MINE FIRE DETECTION

by

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ABSTRACT

The problem of mine fire detection is considered in terms of types of fires, past history of fire incidence, current regulations, detection methodologies, and the general strategy of fire safety. Several research programs that are in the process of being transferred to in-mine technologies are described. These include the continuing development of a tube bundle (pneumatic sampling) technique, the evaluation of a new, prototype fire sensor for combustion generated submicrometer particles, and general studies of the problem of spontaneous combustion in coal mines.

INTRODUCTION

A Bureau of Mines program to develop and evaluate rapid and reliable detectors for explosions and fires in underground coal mines has been in existence since the passage of the Coal Mine Health and Safety Act (Public Law 91-173, December 1969). Early emphasis was on the detection of methane-air face ignitions and dust explosions. Such detectors were needed to activate quenching devices. The emphasis in recent years has been on the detection of fires during their early or incipient stages. The project objective was to explore the problem fundamentally; to develop instruments that detect conditions that may lead to fires; to evaluate and adapt current fire sensors for mine use; and to design, develop, and build new sensors and new detection methodologies.

An underground coal mine fire is exceptionally hazardous because of a mine's extraordinary size and its confining geometry. A mine is a man-made void carved out of a combustible material. It is, in effect, an underground factory with a low, flat roof and long, combustible, escape corridors. A map of a typical section is shown in figure 1. It is the 4 right section of the Somerset mine in Colorado. This section is of particular interest because it was the seat of a spontaneous combustion incident that will be described later. In this underground factory called a mine, the roof, floor, hallways, and rooms are lined with combustible material as are all the passageways leading to the exits. It contains heavy equipment and machinery: Mining machines, shuttle cars, roof bolters, conveyor belts, transformers, locomotives, trolleys, and power cables. Escapeways are long; for example, for the working section shown in figure 1, the distance to the Hubbard portal is about 2 miles with a similar distance to the Elk Creek return portal. In the event of a fire, the ventilation pattern can rapidly contaminate escapeways. In most mines there is limited egress through vertical shaft hoists of limited

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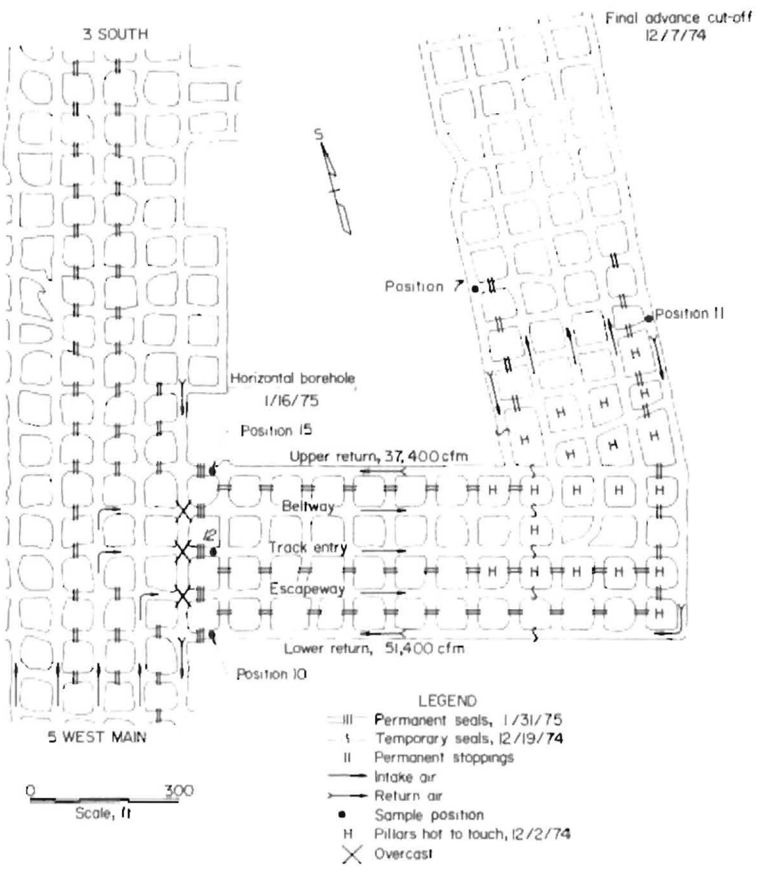


