RI 9551

REPORT OF INVESTIGATIONS/1995

Development of Coal Combustion Sensitivity Tests for Smoke Detectors

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter
cm/s	centimeter per second
cm^2	square centimeter
g	gram
g/cm^3	gram per cubic centimeter
kΩ	kilohm
m	meter
m^{-1}	reciprocal meter
m^{-1}/min	reciprocal meter per minute
m^3/s	cubic meter per second
min	minute
mm	millimeter
pA	picoampere
pct	percent
pct/min	percent per minute
pct/pA	percent per picoampere
V	volt
V ac	volt, alternating current
V dc	volt, direct current
wt pct	weight percent
μA	microampere
°C	degree Celsius
Ω	ohm

DEVELOPMENT OF COAL COMBUSTION SENSITIVITY TESTS FOR SMOKE DETECTORS

By John C. Edwards[1] and Gerald S. Morrow[2]

ABSTRACT

Standard smoldering and flaming combustion tests using small coal samples have been developed by the U.S. Bureau of Mines as a method to evaluate the response of a smoke detector. The tests are conducted using a standard smoke box designed and constructed according to Underwriters Laboratories. The tests provide a standard, easily reproducible smoke characteristic for smoldering and flaming coal combustion, based upon a comparison of the smoke optical density and the response of a standard ionization chamber to the smoke. With these standard tests, the range of threshold limits for the response of a smoke detector and the detector's reliability can be evaluated for nearly identical smoke visibility and smoke physical characteristics. The detector's threshold response limits and reliability need to be well defined prior to the instrument's use as part of a mine fire warning system for improved mine safety.

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INTRODUCTION

The potential loss of life and property associated with mine fires makes their prevention a primary concern in the mining industry. If a mine fire should occur, the mine operator must be alerted to the event through early detection and then must implement miner evacuation and fire suppression measures. Once a fire has increased in intensity, it becomes less likely that fire extinguishment measures can be successfully implemented. This situation focuses paramount significance upon the installation of a reliable fire detection system. Traditional fire monitoring in conveyor belt entries has been by point-type thermal sensors. These sensors, which have been unable to detect some fires, have been replaced by carbon monoxide (CO) monitoring systems in an increasing number of mines because CO sensors provide better and earlier detection. Only in recent years have smoke detectors been tested in some mines.

The early signatures of combustion in a mine are CO and smoke. The physical characteristics of these two signatures are quite different. Carbon monoxide is readily defined as a volume concentration independent of the mode of combustion or gas transport distance from source to detector. Smoke particulates have a more complex characterization. Their particle size, mass concentration, and index of refraction will vary considerably with fuel source and combustion rate. Also, the particle size can vary with transport distance from the fire source. These distinctive characteristics affect the response of ionization and optical smoke detectors.

The U.S. Bureau of Mines' (USBM's) evaluation of the response of mine smoke detectors has been primarily in underground mines (*1*).[3] Currently, there are no performance criteria required for smoke detectors in mines other than intrinsic safety and atmospheric monitoring system requirements as prescribed in the U.S. Code of Federal Regulations (*2-3*). Factors that adversely affect the performance of smoke detectors in the mine environment are dust and relative humidity. These factors can contribute to false alarms. As part of its mission to conduct research that will enhance the health and safety of miners, the USBM developed a standardized coal smoke test that can be used to evaluate the response of smoke detectors.

Although any combustible present in a mine can contribute to a mine fire, the relative abundance of coal within a mine ensures that it is ultimately a likely contributor to a mine fire, if not initially. A coal fire can result from a short-time scale event, such as combustion induced by frictional heating from a conveyor belt roller, or a long-time scale event, such as spontaneous heating of loose coal. The physical characteristics of the smoke are independent of the type of ignition, but will depend upon whether the combustion mode is smoldering or flaming. A standardized method is needed to evaluate the response of a smoke detector to smoke characteristic of both smoldering and flaming coal combustion. A reasonable approach to this problem is to utilize an existing evaluation procedure used for commercial smoke detectors as a basis for development of a standard for the evaluation of in-mine smoke detectors. The USBM used the existing Underwriters Laboratories UL268 Standard for Smoke Detectors for Fire Protective Signaling Systems (*4*) to provide guidance for construction of the physical apparatus (the smoke box), as well as the component measurements of the smoke. This includes both optical measurements and a standard ionization chamber response to the smoke.

SMOKE BOX APPARATUS

The smoke box was constructed according to UL268 specifications (*4*). However, the method of introducing smoke into the box and sampling by the detector differs from the Underwriters Laboratories' method (*4*). A schematic of the USBM-constructed smoke box is shown in figure 1. The smoke was generated from a coal sample heated with a disc heater in a sample chamber. The sample chamber was connected to the smoke box at the access door marked "G" in figure 1. A schematic of the sample chamber is shown in figure 2. Because of the wood construction of the sample chamber, the box was lined with ceramic insulation. Only the circulating fan marked "A" in figure 1 was used for these tests. The fan delivered 0.02 m^3/s airflow. Figure 3 shows the disc heater with the coal sample. The sample used is 80 g of minus 9.4- plus 6.7-mm-mesh Pittsburgh Seam coal. A typical proximate analysis of the coal is shown in table 1 (*5*). The heating element is a Chromalox HSP-31-3, 400-W disc heater with a diameter of 10.2 cm. The heater temperature is monitored by a thermocouple on the heater surface. Initially, the smoldering coal test was developed with the smoke source interior to the smoke box near location G in figure 1. Because it was not possible to maintain a sustained flaming coal source at this position, the fuel source was moved to the sample chamber. This procedure was adapted for both the smoldering and flaming tests. The

