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Diesel-Discriminating Detector Response to Smoldering Fires

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	min	minute
cm	centimeter	μm	micrometer
cm^3	cubic centimeter	m/s	meter per second
g/cm^3	gram per cubic centimeter	m^3/s	cubic meter per second
kg	kilogram	p/cm^3	particle per cubic centimeter
m	meter	ppm	part per million
m^{-1}	reciprocal meter	s	second
mg/m^3	milligram per cubic meter	V	volt

DIESEL-DISCRIMINATING DETECTOR RESPONSE TO SMOLDERING FIRES

By Margaret R. Egan[1]

ABSTRACT

Reliable fire detection is essential for both safe evacuation and containment or extinguishment. In order to increase reliability by reducing the number of nuisance fire alarms in underground mines that use diesel-powered equipment, the U.S. Bureau of Mines has developed a diesel-discriminating fire detector (DDD). It was designed to discriminate between smoke produced by a fire and the smoke-laden exhaust of a diesel engine.

Experiments were conducted by the Bureau to compare the smoke detection capabilities of the DDD with those of conventional fire detectors in response to smoldering coal and conveyor belting. A comparison was made among the alarm times of a carbon monoxide (CO) detector with an alarm threshold of 5 ppm, a smoke detector with an optical density alarm threshold of 0.044 m^{-1}, and the DDD with an alarm threshold of 0.025 V. The results show that the DDD will reliably detect developing coal and conveyor belt fires. The average time delay separating the DDD alarm from the first detector to alarm was 76 s for smoldering conveyor belt and 65 s for smoldering coal. The longest time delay between the response of the DDD and the first detector to alarm was approximately 120 s.

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INTRODUCTION

In an underground mine, diesel engine exhaust products can mix with the ventilation airflow, sometimes resulting in concentration levels sufficient to trigger smoke and carbon monoxide (CO) fire detectors. As of December 1990, there were 1,843 diesel machines in 141 underground coal mines. Of these mines, 48 use CO fire detectors (*1*).[2] Therefore, significant potential for nuisance fire alarms exists. To improve mining safety, the U.S. Bureau of Mines developed the diesel-discriminating detector (DDD) (*2*) to reduce the number of nuisance alarms caused by diesel exhaust. Previous studies (*3*) have demonstrated the DDD's ability to discriminate between smoke produced by a fire and the smoke from a diesel engine. The present studies compare its smoke detection capabilities to those of conventional fire detectors.

The objectives of this study were (1) to analyze the gas production and smoke characteristics of smoldering fires and (2) to compare the response of the DDD to other smoke and CO detectors. Measurements of CO concentration, smoke particulate mass (M_o) and number (N_o) concentrations, light transmission (T) through smoke, and DDD response are used for these comparisons. From these results, the particle diameter and optical density (D) can be calculated.

These experiments were conducted in an intermediate-scale fire tunnel at several air velocities. The detection of smoldering coal and conveyor belt was compared for three types of detectors: CO, smoke, and the DDD. When the DDD was set at an alarm threshold of 0.025 V, it reliably detected a smoldering fire, and the DDD's alarm times compared favorably with those of the conventional smoke and CO detectors.

MATERIALS AND EQUIPMENT

The test apparatus for these experiments included a simulated mine environment, coal or conveyor belting, heating element or strip heaters, and gas and smoke analyzers. Each will be described in some detail. Prior to each experiment, gas calibrations and background readings were recorded. All instruments were continuously scanned and recorded throughout the experiment. A computer program was developed to collect and process the data.

FIRE TUNNEL

The experiments were conducted in the Bureau's intermediate-scale fire tunnel. Figure 1 shows a schematic view of the tunnel with its data-acquisition system. The first horizontal section is cone shaped and 1.5 m long. It is hinged and can be lifted to allow entrance into the tunnel for the placement of the fuel. The section begins with a cylindrical duct that measures 0.25 m long by 0.3 m in diameter and gradually enlarges until it matches the tunnel dimensions. Next is the fire zone, where the ignition source and fuel platform are located. The fire zone and the remaining horizontal section are lined with fire brick and contain the flow probes and sampling ports. This section measures 0.8 m square by 10 m long. The diffusing grid begins the vertical section of the tunnel, which contains an adjustable orifice plate. The final section is horizontal and ends at a two-speed exterior exhaust fan.