FIGURE 1. - Mine map of the 4 right section of the Somerset coal mine during the occurrence of a spontaneous combustion incident.

capacity, and the time required to evacuate can be extraordinarily long. The fire itself can easily generate flow reversals in passageways that would normally be in intake air, and the everpresent methane emissions add the additional danger of an explosive atmosphere.

A variety of current regulations deal with this problem of fire safety and protection. These are general Code of Federal Regulations (CFR) ventilation requirements (30 CFR 75.3), electrical equipment (30 CFR 75.5-75.10), fire protection equipment (30 CFR 75.11), explosives use (30 CFR 75.13), and escapeways (30 CFR 75.1704-75.1707). We are concerned specifically with one small part of the problem; the problem of detecting the presence of fires. What methods are available to detect the presence of a developing fire situation so that effective measures can be taken to avoid the potential loss of life, equipment, and production that can result from a large, uncontrollable fire situation in an underground coal mine?

Fire and Sensor Types

There are three types of fire situations that are possible:

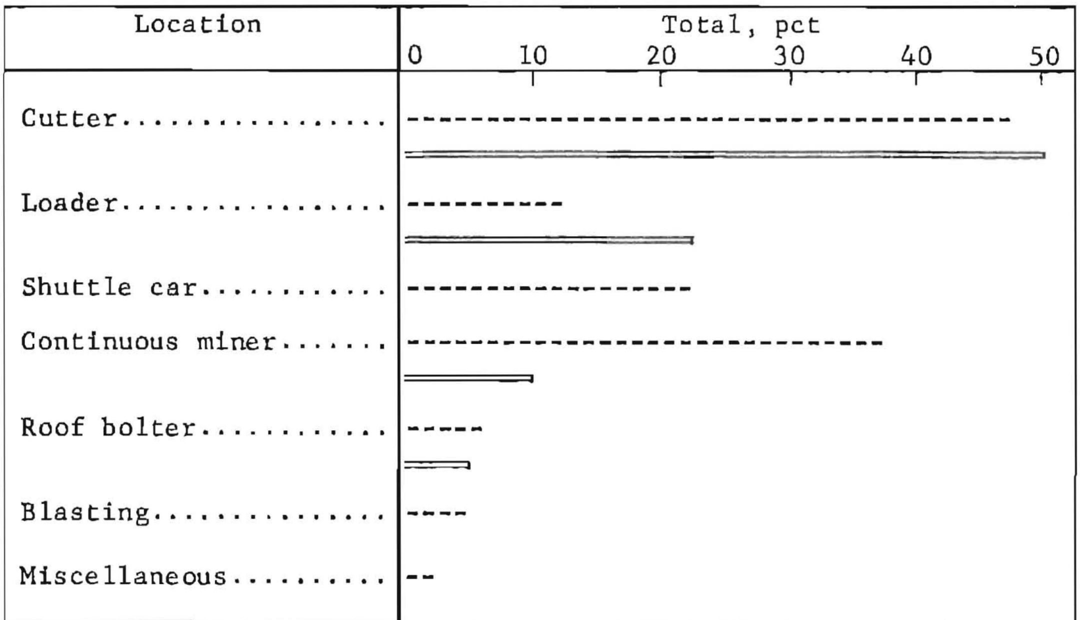
1. A rapidly developing, open fire.

