RELATIONSHIPS BETWEEN SMOKE AND CARBON MONOXIDE AND THEIR IMPLICATION TOWARD IMPROVED MINE FIRE DETECTION

C. D. Litton

Bureau of Mines, Pittsburgh Research Center, USA

ABSTRACT

Tests were conducted to determine the relative levels of carbon monoxide (CO) and smoke produced from smoldering and flaming mine combustibles, including wood, coal, and conveyor belting. The data indicated that smoldering combustibles generate a very low level of CO compared to the level of smoke produced. Even though during flaming, the level of CO relative to that of smoke increases, it is found that a "typical" alarm level for smoke is comparable to a CO level of about 6 ppm. For smoldering the equivalent CO level is in the range of 2 ppm. The implications of these findings in regard to early warning mine fire detection are discussed. The overall results clearly indicate that developing mine fires can be detected earlier using smoke sensors rather than CO sensors.

INTRODUCTION

Mine fires pose a severe hazard to underground personnel. If not detected rapidly and reliably in their initial stages of development, fires can increase in intensity eventually reaching levels sufficient for flame propagation. Further, as the fire intensity increases, so do the levels of smoke and CO. These smoke levels may reach critical levels where smoke obscuration can reduce, if not eliminate, a miner's chance for escape. Similarly, CO levels can increase to dangerous levels thus further reducing chances for successful evacuation.

The sources of fuel available for fires can vary significantly from one location to the next in an underground mine. Fires of liquid or gaseous fuels develop very rapidly and those areas of mines where such fuels exist should be protected by automatic detection systems coupled with automatic suppression capabilities. Fires of solid combustibles usually take longer to develop, and for these types of fires, a well-planned distribution of fire sensors throughout the entries to be protected can provide for warning in sufficient time to safely evacuate and often extinguish the fire locally before it has a chance to spread.

For these types of fires, the solids involved may be wood, coal, conveyor belting, electrical cables, and others, or combinations of these solids. Further, these types of fires may undergo prolonged periods of smoldering prior to the actual development of flames. To detect these fires, CO fire sensors are currently used with alarm thresholds of 10 or 15 ppm of CO above ambient. However, the sensitivity of CO fire sensors to overheating conveyor belts is inadequate in many instances due to the formation of low levels of CO, which when diluted by the ventilation airflow are not high enough to produce sensor alarm. Similar types of occurrences could be expected for other combustible solids.

It is observed, however, that these incidents produce high levels of smoke. As a result, if smoke detectors were used, these types of occurrences would most always be detected. The following paragraphs discuss the formation of CO and smoke and provide insight as to how these two types of fire sensors can most efficiently be utilized for fire detection in underground mines.

SMOKE AND CO FORMATION

In general, smoldering fires produce both smoke and CO. However, the mechanisms responsible for their production are quite different. CO is produced via a chemical reaction by which the carbon in the fuel combines with oxygen in the surrounding environment. Further, the rate at which the CO is produced depends upon the concentrations of carbon in the fuel (% of carbon, usually by weight) and the temperature of the fuel. This rate may also depend upon how the carbon is bound chemically to other molecules within the fuel. From coal and wood, CO can be formed at relatively low temperatures ~150-200° C (even lower for spontaneous heatings). For synthetic materials, such as conveyor belts, the temperatures to produce significant levels of CO are higher due both to the carbon content of belting and to the ways carbon is chemically bound.

Smoke particles, on the other hand, are produced by means of thermal processes whereby the fuel surface heats and expels both solid particulate matter into the environment as well as high molecular weight gases which combine to form smoke particles. Most, if not all combustible solids will produce smoke particles at temperatures in the range of 100° to 200° C. And as the solid surface temperature rises, the rate of emission of smoke particles also increases.

During flaming combustion, the high flame temperatures are sufficient to promote the formation of CO. Also, during flaming, the CO production rate will increase as the oxygen to fuel ratio decreases. This is because the formation of CO_2 (carbon dioxide) diminishes due to reduced oxygen availability and the fuel carbon is mostly used to form CO.

During flaming at high oxygen to fuel ratios (typical of fires that are over ventilated), the formation of CO is directly related to the fire intensity. Further, these rates of formation at high oxygen to fuel ratios represent minimum values. As the fire intensity increases and the oxygen to fuel ratio decreases, the rates of formation of CO per unit fire intensity also increase.