HEAT SOURCES

For the coal experiments, a cylindrical heating element containing four strip heaters was used to simulate an overheated idler roller on a conveyor belt drive. A schematic of this heating element is shown in figure 2. The heating element is capable of reaching 500° C.

For the conveyor belt experiments, three electric strip heaters were clamped to a piece of conveyor belting. The strip heaters were the same size as the ones inside the heating element for the coal experiments.

FLOW PROBES AND PRESSURE TRANSDUCERS

The ventilation through the tunnel was continuously measured using a bidirectional flow probe (*4*) in conjunction with a pressure transducer. The airflow, produced by the exhaust fan, was detected by the flow probe and converted to a linear electrical signal by the pressure transducer. This signal was then scanned, stored, and converted to cubic meters per second by the data-collection software. The locations of all of the flow probes are shown in figure 1. The flow probe centered in the air-intake cylinder was used to obtain the velocity measurements for these experiments.

The stated error of the flow probe is ±7%. The pressure transducer introduces another possible error of

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

±5.3%. Assuming the errors to be independently distributed, the compound error was estimated to be ±8.8%. Averaging over 10 data points improves the precision by the square root of 10, resulting in a total estimated error of ±2.8%.

Before each experiment, velocity readings were also made at the air intake with a vane-type anemometer to ensure that the air velocity was in the desired range.

CO DETECTOR

The CO detector was an Ecolyzer 2000 Series[3] produced by National Drager. Its stated accuracy is within 1% of full range or ±5 ppm. The analyzer was calibrated at the beginning of each experiment.

[3]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

SMOKE DETECTORS

Condensation Nuclei Monitor

The particle number concentration (N_o) was obtained with a Condensation Nuclei Monitor (CNM), manufactured by Environment One Corp. of Schenectady, NY. The accuracy of the instrument and its dilution system is ±21%, making it the least accurate of all instruments.

Tapered-Element Oscillating Microbalance

The particle mass concentration (M_o) was obtained by a tapered-element oscillating microbalance (TEOM) (5).