2. An incipient fire in machinery or equipment.

3. A spontaneous combustion fire in the coal seam itself, in a gob area, or in a sealed area.

The data in tables 1-2 summarize the fire frequency and fatality rates during the period 1952-70.[2] The data show that 70 pct of the fires are of electrical origin. These are strong ignitions associated with power sources and machinery. Examples are roof falls shorting a high-voltage trolley wire, a haulage wreck leading to a similar short circuit, or an overheating, faulty splice in a cable reel. If these occur during normal mining operation in attended areas such as the face, they are usually detected by miners and readily extinguished. The same data show that approximately 15 pct were conveyor belt fires. Most of these were caused by frictional heating. Another 10 pct were gob fires that can be classified as spontaneous combustion. The annual fatality rate from fires during the period averaged three deaths per year, and this was only about 2 pct of the total fatality rate from all accidents. This rate dropped to two deaths per year in the period 1970-76. The average fire frequency dropped from 50 per year in the 1952-70 period and to only 10 per year in the 1970-76 period. This dramatic decrease since 1970 reflects the increased vigilance of all concerned and demonstrates the effectiveness of the regulations.

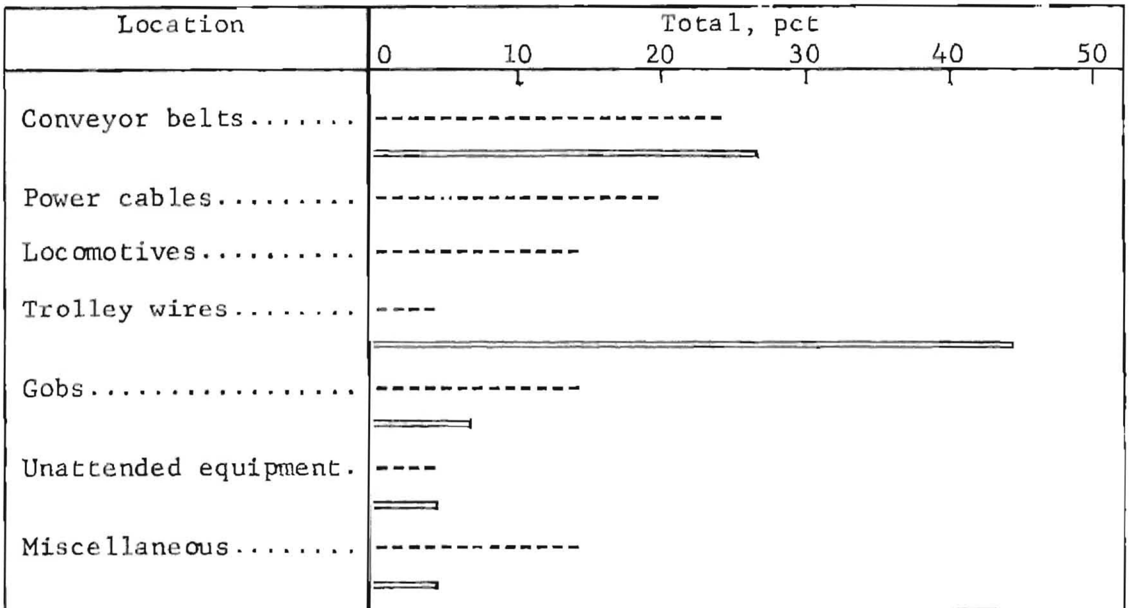
TABLE 1. - Fire frequency and fatality rate in face areas, 1952-70[1]



[1] 357 fires, 61 injuries, 20 fatalities; most of electrical origin.
----- Frequency rate.
═══ Fatality rate.

[2] These data are for reportable mine fires (longer than 30 min duration) and were supplied by J. Nagy and E. M. Kawenski of the Mining Enforcement and Safety Administration (MESA), Pittsburgh, Pa.

TABLE 2. - Fire frequency and fatality rate in nonface areas, 1952-70[1]



[1] 533 fires, 68 injuries, 41 fatalities; 50 pct of electrical origin.
----- Frequency rate.
═══ Fatality rate.