Smoke in a flame is produced primarily as soot particles which recombine and grow in particle size as they move away from the flame. Solid flames usually burn at or near a limit flame temperature (~1500° K) and the yellowish color is due to the burning soot particles as they emit radiant energy. Just as for CO, as the oxygen to fuel ratio decreases, the rates of formation of smoke will increase. And, the rates of formation of smoke at high oxygen to fuel ratios represent approximate minimum rates.

There do exist differences, then, in the ways in which smoke and CO are formed both in smoldering and flaming fires. It should also be noted that the rates of formation divided by the ventilation airflow rate in the area in which either is formed is a dilution effect which also serves to reduce the smoke and CO levels. This effect must always be taken into account when discussing detectable levels of either smoke or CO.

The units for measurement of CO common to all CO fire sensors are parts per million (ppm) of CO. 1 ppm of CO equals 2.69×10^{19} molecules of CO per cubic meter of air, or 1.25 milligram of CO per cubic meter of air. Smoke may be measured in terms of the number of smoke particles per unit volume of air or the mass of smoke particles per unit volume of air. However, for smoke fire sensors, the units of measurement are usually in terms of the optical density (OD) of the smoke. The optical density is a measure of the ability of the smoke to obscure visibility. The greater the optical density, the greater the obscuration. Optical density is a function of the number, or mass, of smoke particles and the average diameter of the smoke particles.

EXPERIMENTAL

To determine the CO and smoke levels that are produced from smoldering and flaming mine combustibles, experiments were conducted in an intermediate-scale fire tunnel. The tunnel, described in detail in previous reports (Egan, 1986, Egan, 1987), is 10 meters long with a square cross-section of 0.64 m^2. It is completely lined with fire brick and a fan at the exhaust end of the tunnel provides for ventilation air velocities of 0.20 to 2.0 m/sec.

With the exception of coal, all flaming fire tests were conducted using a natural gas burner igniter mounted on the tunnel floor. Once flaming had been achieved, the burner was turned off and the combustible sample allowed to burn. For coal, ignition was achieved using three electrical strip heaters buried in a pile of coal. For all the flaming tests, the data reported below are for steady-state burning of the combustibles.

For all the smoldering fire tests, the combustibles were heated to a point of steady-state smoldering using electrical strip heaters. All data reported below are for the steady-state smoldering. For conveyor belting, smoldering tests were conducted at strip heater surface temperatures of 275° C, 450° C, and 600° C. For all other combustibles, smoldering tests were conducted at a standard heater surface temperature of 450° C only.

Gases and smoke were extracted from the tunnel at a point ~8.0 m downstream of the fire where the combustion products are completely mixed with the ventilation airflow. The exception to this procedure is the measurement of smoke obscuration which is made with a three wavelength probe (Cashdollar, 1979) mounted within the tunnel approximately 0.15 m upstream of the gas and smoke sampling probes. Smoke obscuration is measured at three wavelengths, 0.45 μm, 0.63 μm, and 1.0 μm. For the data reported here, the smoke optical densities, expressed in units of m^{-1} are the averages of the values measured at 0.45 μm and 0.63 μm.

All CO measurements were made using an eCOlyzer Model 2100 CO Analyzer with dual ranges of 0 to 100 and 0 to 500 ppm. This analyzer has an accuracy of ±1% of the full-scale reading. Smoke mass concentrations were made using a Tapered Element Oscillating Microbalance (TEOM) (Patashnick, 1986) with an accuracy of ±5% of the full-scale reading, which was typically set at 200 mg/m^3.

Air velocities were measured using a bi-directional flow probe (McCaffrey, 1976) with an accuracy of ±7% of the indicated reading.

All gas, smoke, and velocity data were recorded using a PDP 11/44 computer and subsequently transferred to files of a larger VAX 11/780 for reduction and analysis.

TEST RESULTS

Simultaneous measurements of ppm of CO, smoke mass concentration, M_0, and smoke optical density, OD, allow for the data to be expressed in terms of ratios. Three ratios are of particular interest:

1) The first ratio, denoted by R1, is the ratio of smoke optical density, OD, in units of m^{-1}, to smoke mass concentration, M_0, in units of mg/m^3. The ratio R1 is a measure of the ability of the smoke to obscure visibility per unit mass concentration. The larger the value of R1, the more efficient is the smoke in reducing visibility. The

smaller the value of R1, the less efficient is the smoke in reducing visibility.