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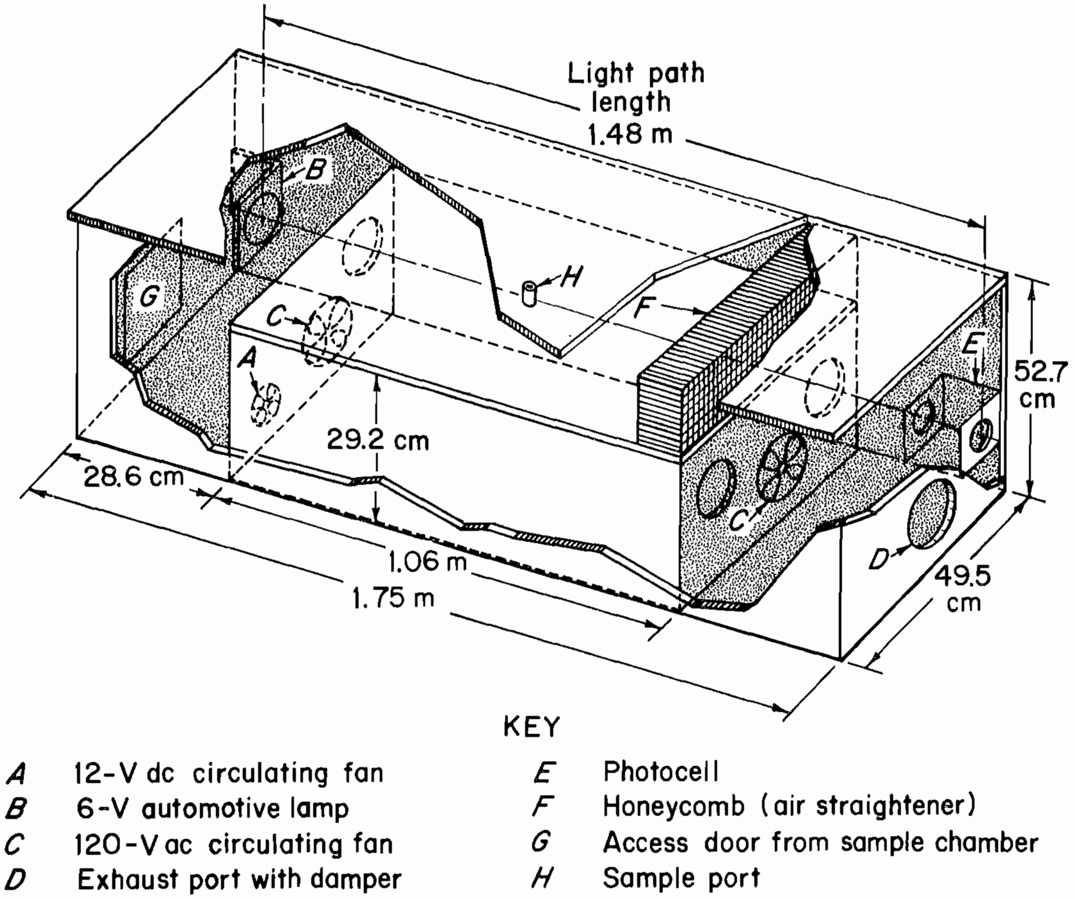
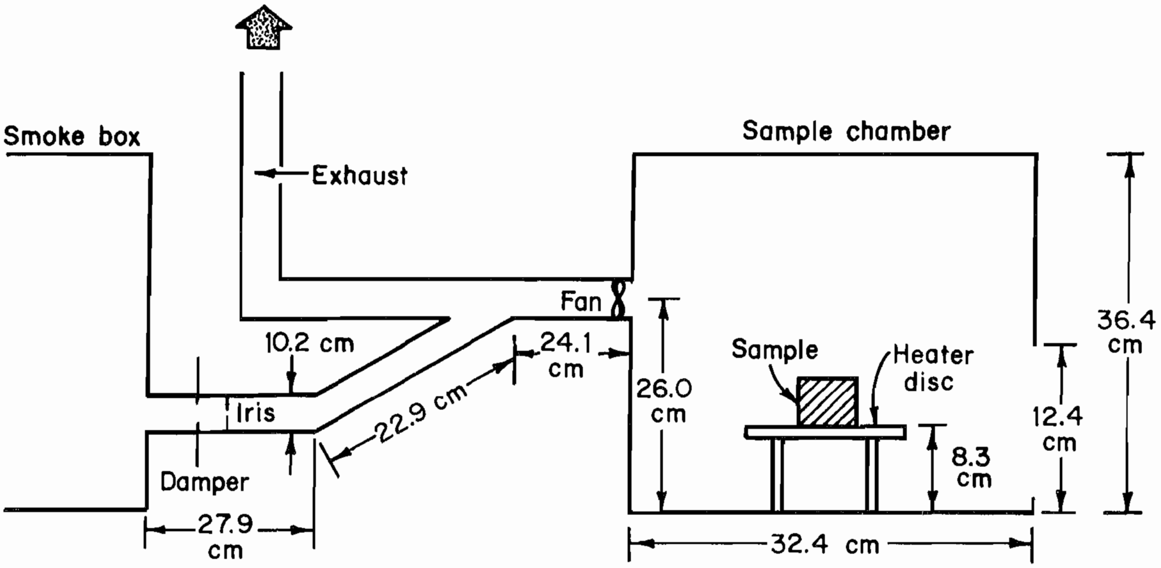
[3] Italic numbers in parentheses refer to items in the list of references preceding the appendixes at the end of this report.