But there is no justification for complacency either with the Bureau or at MESA. The data for metal mine fire fatalities show the reverse trend, mainly because of the Sunshine mine fire of 1972 that caused 91 deaths. From a metal and nonmetal mine fatality rate of nearly zero in the 1952-70 period, the rate jumped to 15 deaths per year for the 1970-76 period. The potential for a major fire disaster in underground mines is everpresent, and as indicated earlier, it is almost inherent in the nature and structure of that large underground factory called a coal mine. If the same structure and equipment were located above ground with the same combustible loading, ventilation, and limited egress, there is not a municipality in the Nation that could legally issue a permit for its construction or occupancy.

Another reason for avoiding complacency relates to the expected increase in the spontaneous combustion hazard as mining shifts westward and longwall methods become more prevalent.

There is little doubt that the rapid and reliable detection of a fire is the essential first step in the use of any fire-suppression system or in the activation of any alarm system and escape plan.

The traditional methods of detecting the presence of fires may be classified according to the type of detector used, as follows:

1. Thermal contact.

2. Optical view field.

3. Products of combustion.

4. Flow field or aerodynamic.

5. Human.

Thermal sensors respond to the temperature or the rate of temperature increase at a point, or along a continuous line sensor. Examples are the fusible alloy plug of a sprinkler head, thermocouples, bimetallic elements, twisted wire with insulation that melts at a given temperature, and a variety of other devices. Generally, these thermal sensors require that the detector be very close to the fire for them to alarm.

Optical sensors respond to the light emitted by a fire or flame and these are limited by view field constraints. The sensor must actually "see" flames; the emitted radiant energy from the fire or from surfaces heated by the fire.

Any fire generates products of combustion and these are carried to regions far removed from the fire by the mine ventilation or by the fire's own convection currents. Examples of combustion products that can be detected routinely are carbon monoxide (CO), carbon dioxide (CO_2), smoke (visible), submicrometer particles (invisible smoke), and a variety of pyrolysis products.

Aerodynamic sensors respond to the flow disturbances or convection currents induced by a flame. These are useful for explosion detection but are rarely used for fires.

The human sensor is the most versatile, and it is a combination of the first three types. The human body responds easily to temperatures well below those usually used as the alarm points for thermal sensors. The eye usually responds to flame or smoke long before such temperatures are reached. And, although we are not at all certain of which product of combustion we are smelling, the nose is probably a very effective product of combustion sensor for almost all fires. Virtually all of the fires reported in tables 1-2 were detected by human sensors, that is, by miners.

But the human observer has serious limitations. He is present only part of the time in a limited region; the attended areas. He is absent part of the time in all areas and most of the time in remote areas and older workings. The human observer is not available in sealed areas and gobs. One can actually attribute the improvement in coal mine fire frequency rate since 1970 in part to the trend of replacing the human observer by automated or semi-automated sensing and extinguishing systems. This is specifically the case for the automated prevention, detection, and extinguishment systems that were required on belts and in belt haulageways.

There is little doubt that products of combustion sensors are available that are far more sensitive than human observers, but current practice generally assumes the presence of human observers. The only current coal mine requirements for automatic fire sensors relate to their use with underground belt conveyors. These regulations (30 CFR 75.1103) are summarized in table 3. The regulations for conveyor belt haulageway protection in coal mines are written in terms of thermal, point-type sensors. Products of combustion sensors can be used only if they offer equivalent protection. Equivalency is in the process of being defined by current MESA testing in participation with the Bureau of Mines. While current metal and nonmetal mine regulations require fire alarm systems and mine evacuation drills (30 CFR 57.4), there are no requirements for automated sensors to actuate the alarms. Hence, current practice in most cases would appear to depend mainly on the human observer.

TABLE 3. - Automatic fire sensors required on underground belt conveyors, CFR 75.1103

(Thermal-type or equivalent)

Thermal (point-type) sensors:
- At the beginning and end of each flight.
- At the belt drive.
- At increments along the belt not to exceed 125 feet high at or above the top belt.