2) The second ratio, R2, is the ratio of smoke optical density to ppm of CO. This ratio is important because it provides a measure of the relative effectiveness of smoke and CO fire sensors with fixed alarm thresholds.

3) The third ratio, R3, is the ratio of smoke mass concentration to the mass concentration of CO, both quantities being expressed in units of mg/m^3. This ratio is important because it represents a measure of the relative levels of smoke and CO produced from different combustibles and during different stages of combustion (flaming or smoldering).

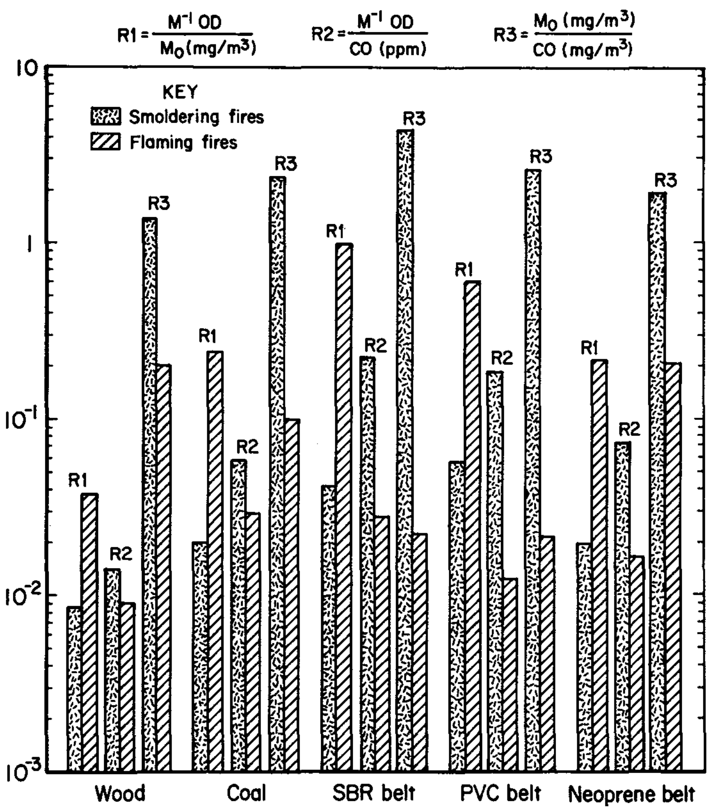

Figure 1. - Values of the three defined ratios for combustibles during both smoldering and flaming.

The average data obtained during these tests for materials which underwent flaming as well as smoldering combustion are shown in Figure 1. In Figure 1, the open vertical bars represent the average data for smoldering while the solid vertical bars represent the average data for flaming. Several aspects of these data that are noteworthy include:

1) All of the combustibles tested have higher R1 values during flaming than during smoldering, indicating that smoke from flaming fires is more efficient in obscuring visibility.

2) All of the combustibles show lower R2 values during flaming than during smoldering. This is reasonable, since at the higher temperatures reached during flaming more CO should be formed.

3) All combustibles tested yielded much higher R3 values during smoldering than during flaming. Again, this is reasonable since at lower temperature smoldering, less CO is produced.

In addition to these data, data from flaming fires of transformer fluids and data from smoldering fires of PVC line brattice were also obtained. For flaming transformer fluid fires, the ratio values were:

R1 = 0.27
R2 = 0.067
R3 = 0.20

For smoldering PVC brattice tests, the ratio values were:

R1 = 0.020
R2 = 0.046
R3 = 1.84

RELEVANCE TO FIRE DETECTION

The data presented in the previous section allow for the estimations of:

1) The expected average smoke optical density at a CO fire sensor alarm threshold of 15 ppm and the resultant obscuration level; and

2) The expected average CO level at a smoke fire sensor alarm threshold of 0.10 m^{-1} OD.

Table 1 lists the % obscurations over a 3.0 m path that would exist at the 15 ppm alarm threshold for CO fire sensors.These comparisons indicate that, on the average, at CO alarm levels, the smoke obscurations can be significant, even for flaming fires. For smoldering fires, these smoke levels reduce visibility to a very low level.

Table 2, below list the CO levels that would exist at typical smoke sensor alarm thresholds of 0.10 m^{-1} OD.