Figure 1



Schematic of USBM-constructed smoke box.

Figure 2



Schematic of sample chamber.

coal sample is placed directly on the disc heater and contained on the sides by a 6.3-cm-high, 8.3-cm-diameter wire mesh with a 0.24-cm mesh size. The smoke generated in this sample chamber was drawn into the smoke box through a 10-cm-diameter horizontal duct by a 120-V ac fan powered by a variac set at 57.5 V. The fan delivers a volumetric airflow of 0.02 m^3/s at 120 V. The horizontal duct is split into two branches. One branch vents through a variable iris (figure 2) with diameter ranging from 0.32 to 7.62 cm into the smoke box at location G (figure 1). The other branch exhausted the smoke outside the laboratory by natural ventilation. The linear airflow in the smoke box is about 0.38 cm/s as a result of the circulating fan at location A (figure 1). The introduction of smoke into the smoke box was controlled differently for the smoldering and flaming coal tests.

Table 1.—Proximate analysis of Pittsburgh Seam coal

Component	Analysis, wt pct
Ash	5.6
Fixed carbon	53.9
Moisture	1.7
Volatile matter	38.8

For the smoldering test, the iris opening is set to 1.27-cm diameter. Smoke is vented into the smoke box for the entire test.

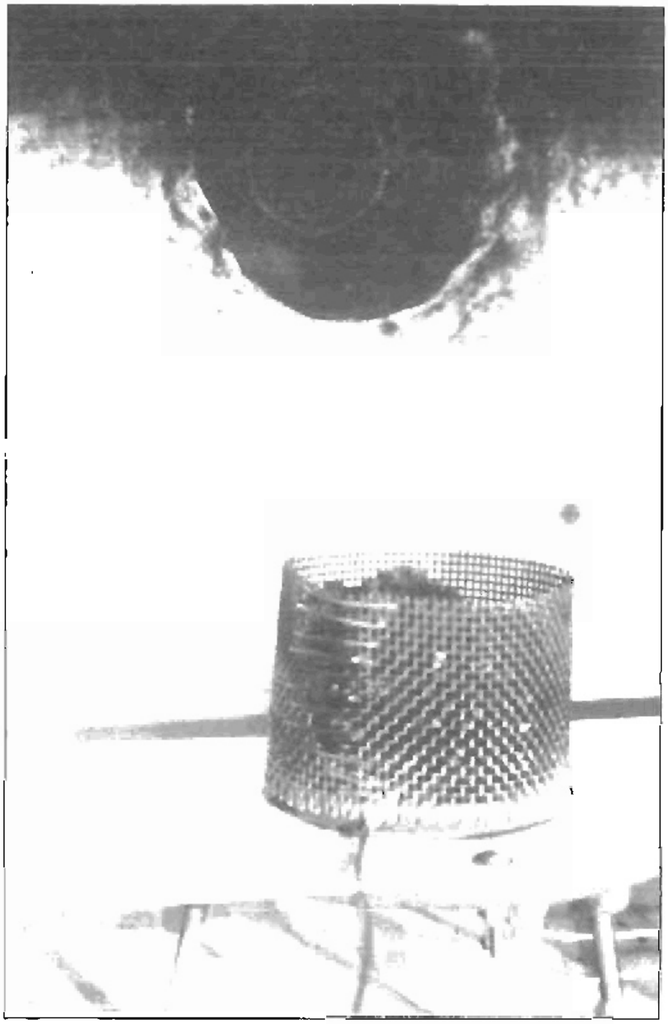
For the flaming test, the iris is initially closed, and smoke bypasses the smoke box and passes through the exhaust duct. When the disc heater reaches 500 °C, the vapors above the coal are ignited with a match. Once the flame is established, which occurs within about 1 min, the iris is opened to allow smoke to pass into the smoke box. The procedure was adopted so that smoke from the smoldering stage would not be included in the test. The diameter of the iris is opened to 0.635 cm for the flaming test.

The iris settings were selected to ensure that the time rate of change of optical transmission through the smoke decreased at a rate of approximately 2 pct/min. This was necessitated by the practical limitations of data recording. The pressure drop across the orifice is primarily controlled by the fan in the sample chamber.

The iris openings selected were determined by the flow characteristics of the smoke box as constructed and the natural ventilation, which exhausted smoke prior to entering the smoke box. Variations in either the smoke box dimensions or exhaust ventilation could require a different iris diameter opening.

The smoke obscuration in the smoke box is characterized by the smoke optical density, D. D is calculated from the reduction in measured light intensity from a constant illumination source along a path length ℓ to a photodetector. D is calculated from the photocell current I_{P_0} in clear air and current I_P in smoke-laden air, as defined by Underwriters Laboratories (*4*) and by equation 1:

Figure 3



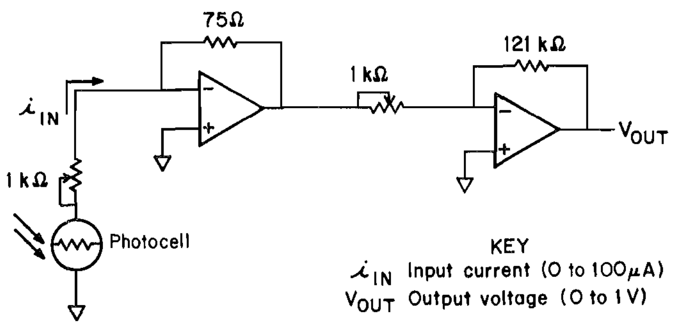
Coal sample on disc heater.

$$D = -\frac{1}{\ell} \text{LOG}_{10} (I_P/I_{P_0}). \qquad (1)$$

The USBM-constructed smoke box uses the Huygen Corp.'s Weston model 594, type RR photronic cell in the photoconductive mode. The cell is illuminated by a 6-V automotive halogen lamp operated at approximately 2.75-V dc across a path length ℓ of 1.483 m. The photocell is operated in its linear range, where I_{P_0} = 100 μA corresponds to 100 pct transmission of the light. Figure 4 is a schematic of the electronic circuit used to convert the current from the photocell to a scaled voltage for the strip chart recorder.