Other sensors:
- Equivalent protection must be provided.
- Equivalency is in the process of being defined.

Other requirements:
- Minimize damage from roof falls.
- Protection from dust and moisture if sensor is contaminated by them.
- Maximum sensor voltage (120 v).
- Sensor system must be operable for at least 4 hr after power is off, otherwise the entire belt haulageway must be walked and examined for hot rollers.
- Automatic warnings, both visual and audible, that permit rapid location of fire and alerting endangered miners.
- Manual reset and fault locators.
- System must be inspected weekly and tested annually.

Tube Bundle Sampling

One area of research that is actively being pursued is the continuing development of a continuous-monitoring technique that was pioneered by the National Coal Board (2, 9).[3] Spontaneous heating in the gob (goaf) regions of advancing longwall systems are now routinely monitored by gas sampling tubes. A branching tree of tubes pneumatically conveys mine air from each zone of interest to a central trunk station for analysis. The analysis station is conveniently located above ground, and it is reliably maintained with sensitive detectors. Any unexplained upward drift in the CO level above the normal background is taken as a warning of the onset of spontaneous combustion in an area.

The Bureau of Mines, in cooperation with United States Steel Co. and MESA, is involved in the development of such a system at the Somerset mine in Colorado. An earlier version of the system monitored 38 points at various intakes, returns, working sections, and sealed areas (1). Regions as far as a mile from the sensing station were routinely monitored. During the course of the study, it was possible to follow the actual growth of a spontaneous combustion situation in a conventional room and pillar section. When attempts to