Table 2 is a clear indication of the superiority of smoke fire sensors to CO fire sensors. Both for flaming and smoldering fires, smoke fire sensors will, on the average, alarm before the CO reaches the 15 ppm threshold.

Table 3, below lists the average mass concentration of both smoke and CO (both in mg/m^3) at the smoke sensor alarm threshold of 0.10 m^{-1} OD.

This table indicates that during flaming the smoke mass concentrations at alarm are much, much lower than the CO mass concentrations. For smoldering, the smoke mass concentrations are higher than the CO mass concentrations by an average factor of ~2.5. However, during smoldering much less CO is produced.

Table 1: Relative values of smoke obscuration over a 3 meter path at the CO alarm level of 15 ppm

	% Obscuration over a 3 m path	
Fuel	Flaming	Smoldering
Wood	33	47
Coal	73	92
SBR belt	70	100
PVC belt	42	100
Neoprene belt	51	96
Transformer fluid	95	-
PVC brattice	-	87

Table 2: Relative values of CO at a smoke sensor alarm level of 0.10 m^{-1} OD

Fuel	ppm CO Flaming	ppm CO Smoldering
Wood	11.1	7.1
Coal	3.4	1.8
SBR belt	3.7	0.5
PVC belt	8.3	0.6
Neoprene belt	6.3	1.4
Transformer fluid	1.5	-
PVC brattice	-	2.2

Table 3: Mass concentration (mg/m^3) of both smoke and CO at a smoke sensor alarm level of 0.10 m^{-1} OD

Fuel	Flame		Smolder	
	Smoke Mass	CO Mass	Smoke Mass	CO Mass
Wood	2.7	13.9	11.9	8.9
Coal	0.42	4.3	5.0	2.2
SBR belt	0.10	4.6	2.4	0.57
PVC belt	0.17	10.4	1.8	0.69
Neoprene belt	0.48	7.8	5.3	1.7
Transformer fluid	0.37	1.9	-	-
PVC brattice	-	-	5.0	2.7

DISCUSSION

During smoldering combustion, typical mine combustibles produce about 2.5 times more smoke than CO. As fires develop to their flaming stages, the trend reverses and about 8 times as much CO is produced as smoke. However, the resultant optical densities per unit mass concentration of smoke increases from an average value of 0.027 during smoldering to an average value of 0.38 during flaming. The data indicate that smoke produced from flaming fires is much more efficient in attenuating light and reducing visibility. Further, much lower levels of smoke are required to produce optical densities equal to 0.10 m^{-1} OD alarm thresholds.
The results of these experiments is straight forward. Typical alarm levels for smoke occur at equivalent CO levels significantly less than CO alarm levels. This means that a typical smoke detector would detect a fire earlier than a typical CO sensor. This is particularly true for smoldering fires. Consequently, the use of smoke sensors in underground mines has the potential to improve fire detection capabilities and increase the level of fire safety.

REFERENCES

Egan, M. R. and C. D. Litton. Wood Crib Fires in a Ventilated Tunnel. BuMines RI 9045, 1986, 18 pp.

Egan, M. R.. Coal Combustion in a Ventilated Tunnel. BuMines IC 9169, 1987, 13 pp.

Cashdollar, K. L., C. K. Lee and J. M. Singer. Three-Wavelength Light Transmission Technique to Measure Smoke Particle Size and Concentrations. Appl. Optics, v. 18, No. 11, 1979, pp. 1763-1769.

McCaffrey, B. J. and G. Heskestad. A Robust Bidirectional Low-Velocity Probe for Flame and Fire Application. Combust. and Flame, v. 26, No. 1, 1976, pp. 125-127.

Patashnick, H. and G. Rupprecht. Microweighing Goes On-Line in Real Time. Res. and Dev., v. 28, No. 6, 1986, pp. 74-78.

RAPPORTS ENTRE LA FUMEE ET LE CO - LEUR PORTEE SUR L'AMELIORATION DE LA DETECTION DES INCENDIES MINIERS

C.D. Litton

Des essais ont eté effectués pour déterminer les niveaux relatifs de CO et de fumée produits par des combustibles miniers incandescents ou en flammes. Les données obtenues indiquent que de nombreux types de convoyeurs à courroies produisent une quantité très faible de CO comparée à la quantité de fumée produite. Ces résultats rejoignent ceux de rapports concernant des courroies incandescentes qui ne produisent pas suffisamment de CO pour déclencher les systèmes de détection d'incendies. Au cours des incendies, le niveau de CO augmente par rapport à celui de la fumée, mais un niveau d'alarme "typique" de fumée est comparable à un niveau de CO de moins de 5 ppm. Pour des combustibles incandescents, le niveau équivalent de CO est de 1 ppm environ. Ces résultats ont d'importantes répercussions sur les systèmes de détection d'incendies à l'avance et notre rapport les examine en détail.