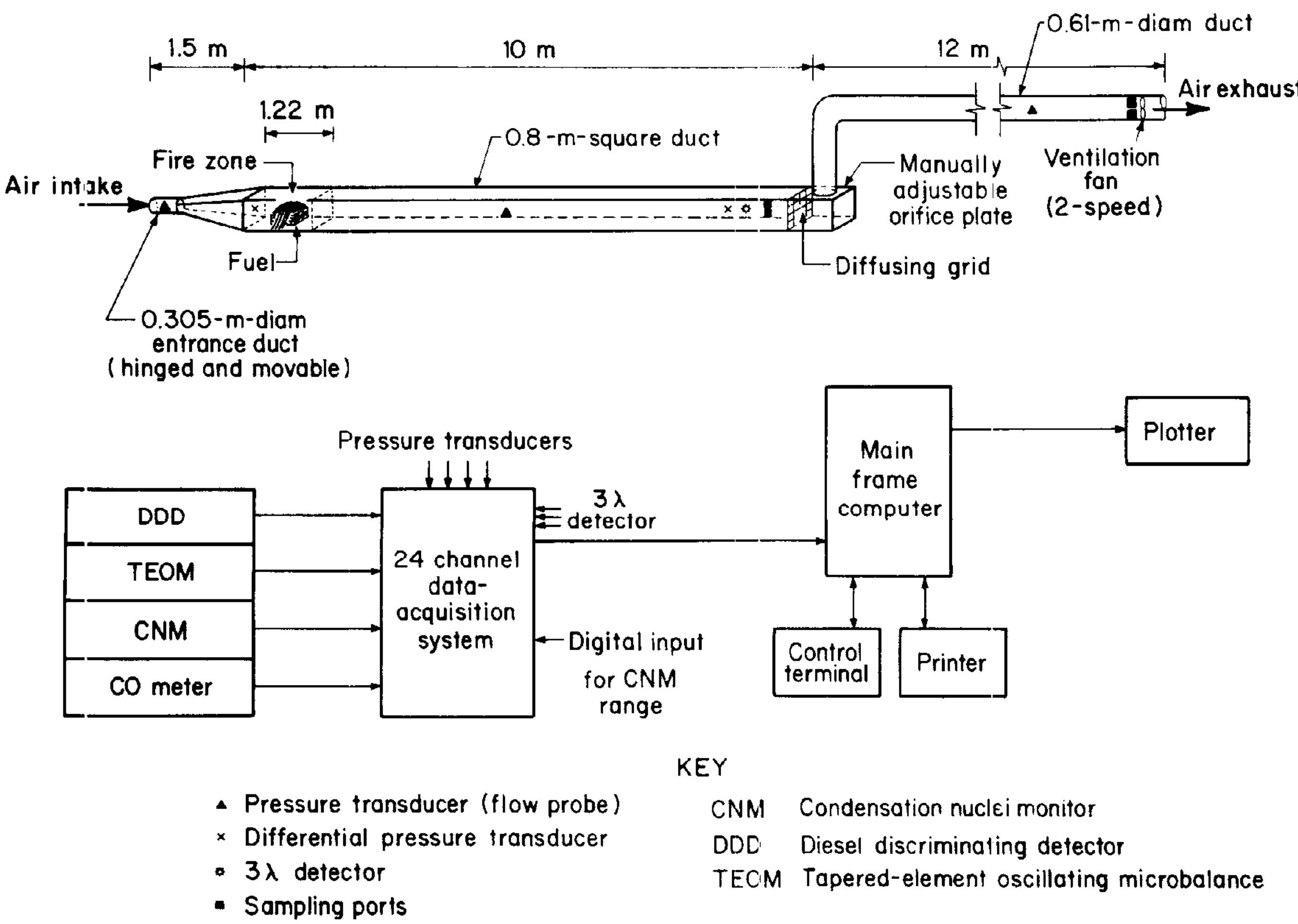

Figure 1.–Schematic of intermediate-scale fire tunnel (top) and data-acquisition system (bottom).

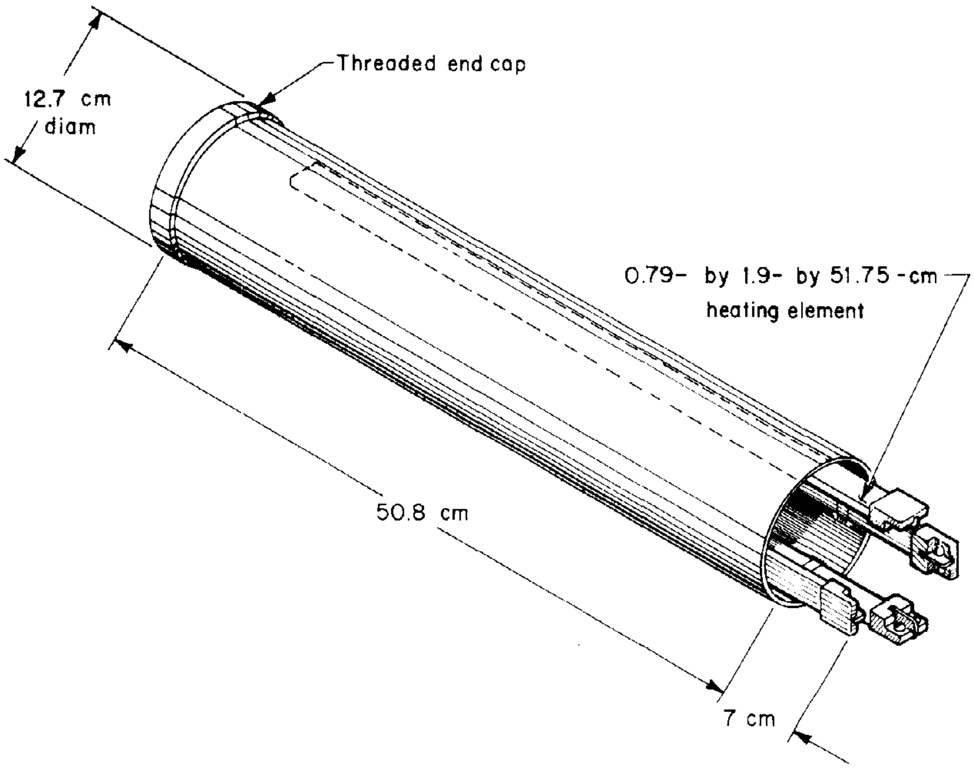

Figure 2.—Schematic of heating element.