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

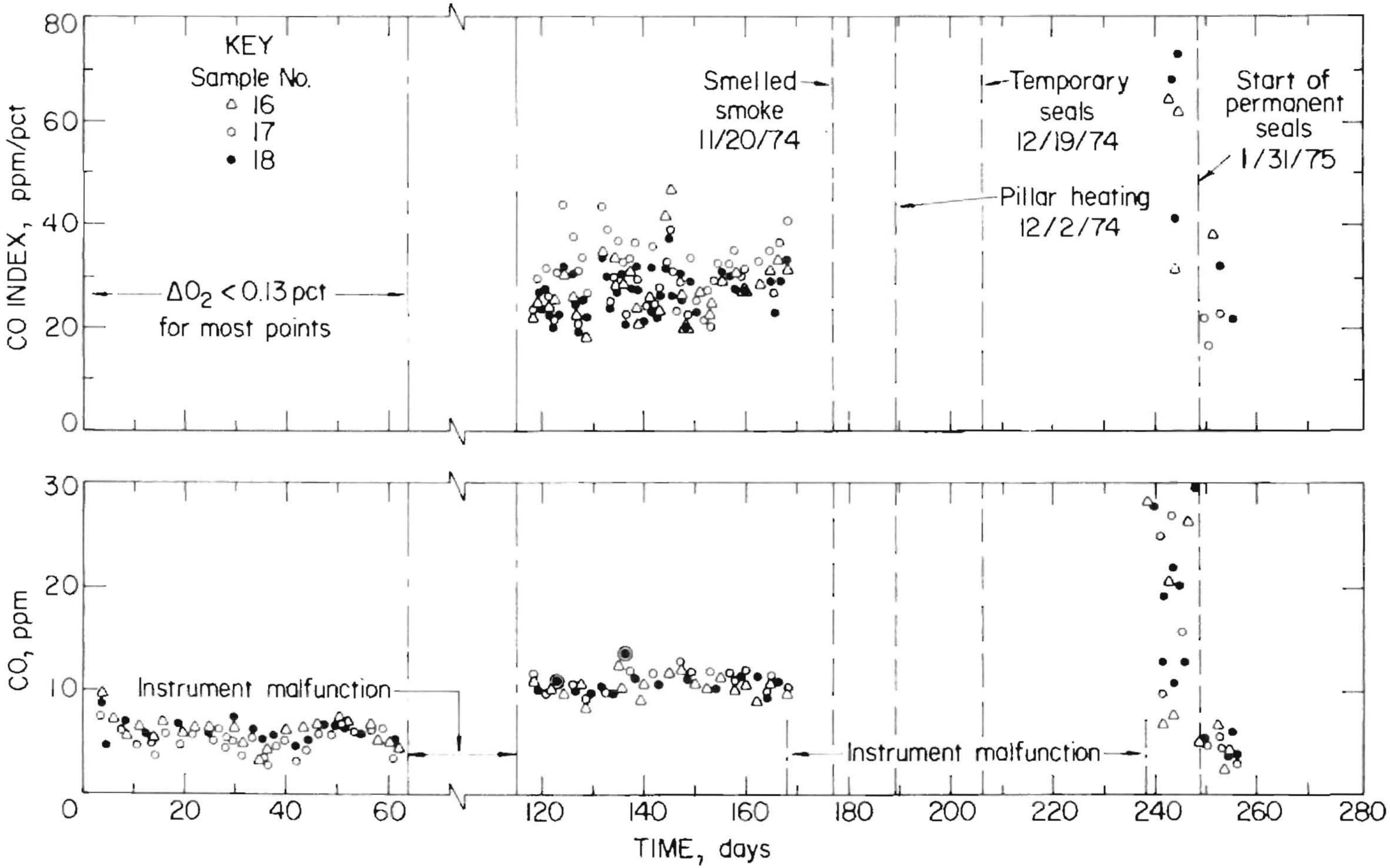


FIGURE 2. - CO concentrations and CO index at three sample points in a return from the 4 right section.