A secondary measurement of the smoke particulate concentration is made with the measuring ionization chamber (MIC) (*6*). The MIC operates on the principle of diffusion of smoke particulates that have acquired a net

Figure 4



Circuit to convert photocell current to scaled voltage.

charge from the attachment of air ions. The charged smoke particulates have a reduced mobility compared to air ions. This enhances the recombination of ions and consequently reduces the measurable current between electrodes. The MIC has international acceptance, and therefore its measured results may be used as a comparative standard.

Both the optical density D and MIC can be used to establish threshold limits for a smoke detector. Visual obscuration limits established by the optical density for a specified range of MIC output current indicative of a specific smoke concentration and particulate size can be used to characterize the minimum D at which a detector should alarm to avoid nuisance alarms and the maximum D to ensure adequate fire alarm warning.

Appendix A lists the operational instructions for utilization of the smoke box as constructed. These instructions should be adapted to the modifications made by the user to the smoke box.

RESULTS OF SMOLDERING AND FLAMING COAL TESTS

Eight smoldering (S1 to S8) and eight flaming (F1 to F8) coal tests were conducted with 80 g of Pittsburgh Seam coal ground to minus 9.4- plus 6.7-mm mesh.

Figure 5 shows the measured heater disc temperature at the base of the coal sample during three smoldering (S1, S2, and S3) and three flaming (F3, F5, and F8) tests. The agreement between the data points in figure 5 is not expected to be close because of the nonuniform heat transport processes through the coal sample. The disc heater temperature rise of approximately 500 °C in 10 min for the test procedure adapted here defines the rate of smoke generation.

Figure 6 shows the reduction in optical transmission T with respect to time for the smoldering coal tests. The data in figure 6 show that the rate of decrease in T with respect to time is within an envelope bounded by rates of approximately 1.3 and 3.7 pct/min.

The optical density D is calculated from equation 1. Figure 7 shows D versus time for the smoldering coal tests. The D value of 0.046 m^{-1}, corresponding to 10-pct reduction in optical transmission T over a 1-m path, occurred consistently between 11.6 and 16.9 min after application of power to the disc heater. The curves in figure 7 show the rate of change in D is approximately between 0.0046 and 0.012 m^{-1}/min for the first 15 min of the test after smoldering commences. The time lag for the commencement of smoldering, based upon the results shown in figure 7, is approximately 5 min. This indicates D of 0.046 m^{-1} will be reached between 6 and 12 min after smoldering commences.

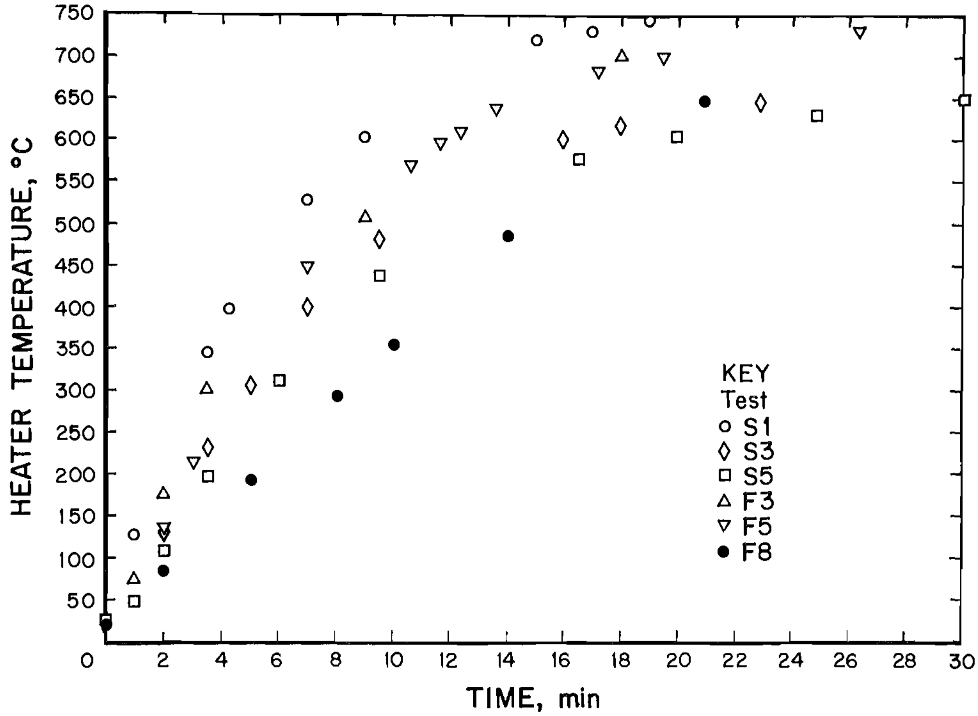
The optical transmission T versus MIC current is shown in figure 8. These curves are approximately bounded by an envelope with a rate of change between 0.51 and 0.66 pct/pA. Although T versus time (figure 6) has a rather wide envelope for the eight tests, the values of T versus MIC current is much closer for the tests as a group. A previous study (*7*) has shown that T and smoke ionization depend upon particulate size and concentration. This relationship will be developed subsequent to a presentation of the flaming combustion tests.