It measures the mass directly by depositing the particles on a filter attached to an oscillating tapered element. The oscillating frequency of the tapered element decreases as the deposited mass increases. The apparatus is capable of accurately measuring the particulate concentration to within 5% at the level used. According to the manufacturer, the filter collects at least 50% of all particles with a volume mean diameter of 0.05 μm, with increasing collection efficiency as the diameter increases. Actual data obtained by the Bureau using particles of volume mean diameter equal to 0.048 μm indicated a collection efficiency closer to 90%.

Since the diameter of average mass (d_m) is calculated from the mass and number concentrations, its accuracy was dependent upon the precision of the TEOM and CNM. Considering the error band of the mass and number concentrations from the conveyor belt experiments, the diameter of average mass could vary by 10%.

Three-Wavelength Smoke Detector

A three-wavelength light transmission technique developed by the Bureau (*6*) was also used to measure particle size (d_{32}) and smoke obscuration. White light was transmitted through a smoke cloud to the detector. The beam was split into three parts, and each passed through an interference filter centered at wavelengths of 0.45, 0.63, and 1.00 μm. Each of the resulting beams was measured by a photodiode. All photodiode outputs were amplified and recorded.

Diesel-Discriminating Detector

The Bureau developed the DDD to distinguish between the emissions from diesel engines and fire smoke. The DDD's design is based on the fact that internal combustion engines generate particulates at much higher temperatures than can be found in most fires. The number of fire smoke particles increases when heated to 300° C, but particulates from internal combustion engines do not. A submicrometer-particle detector developed by the Bureau was fitted with a dual-input ionization chamber. One portion of the smoke passes around a ceramic rod heated by a nichrome wire. The remaining portion of the smoke is unheated. A comparison is made between the number of particles from the heated and the unheated smoke. If only smoke from an internal combustion engine is present, the output signals cancel each other and no alarm is triggered. If only fire smoke is present, the signal from the heated sample is higher than the signal of the unheated sample. An imbalance of 0.025 V can trigger an alarm. When both fire smoke and diesel exhaust are present, an alarm is also triggered because the signal components associated with the engine smoke are canceled, but the fire smoke signals remain.

EXPERIMENTAL METHODS

COAL

Six experiments with Pittsburgh Seam coal (tests 1 through 6) were completed. Three tests were conducted at each air velocity (V_o), which resulted in fire zone ventilation rates (V_oA_o) of 0.13 and 0.31 m^3/s. The coal rested on a platform 38 cm high. This reduced the air space above the coal to 40 cm. Approximately 9 kg of coal was broken into pieces measuring 125 cm^3 or less and was piled on and around the simulated roller. From 5 to 7.5 cm of coal rested on top of the roller, thus producing a pile of coal approximately 18 cm high and 27 cm wide at its base. The timing of all experiments began when the heating element was turned on. The heater was set at 150 V for 15 min and then raised to 200 V. Smoke was sighted after 17 min and flames erupted after 35 min. Thirty minutes after flaming combustion was sighted, the power was turned off. The coal continued to sustain flaming combustion. The experiments were terminated after approximately 95 min while the coal was still flaming.

CONVEYOR BELTING

Four conveyor belting experiments (tests 7 through 10) were completed. In each test, three electric strip heaters were clamped to the top of a 23- by 30-cm section of styrene butadiene rubber (SBR) belting. Each test lasted about 20 min. The strip heaters were energized to 200 V for about 10 min and then turned off. Smoke was sighted after 3 min. After smoldering for 8 min, the belt in experiment 7 burst into flames. In all other experiments, the belts smoldered without flaming combustion. The ventilation rate averaged 0.12 m^3/s for all belt experiments.