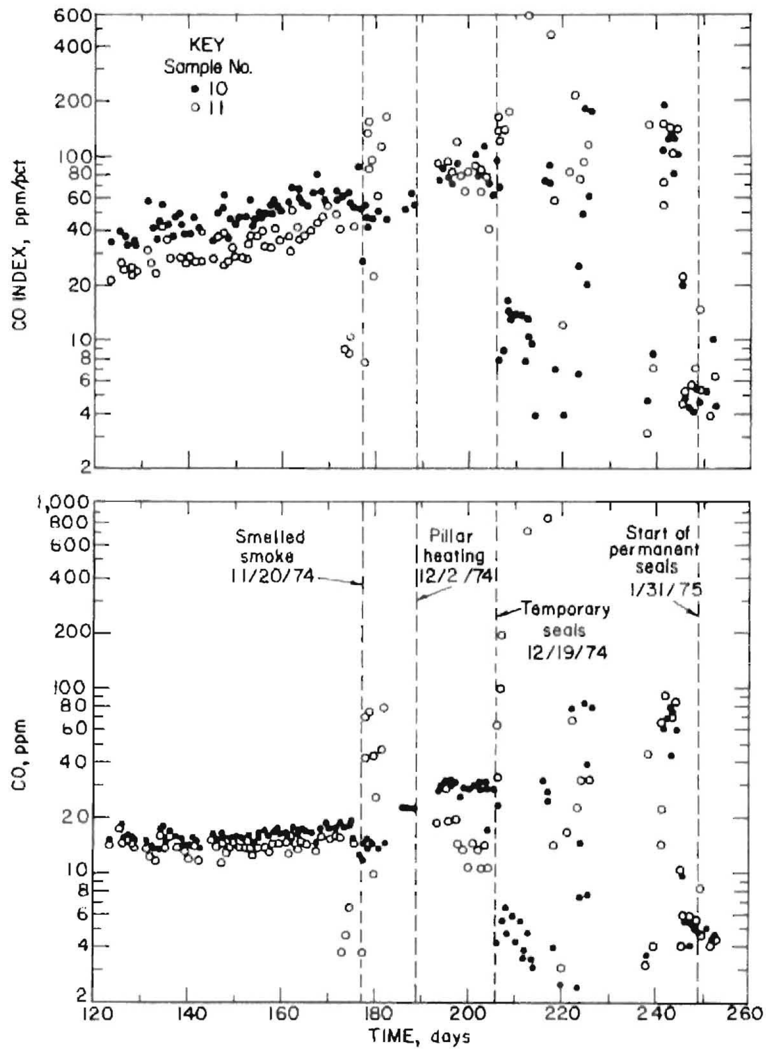


FIGURE 3. - CO concentrations and CO index at two sampling points in the return splits within the 4 right section.

arrest the fire development were unsuccessful, the section was eventually sealed. A map of the section, 4 right of the Somerset mine, was shown in figure 1. The data obtained are shown in figures 2-3. The data in figure 2 are from three stations in the ventilation return from the section. The CO level and the CO index (ppm CO per pct O_2 absorbed) are shown as a function of time. Normal CO levels emanating from the section from day 1 to day 62 were in the range 5±2 ppm. By day 120, the CO level had risen to over 10 ppm. Although the CO index could not be determined between days 1 and 62 because of limitations in the accuracy of the oxygen sensor, there is a clear upward trend in the index between days 120 and 170. It rose significantly from 20 ppm per pct O_2 absorbed to a value of over 30.

The data in figure 3 are for two stations that were actually in the section, in the return splits from the actual face area of 4 right. They also show the high CO level from day 120. The index shows a clear upward trend until smoke was detected by smell on day 177. During the following 29-day interval from day 177 to day 206, various measures were taken to arrest the self-heating including the use of water sprays on the hot pillars. The pillars that were self-heating so markedly that they were hot to the touch are shown in figure 1. Temporary sealing was started on day 206 and with the final erection of permanent seals, the CO levels and the CO index values eventually fell to their normal values. These normal levels were detected in the sealed section that was not accessible to the human observer. The results show that careful attention to the data trends would have enabled one to detect this spontaneous combustion situation long before it developed into a large smouldering fire problem. Such a system is adaptable to gobs, abandoned regions, and sealed areas of a mine where the human observer is not present. There is also little doubt that even in attended areas, this type of system detects the problem much earlier than the unaided human senses.

This mine monitoring system at Somerset is undergoing further development. The analysis station is being located above ground so that it is independent of mine power fluctuations, it can be serviced readily, and it will continue to function if the mine is evacuated and the power is turned off. Also, the system is being divided into two subsystems; one for the active areas and another for the sealed areas. In addition, the development of a more accurate oxygen sensor will allow the CO index to be measured in the active areas even when the pct O_2 absorbed is very low.

Other Bureau research involves the general evaluation of the tube bundle sampling method (3). This involved theoretical, experimental, and practical studies of the advantages and limitations of the method, not only as it applied to spontaneous combustion detection, but also its possible application to the more rapidly developing fire scenarios. Traveltimes through tubes of varying length, width, and pressure drop were measured, cycling time constraints were studied, and the transmission losses of submicrometer smoke particles were measured.

Laboratory studies indicate that submicrometer particles are more universal indicators of spontaneous self-heating than CO detection. Other mine combustibles such as wood, cellulose, and plastics generate these particles at a much earlier stage of heating than the temperatures at which they generate CO (4). A highly sensitive and inexpensive sensor for these particles is shown in figure 4. It is a Bureau of Mines invention (8) that is compatible with a properly designed tube bundle sampling system. Several of these prototype instruments are available for in-mine evaluation of their performance.