The decrease in optical transmission T with time after the onset of flaming is shown in figure 9 for the eight flaming coal combustion tests. Exclusive of test 1 (F1), the rate of decrease in light transmission is bounded by an envelope defined by rates between 1.7 and 2.4 pct/min. This envelope for flaming falls within the envelope for smoldering coal. Test F1 was conducted with an iris diameter of 1.27 cm instead of the 0.635-cm diameter used for the other tests. This accounts for the rapid decrease in T with time.

Figure 10 shows the change in optical density D with respect to time for each of the eight flaming coal combustion tests. The envelope of the rate of change in D with respect to time is, exclusive of test F1, between 0.0054 and 0.0087 m^{-1}/min for the flaming combustion tests.

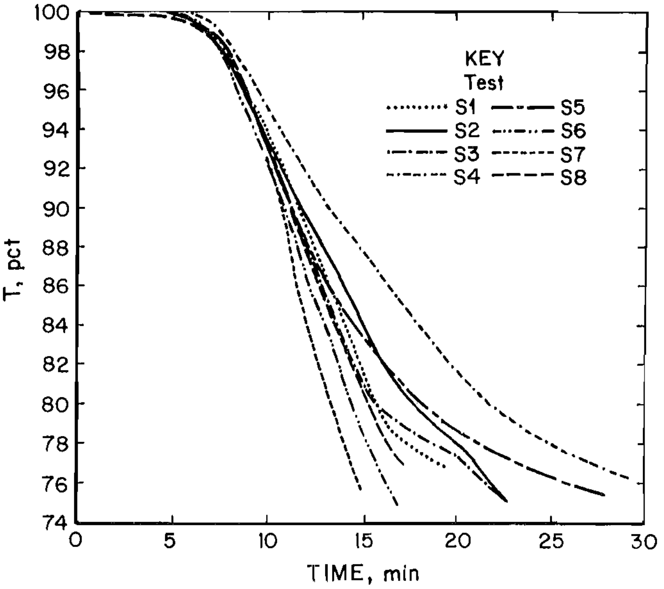
The optical transmission T versus MIC current is shown in figure 11 for each of the flaming coal combustion tests. Although flaming coal combustion test F1 was conducted with a larger iris opening than for the other flaming combustion tests and, as shown in figure 9, T had a more rapid decrease with respect to time than for the other flaming coal tests, this effect is not evident in the plot of T versus MIC current. The two measurable quantities, T and MIC current, show a strong correlation. A comparison with the results in figure 8 for the smoldering tests shows the decrease of T with MIC current is not linear for the

Figure 5



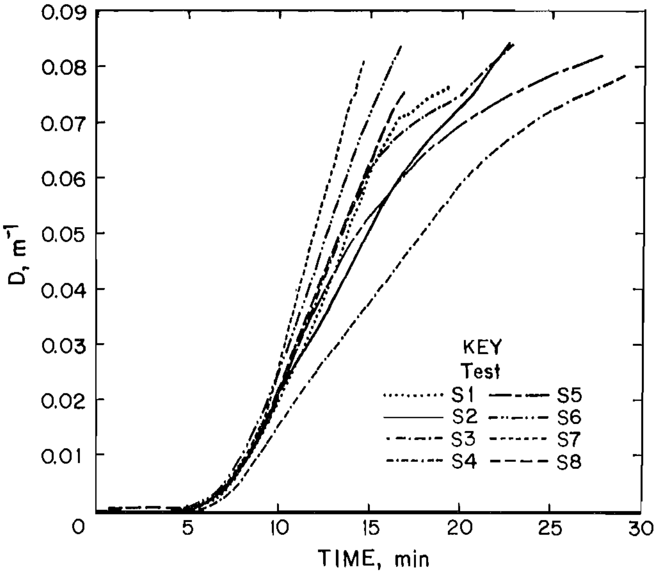
Heater temperature at base of coal sample for smoldering and flaming coal tests.

Figure 6



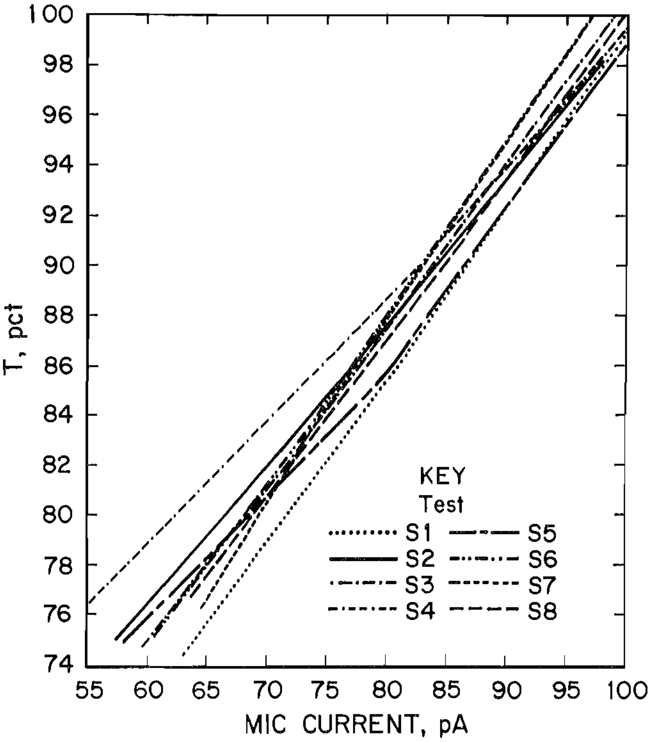
Optical transmission versus time for smoldering coal combustion tests.