CALCULATIONS

SMOKE INTENSITY PARAMETERS

The transmission of light through smoke (T) can be measured using the three-wavelength smoke detector. Some factors influencing T are the particle density, particle size, M_o, complex refractive index, light wavelength, and optical path. T is calculated from the expression

$$\%\ T = \frac{I_s - I_o}{I - I_o}(100), \tag{1}$$

where I_s = intensity of light in the presence of smoke,

I = intensity of light in the absence of smoke,

and I_o = background reading in the absence of light.

A convenient measurement of smoke density is to examine the obscurant effect of smoke. It is calculated from the expression

$$\%\ \text{obscuration} = \frac{(I - I_o) - (I_s - I_o)}{I - I_o}(100). \tag{2}$$

Smoke evolution is most often expressed in terms of its optical density (D), which correlates directly with visibility. D is related to T by the following expression:

$$D = -\frac{1}{\ell}(\log T), \tag{3}$$

where ℓ = path length, m. D becomes a convenient measure of fire hazard and detectability, because escape and rescue are dependent upon visibility. Most smoke detectors are triggered at a D of 0.044 m^{-1} or less. The probability of escape and rescue is reduced significantly once the critical level of smoke (D = 0.218 m^{-1}) has accumulated (7). The obscuration and D values presented in this report are an average of the attenuation of the beam of light at the two wavelengths in the visible range, 0.45 and 0.63 μm, the average corresponding to the wavelength of maximum sensitivity for the human eye.

SMOKE PARTICLE DIAMETERS

Measurements of both M_o and N_o of the smoke can be used to calculate the average size of the smoke particles, using the expression

$$\frac{\pi d_m^3}{6}(\rho_p)(N_o) = 1 \times 10^3\ M_o, \tag{4}$$

where ρ_p = individual particle density, g/cm^3;

d_m = diameter of average mass, μm;

M_o = mass concentration, mg/m^3;

and N_o = number concentration, p/cm^3.

Assuming a value of ρ_p = 1.1 g/cm³ (*8*), then the diameter of average mass (d_m) can be calculated (in micrometers) from

$$d_m = 12.02 \left[\frac{M_o}{N_o}\right]^{1/3} . \quad (5)$$

The size of the smoke particles can also be determined using the three-wavelength smoke detector. The extinction-coefficient ratio can be calculated for each pair of wavelengths (λ) from the following log-transmission ratios:

$$\frac{\ln T_{\lambda=1.00}}{\ln T_{\lambda=0.63}}, \quad \frac{\ln T_{\lambda=1.00}}{\ln T_{\lambda=0.45}}, \quad \text{or} \quad \frac{\ln T_{\lambda=0.63}}{\ln T_{\lambda=0.45}} .$$

Using these extinction coefficients and the curve in figure 11 of reference 6, the volume-to-surface mean particle diameter (d_{32}) can be determined. (Calculation of the extinction-coefficient curves assumes spherical particles with an estimated refractive index.) The T must be less than 0.85 to reliably calculate d_{32} using this technique.

SMOLDERING COMBUSTION EMISSIONS

Table 1 lists average CO concentration and smoke characteristics produced by smoldering coal and SBR belt. The data for each test represent an average of the entire smoldering period, including the decaying phase when the heat source was turned off. The air velocities were chosen so that the emissions were at comparable production rates. Therefore, the SBR belts were burned at a slower air velocity than the coal.

COAL

The coal experiments were conducted at two air velocities. Air velocity is a critical consideration in fire detection underground. Early detection capabilities could be jeopardized with increased air velocity because the level of combustion emissions could be diluted to below the detector alarm threshold. In these tests, the CO and smoke concentrations did decrease when the air velocity was increased, but all were above the alarm thresholds. Larger particles may have resulted at the lower air velocity, but this cannot be confirmed from these experiments because of the low smoke concentrations.

STYRENE BUTADIENE RUBBER BELT

In test 7, the SBR belt burst into flames. The CO concentration and smoke obscuration did not peak but kept rising. The CO reached a concentration of 350 ppm and the obscuration was 76% at the time the experiment was terminated. For this reason, the results of test 7 are not included in the average calculation that reflects the emissions from smoldering belts.

