levels were obtained by placing two 23- by 61-cm strips of belting on top of the coal pile.

Table 4.—Alarm times of fire sensors during liquid fuel-belt fire in presence of diesel exhaust

Sensor	Diesel exhaust		Fuel-belt fire	
	Alarm time, min:s	Maximum CO, ppm	Alarm time, min:s	Maximum CO, ppm
CO-50-roof . .	1:53	28	X	82
CO-50-mid . .	NA	9	NA	9
CO-roof	14:40	11	X	28
CO-roof-B . .	12:45	18	X	32
CO-rib	NA	7	29:40	23
Smoke	10:45	[1]1	X	NAp
DDD	NA	NAp	31:30	[1]20

DDD Diesel-discriminating detector.
NA Fire sensor did not alarm; 10-ppm alarm level for CO sensors.
NAp Not applicable.
X Fire sensor in alarm mode.
[1]CO level at Smoke and DDD alarms.

The thermal wire detector alarmed 25.5 min after the heating elements in the coal pile were energized and 9.5 min after visual flames appeared. The temperature, as measured by the thermocouple at this time, was 45° C,

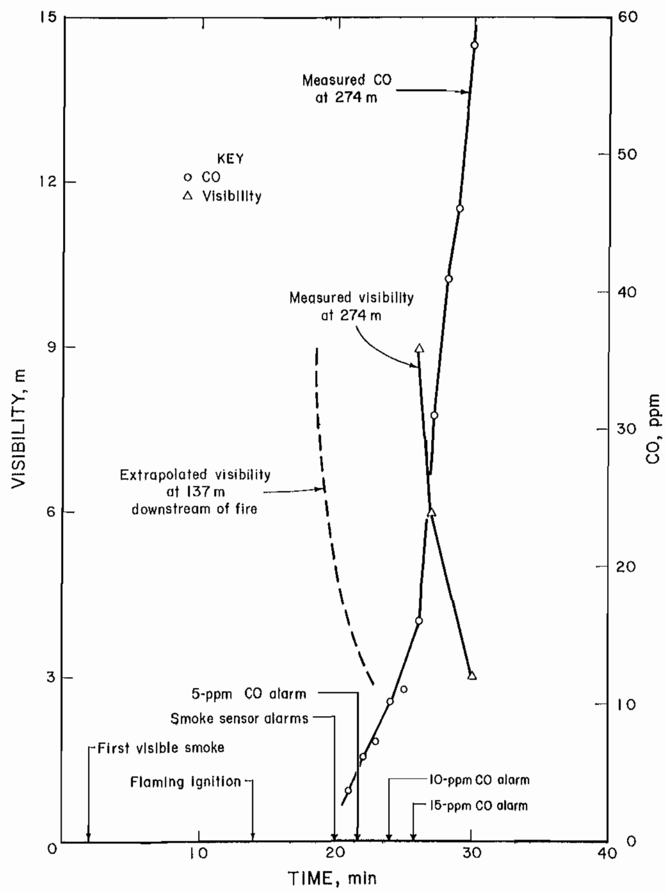

Figure 16.—Relationship between visibility and CO concentration 274 m downstream with respect to sensor alarms.

well below the 57° C alarm setting of point-type thermal sensors. The Smoke sensor and DDD at 274 m alarmed at 20 min, and the average alarm time of the three CO sensors was 24 min. Complete obscuration of the 9-, 6-, and 3-m placards near the 274-m locations occurred at 26, 27, and 30 min, respectively, after the start of the test. Corresponding CO levels at these times were 12, 24, and 36 ppm. The data indicated that the thermal line detector over the fire alarmed 5.5 min after the smoke sensors alarmed 274 m away and at the same time as the 10-ppm CO sensor, also located at 274 m. Visibility at the 274-m station was reduced to zero within minutes of the sensor alarms.

In another underground fire detection test, the time of a change in the ambient odor at the 274-m station was compared with times of visual smoke arrival and smoke sensor alarm. A coal-conveyor belt fire similar to that in the previous test was used at a slightly greater airflow of 0.4 m/s. An odor, followed by visible smoke, was noticed 2 min before both smoke sensors alarmed. The thermal wire detector did not alarm and the maximum temperature as measured by the thermocouple at this time was 46° C. The CO sensors at the 274-m location alarmed 7 min after the smoke sensors alarmed.

For a rapid-burning liquid fuel fire, visible smoke was observed near the roof, and the smoke propagated toward the camera 10 s before the Smoke sensor alarmed and 2 min before the DDD alarmed. Dense smoke continued to fill the entire cross section of the entry, and within several minutes visibility was reduced to zero.

SUMMARY AND CONCLUSIONS

The results clearly indicate that in these full-scale tests the sensitivity and response times vary depending on the type of sensors, their locations, and the ventilation rate. Smoke sensors alarm more quickly, usually when CO levels are in the range of 1 to 2 ppm. At low airflows, travel times from the fire to the sensors can be significant and effectively degrade early warning capability. Sensor placement near the roof takes advantage of buoyancy-induced stratification and allows response much earlier to fires located in close proximity upstream of the sensors. Variations in the response time and level of response of two brands of electrochemical CO sensor may be due to the internal placement of the sensing cell of each unit, or to the method of sensor calibration.

The results also demonstrate the unique ability of the diesel-discriminating detector to prevent false alarms in the presence of diesel exhaust, unlike other sensors, while still maintaining the capability to respond rapidly to a developing fire.

Visual observations 274 m downstream of the fire indicated a change in the ambient odor followed by visible smoke 2 min before the Smoke sensor alarmed for a slow-developing coal-belt fire. The reduced visibility from the smoke produced from the fire indicates that critical smoke levels are obtained before hazardous concentrations of CO are reached, and that early detection of fires will improve the probability of miners' escape.

The thermal line-type fire detector did not alarm during any of the underground fire tests, except for the coal fire with added conveyor belting at low airflows, indicating that temperatures over the fires near the roof did not exceed the alarm level of 68° C. The temperature increase measured by the thermocouple for those fires was only 7° to 12° C above ambient. The data clearly show the advantages of smoke and CO sensors compared with the thermal sensors that were evaluated during these tests.

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