Figure 7



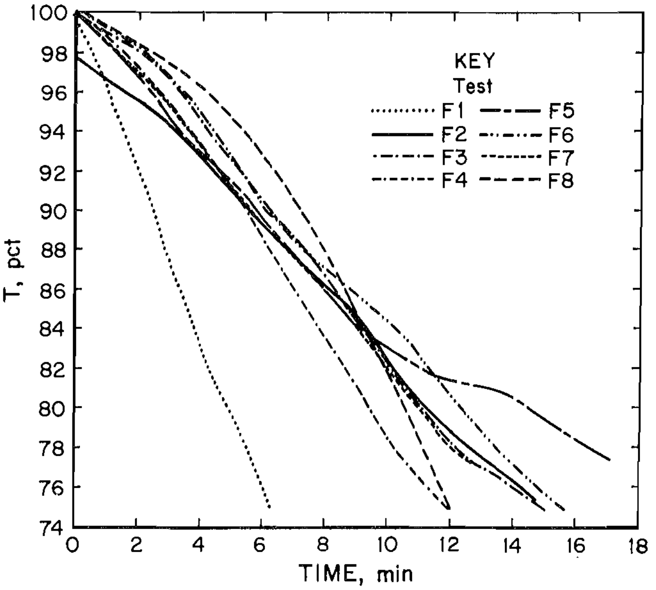
Optical density versus time for smoldering coal combustion tests.

Figure 8



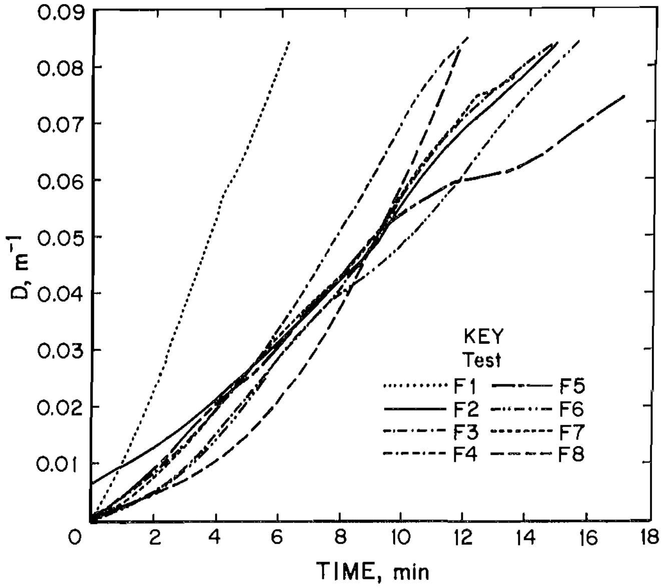
Optical transmission versus MIC current for smoldering coal combustion tests.

Figure 9



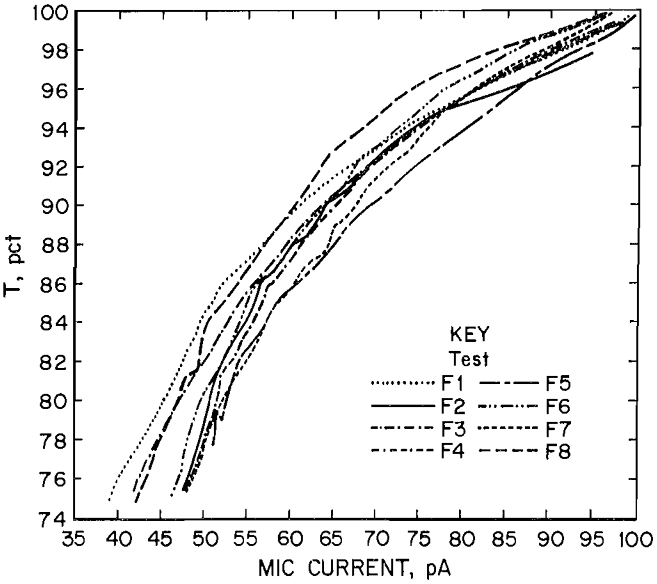
Optical transmission versus time for flaming coal combustion tests.

Figure 10



Optical density versus time for flaming coal combustion tests.

Figure 11



Optical transmission versus MIC current for flaming coal combustion tests.

flaming combustion tests as it was for the smoldering combustion tests. Factors that affect T are properties of the smoke particulates such as smoke particle size, smoke mass concentration, and particulate index of refraction.

The observation with regard to the smoldering and flaming coal combustion tests that the optical transmission T through the smoke and the measurable ionization current are strongly correlated can be explained through a consideration of their dependence upon smoke concentration. T is defined in terms of the smoke mass concentration, C_m; mass density, ρ; particulate volume-surface diameter, d; and extinction coefficient, Q, according to Bouguer's law (*8*):

$$T = \exp(-3QC_m\ell/2\rho d). \qquad (2)$$

The MIC measurable quantity Y is determined from the MIC measurable current I in the presence of smoke through the following relationship:

$$Y = X\,\frac{2-X}{1-X}, \qquad (3)$$

where X = MIC current ratio, $1 - I/I_0$,

and I_0 = MIC measurable current in clear air.

The advantage of considering Y is that Y is directly proportional to the number of smoke particles per unit volume, n (*6*, p. 17). This can be expressed as:

$$Y = K\,n, \qquad (4)$$

where K = proportionality constant.