Table 1.—CO concentrations and smoke characteristics

Test	CO, ppm	M_o, mg/m³	N_o, 10^5 p/cm³	d_m, µm	Obscuration, %	D, m^{-1}	d_{32}, µm	DDD,[1] V
SMOLDERING COAL EMISSIONS, V_o 1.41 m/s								
1	16	17.6	10.49	0.308	5.81	0.418	ND	0.129
2	27	11.7	9.26	.280	11.73	.779	ND	.310
3	32	ND	7.13	ND	12.16	.728	ND	.240
Av	25	14.7	8.96	.294	9.90	.642	ND	.226
SMOLDERING COAL EMISSIONS, V_o 0.57 m/s								
4	79	34.7	7.79	0.426	22.11	1.374	0.500	0.181
5	85	32.4	6.70	.438	22.97	1.225	.438	.139
6	92	38.0	7.63	.442	23.82	1.281	.490	.090
Av	85	35.0	7.37	.435	22.96	1.294	.476	.137
SMOLDERING SBR BELT EMISSIONS, V_o 0.19 m/s								
7[2]	61	68.8	8.19	0.507	34.72	1.992	0.388	0.219
8	38	46.9	16.28	.368	20.57	1.056	.263	.157
9	29	10.6	9.52	.263	13.22	.592	.293	.143
10	41	14.3	9.83	.294	9.60	.452	.249	.266
Av[3] ...	36	24.0	11.88	.309	14.46	.700	.269	.189

ND Not determined.
[1]Average positive response.
[2]Average excludes flaming emissions.
[3]Average excludes test 7.

DETECTOR RESPONSE COMPARISONS

Table 2 lists the times required for the three detectors to reach their respective alarm levels. The alarm thresholds of the three types of fire detectors are as follows: CO, 5 ppm; smoke, D of 0.044 m^{-1}; and DDD, 0.025 V. The CO detector usually responded first to smoldering coal (four out of six times regardless of the air velocity). The smoke detector usually responded second (four out of six times). The DDD responded last (five out of six times), an average of 37.2 s after the smoke detector. Because this was a rapid heating, all these detectors responded quickly and, on the average, only 76 s separated the first to alarm from the last to alarm. For smoldering SBR belt, the smoke detector responded first in three of the four tests. In test 10, the CO detector responded first and was 2.77 min ahead of the smoke detector, which responded last.

Table 3 lists the relative levels of smoke and CO at respective alarm thresholds. For example, in test 1, when the DDD reached its alarm threshold of 0.025 V, the D was 0.045 m^{-1} and the CO was 5.63 ppm. Both of these detectors had reached their alarm threshold. When the smoke detector in test 1 had reached its alarm threshold of 0.044 m^{-1}, the CO detector measured 5.6 ppm, also above its alarm threshold of 5 ppm. In this test, the CO detector was the first to alarm, as seen in table 2. Test 10 is unique; the CO concentration was already above 33 ppm when both the smoke and DDD alarmed.

Initially, the response of the DDD may be negative, as seen in figure 3. In this particular test, smoke was sighted at the 23d minute and flaming combustion was sighted at the 35th minute. A slight dip is seen about the 20th minute. This behavior would indicate the potential for a built-in time delay that could be used to eliminate nuisance alarms. For example, the detector could be designed so that the alarm voltage of 0.025 V must be sustained. Once the detector reaches 0.025 V, an alert condition is issued, which becomes an alarm if this output level is sustained.

Table 2.—Alarm times, in minutes, in response to smoldering coal and SBR belt

Test	CO	Smoke	DDD
SMOLDERING COAL EMISSIONS, V_0 1.41 m/s			
1	22.86	23.12	23.13
2	24.20	23.01	23.15
3	22.60	23.06	24.19
SMOLDERING COAL EMISSIONS, V_0 0.57 m/s			
4	22.52	21.62	22.81
5	20.01	21.34	21.36
6	21.60	22.36	23.59
SMOLDERING SBR BELT EMISSIONS, V_0 0.19 m/s			
7	5.80	4.99	5.19
8	5.32	3.19	4.94
9	5.72	4.80	5.86
10	6.35	9.12	8.38

Table 3.—Relative levels of smoke and CO at respective alarm thresholds for smoldering combustion