ZUSAMMENHANG ZWISCHEN RAUCH UND CO UND IHRE ROLLE IN DER VERBESSERUNG DER GRUBENBRANDENTDECKUNG.

C. D. Litton

Untersuchungen zur Bestimmung der relativen Menge von CO und Rauch, die in Schwelbränden und offenen Bränden von brennbaren Materialien in Gruben entstehen, wurden durchgeführt. Die Ergebnisse zeigen, daß viele Sorten von Fördergurten einen geringen Anteil von CO, verglichen mit dem erzeugten Rauch, erzeugen. Diese Erkenntnisse stimmen mit Berichten überein, nach denen schwelende Gurte nicht genügend CO produzierten, um das Feueralarmsystem zu aktivieren. Während des offenen Brandes erhöht sich der Anteil des CO relativ zum Rauch, doch ergab sich, daß eine typische 'Alarmstufe' für Rauch einem CO Anteil von weniger als 5 ppm vergleichbar ist. Bei Schwelbränden würde der entsprechende CO Gehalt um etwa 1 ppm oder darunter liegen. Diese Erkenntnisse haben wichtige Auswirkungen auf die Brandfrüherkennung und werden im Vortrag weiter behandelt.

ИСПОЛЬЗОВАНИЕ СООТНОШЕНИЯ ДЫМА И ОКИСИ УГЛЕРОДА (СО) ДЛЯ УСОВЕРШЕНСТВОВАНИЯ СПОСОБОВ ОБНАРУЖЕНИЯ ПОЖАРА В ШАХТАХ

К.Д. Литтон

Испытания были направлены на определение относительных уровней СО и дыма, появляющихся при тлении и воспламенении горючих элементов в шахте. Данные, полученные при испытаниях, показывают, что многие типы транспортерных лент порождают очень малое, по сравнению с дымом, количество углерода. Эти выводы согласуются с более ранними результатами, когда в случаях тления транспортерных лент выделялось столь несущественное количество окиси углерода, что не срабатывала противопожарная система. В процессе горения уровень СО по отношению к дыму возрастает, но было установлено, что "типичный" опасный уровень дыма может быть приравнен к уровню СО 5 г/т. В процессе тления опасным уровнем считается 1 г/т СО или меньше. Эти результаты могут найти важное применение в разработке системы своевременного предупреждения пожара. Они будут более подробно рассмотрены в самом докладе.

烟和一氧化碳之间的关系及它们对矿火测定改进的关连

C．D． 列顿

我们举行了测定从矿里可燃物熏烧和燃烧所产生的一氧化碳和烟的相对含量的试验。试验的结果指出很多种输送机皮带产生的一氧化碳还较烟为低。这种现象与皮带熏烧时所产生的一氧化碳往往不足以驱动测火器报警的实际情形相符合。燃烧时一氧化碳的含量较烟增加得快。烟的"典型"报警程度相当于百分之五以下的一氧化碳含量。熏烧时一氧化碳含量在百分之一以下。这些数据对于及早测火警告系统有很重要的关系。在本文中将有详细的讨论。

U.S. BUREAU OF MINES
OPEN FILE REPORT
OFR 27-89

PROCEEDINGS OF THE

23RD INTERNATIONAL CONFERENCE OF SAFETY IN MINES RESEARCH INSTITUTES

23 МЕЖДУНАРОДНАЯ КОНФЕРЕНЦИЯ НАУЧНО-ИССЛЕДОВАТЕЛЬСКИХ ИНСТИТУТОВ ПО ГОРНОЙ БЕЗОПАСНОСТИ

23. INTERNATIONALE KONFERENZ GRUBENSICHERHEITLICHER VERSUCHSANSTALTEN

23ème CONFERENCE INTERNATIONALE DES INSTITUTS DE RECHERCHES SUR LA SECURITE DANS LES MINES

第23届采矿安全研究学院国际会议

Washington, DC
September 11-15, 1989

Organized by the U.S. Department of the Interior, Bureau of Mines