The mass concentration, C_m, is related to the smoke particle number concentration, n, by

$$C_m = \frac{2}{3}\,dAn\rho, \qquad (5)$$

where $A = \pi/4\,d^2$.

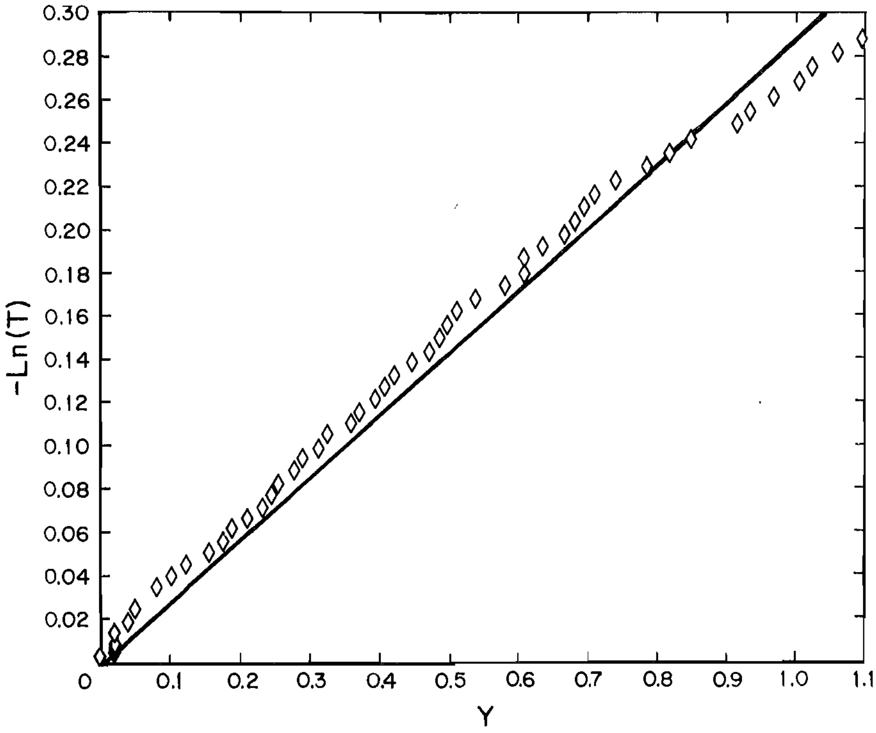
The quantity A is the effective cross-sectional area of the smoke particle.

A combination of equations 2, 4, and 5 yields a linear relationship between Ln(T) and the MIC quantity Y:

$$-\mathrm{Ln}\,(T) = \frac{Q\ell A}{K}\,Y. \qquad (6)$$

Figures 12 and 13 show the correlation between -Ln(T) and Y for a representative smoldering coal test (S3) and a representative flaming coal test (F3). A linear

Figure 12

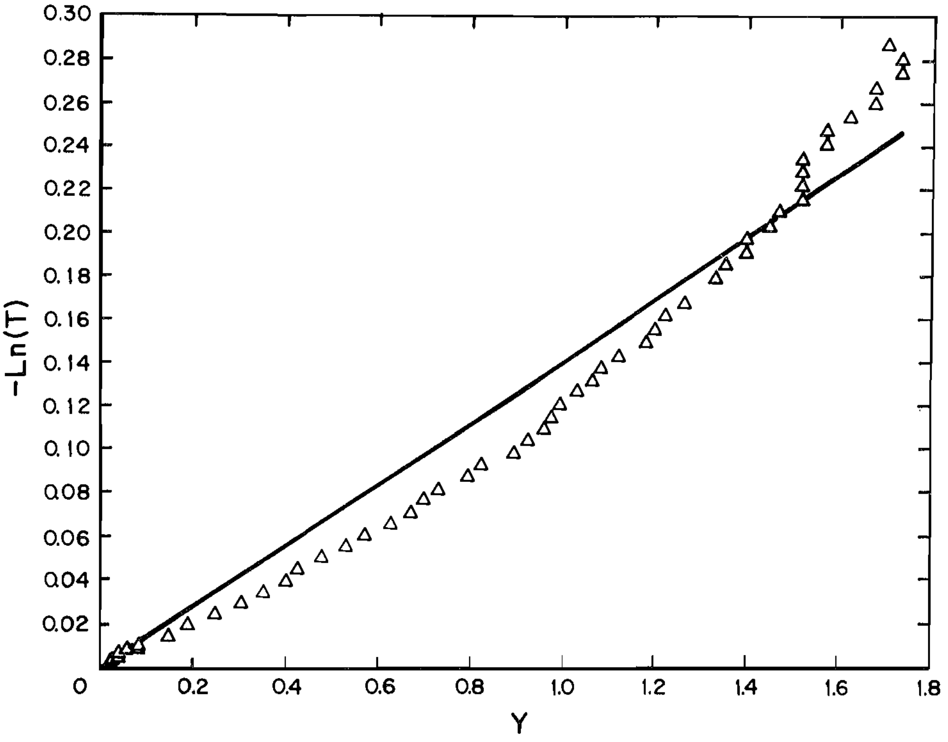


Correlation between optical and MIC measurements for smoldering coal combustion test S3.

regression of the slope, $Q\ell A/K$, was developed for each of the tests. An average slope equal to 0.284 with a standard deviation of 0.0257 was determined for the eight smoldering tests. An average slope equal to 0.140 with a standard deviation of 0.0115 was determined for the eight flaming coal tests. Independent tests conducted by the USBM have shown that the smoke particulate diameter d is smaller for flaming combustion than for smoldering combustion (*7*). This would indicate that the proportionality constant K is proportional to d.