Test	D, m^{-1},	CO, ppm	
	0.025-V DDD	0.025-V DDD	0.044-m^{-1} smoke detector
SMOLDERING COAL EMISSIONS, V_0 1.41 m/s			
1	0.045	5.63	5.60
2	.051	2.37	2.02
3	.135	10.34	6.20
SMOLDERING COAL EMISSIONS, V_0 0.57 m/s			
4	0.153	6.23	2.10
5	.028	9.96	9.82
6	.147	14.65	7.63
SMOLDERING SBR BELT EMISSIONS, V_0 0.19 m/s			
7	0.120	0.97	0.97
8	.235	2.43	0
9	.171	5.91	.97
10	.016	33.44	36.64

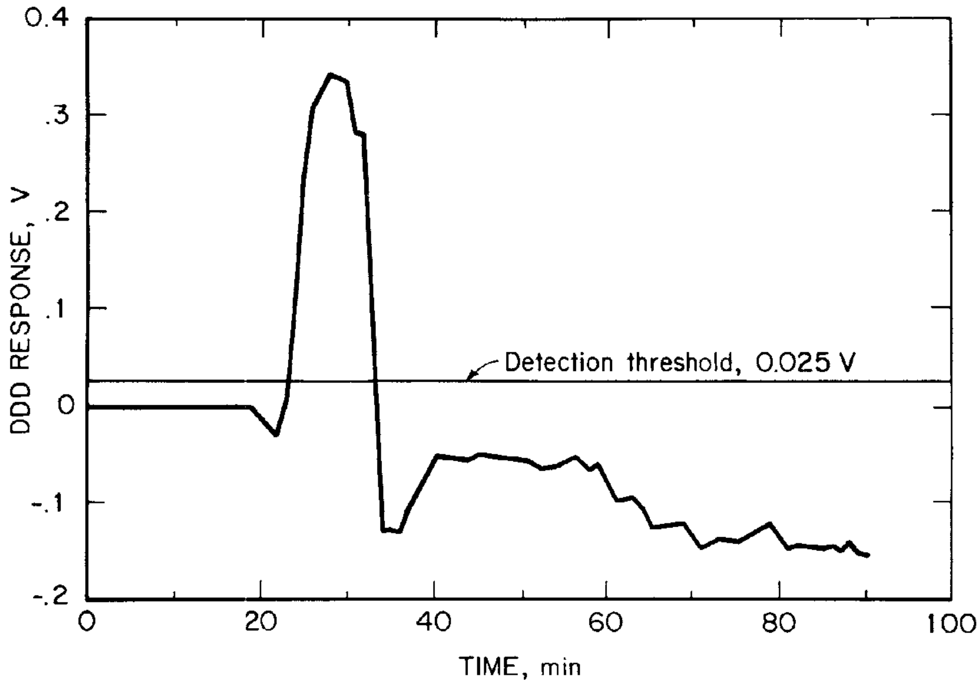

Figure 3.—Response of DDD in test 3 to smoldering coal.

CONCLUSIONS

The Bureau, in its effort to increase the reliability of fire detection systems, has developed the DDD. The DDD has already proven its ability to discriminate between diesel exhaust and fire emissions. The present experiments were conducted to compare its performance with that of conventional fire detection devices. As a fire detector, the DDD was as efficient as a conventional smoke detector. Its average response was 36 s after the smoke detector and 69 s after the first detector to alarm. In these tests, smoldering coal was best detected by a CO detector with an alarm threshold of 5 ppm, and smoldering SBR belting was best detected by a conventional smoke detector with an optical density alarm threshold of 0.044 m^{-1}.

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APPENDIX.—SYMBOLS USED IN THIS REPORT

D	optical density per unit path length, m^{-1}
d_m	diameter of average mass, µm
d_{32}	volume-to-surface mean particle size, µm
I_x	intensity of light
ℓ	optical path length, m
log	logarithm
ln	logarithm, natural
M_o	particle mass concentration, mg/m^3
N_o	particle number concentration, p/cm^3
p	particle
T	transmission of light, %
V_o	air velocity, m/s
V_oA_o	ventilation rate, m^3/s
λ	wavelength of light source, µm
ρ_p	individual particle density, g/cm^3

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