A commercially available ionization smoke detector used in mines sampled the smoke cloud in the smoke box for two coal smoldering tests (S6 and S8) and three flaming tests (F6, F7, and F8). The smoke detector, which had a mechanical pump, was located external to the smoke box. The sample line from the smoke detector was connected to the smoke box. The smoke detector gave an alarm at an optical density D between 0.004 and 0.012 m^{-1} for the smoldering tests, and at D between 0.0027 and 0.0054 m^{-1} for the flaming tests. The alarm threshold was set by the manufacturer. These values are less than the maximum values of 0.0581 and 0.150 m^{-1} reported (*4*, p. 24) for gray and black smoke, respectively, from a smoldering wick source. For the smoldering tests (S6 and S8), the smoke detector alarm occurred with a 4- and 2-pct obscuration and a decrease of 7 and 3 pA in the MIC current. For the three flaming tests (F6, F7, and F8), the optical obscuration had increased less than 2 pct, with decreases in MIC current ranging from 8 to 14 pA when the smoke detector alarmed. The experimental error in the optical transmission T measurement is less than 0.5 pct. This is indicative of the capability of the smoke box to be utilized as a comparative instrument for the evaluation of the performance of smoke detectors.

Figure 13



Correlation between optical and MIC measurements for flaming coal combustion test F3.

CONCLUSIONS

Reproducible smoldering and flaming coal combustion test procedures were developed that can be used for the evaluation of smoke detectors for underground coal mines. The test procedures involve a modification of the UL268 standardized test procedure developed by Underwriters Laboratories (*4*). Both the smoldering and flaming coal combustion tests showed a similar decrease in optical transmission T per unit time through the smoke. The measured value of T through the smoke is closely correlated with the MIC current for the smoldering and flaming tests. It was shown for the experimental conditions considered that a linear relationship exists between the logarithm of T and the MIC quantity Y. The proportionality factor, $Q\ell A/K$, characteristic of smoldering coal combustion is distinct from the proportionality factor characteristic of flaming coal combustion.

The developed test procedures can be used by smoke detector manufacturers to create a controlled smoke environment for smoldering and flaming coal combustion to ascertain the threshold limits and reliability of the detector. Acceptable standards for a smoke detector alarm that avoids nuisance alarms can be developed from such efforts. The long-term implication is the implementation of a more effective fire warning system.

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APPENDIX A.—STANDARD OPERATING PROCEDURES FOR SMOKE BOX TESTS

Coal Preparation:

1. Select bituminous coal sample.
2. Dry coal sample.
3. Grind coal sample to size minus 9.4- plus 6.7-mm mesh.

Smoldering Test:

1. Turn on power supply for lamp.
2. Turn on MIC and detector to be tested.
3. Turn on interior circulation fan.
4. Close smoke evacuation exhaust damper.
5. Ensure that sample box exhaust damper is open.
6. Open iris to 1.27 cm and open lower damper on sample chamber.
7. Place coal sample on heater assembly and set window on sample chamber to 12.4 cm.
8. Turn on sample chamber vent fan. (Set variac to 50 pct full scale or to 57.5 V ac.)
9. Connect detector to be tested to sample port on smoke box (for flow type) or place detector in the test area of the smoke box (for diffusion type).
10. Set heater voltage for 500 °C rise in approximately 10 min.
11. Turn on heater and mark data collection system for time zero.
12. Note time, transmission, and MIC output at detector alarm.
13. At completion of test, turn on building exhaust, open chamber exhaust damper, fully open iris, turn off power to sample box vent fan, and turn off power to heater.
14. Fully evacuate smoke from box prior to next test.

Flaming Test:

1. Turn on power supply for lamp.
2. Turn on MIC and detector to be tested.
3. Turn on interior circulation fan.
4. Close smoke evacuation exhaust damper.
5. Ensure that sample box exhaust damper is open.
6. Close iris and bottom damper of sample chamber.
7. Place coal sample on heater assembly and set window on sample chamber to 12.4 cm.
8. Turn on sample chamber vent fan. (Set variac to 50 pct full scale or to 57.5 V ac.)
9. Connect detector to be tested to sample port on smoke box (for flow type) or place detector in the test area of the smoke box (for diffusion type).
10. Set heater for 500 °C rise in approximately 10 min.
11. Turn on heater and observe thermocouple readout.
12. At a thermocouple temperature of 500 °C, ignite vapors above coal sample; after 1 min, open iris to 0.635 cm, open lower damper, and mark the event as time zero on the data collection system.
13. Note time, transmission, and MIC output at detector alarm.
14. At completion of test, turn on building exhaust, open chamber exhaust damper, fully open iris, turn off power to sample box vent fan, and turn off power to heater.
15. Fully evacuate smoke from box prior to next test.

APPENDIX B.—SYMBOLS USED IN THIS REPORT

A	effective cross-sectional area of smoke particle, cm^2
C_m	smoke mass concentration, g/cm^3
D	optical density, m^{-1}
d	smoke particle volume-surface diameter, cm
I	MIC measurable current in smoke, μA or pA
I_o	MIC measurable initial current in clear air, pA
I_P	photocell current for smoke-laden air, μA
I_{Po}	photocell current for clean air, μA
K	proportionality constant, particles per cubic centimeter
n	smoke particle number concentration, number of particles per cubic centimeter
Q	extinction coefficient, 1
T	optical transmission, 1
X	MIC current ratio, 1
Y	MIC measurable quantity, 1
π	3.141593
ρ	smoke mass density, g/cm^3
ℓ	optical path length, m

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