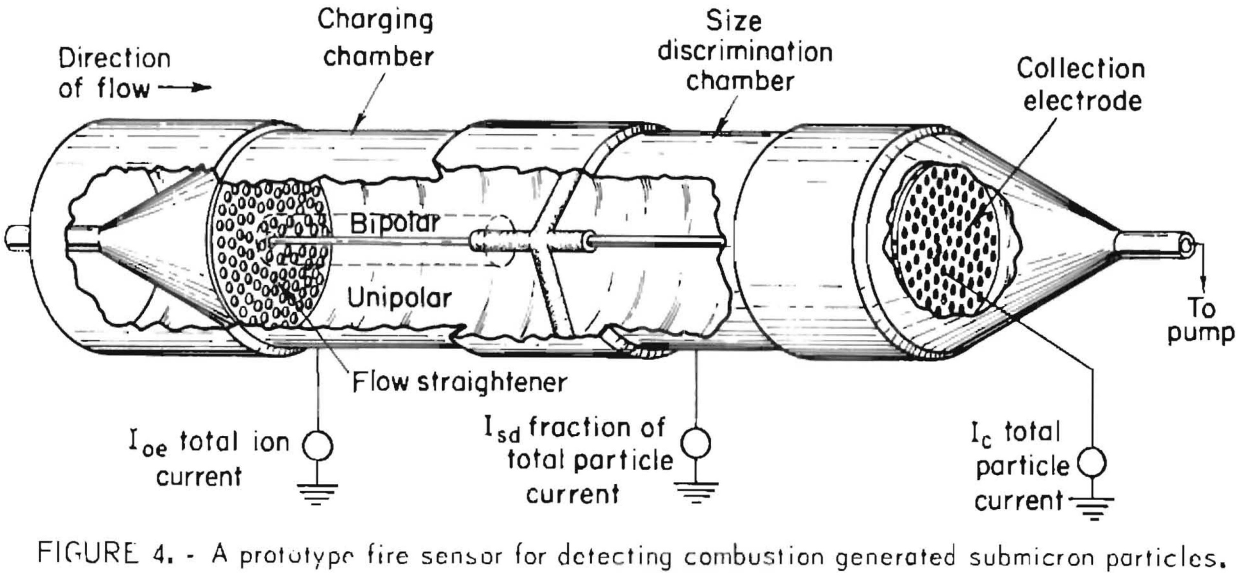


FIGURE 4. - A prototype fire sensor for detecting combustion generated submicron particles.

Spontaneous Combustion and Its Detection

The natural geochemical evolution of a coal seam occurs under anaerobic conditions during an extended geological time scale. A mine is a large, man-made void in the coal deposit which is generated rapidly relative to that geologic time. The deposit that had coalified under anaerobic conditions at high pressure, "suddenly" finds a cavity within itself, and a large surface area is exposed to air at atmospheric pressure and to its oxygen content. This first exposure to air occurs directly during heading development and face cutting or indirectly in the form of roof caving, the fracturing of adjacent parts of the seam by the mining induced stresses, or from large ventilation pressure differences across zones of enhanced permeability. The surfaces that are freshly exposed may consist of the free surface of the roof, floor, and ribs; the pulverized surface area of coal residues in a gob; the fissure area of the fracture pattern; the internal void area left by methane flowing into the lower pressure of the mine void; or finally, the internal surface area generated by the drying of a coal. In all such cases, oxidation is the inevitable result of this exposure of fresh coal surfaces to air. Since the oxidation process is exothermic, heat is generated which can accumulate in the mass that is self-heating. For a given geometric configuration and exposed area, there is a range of airflow velocities for which the self-heating process becomes self-accelerating. The result is first a smouldering mass and then an open fire which can spread rapidly throughout the mine.

Most of the applied research in this field has been done abroad, and the mines studied were predominantly longwall systems in the United Kingdom, the Soviet Union, France, and Central Europe (2, 5, 7, 9, 11). A major factor that determines the spontaneous combustion hazard is the mining method itself, and hence, it may be difficult to apply those longwall studies to other mining methods. The Bureau of Mines research in this area is more recent, and it is limited to the detection studies just described and to laboratory evaluations of the relative tendencies of various eastern and western coals to self-heat in an adiabatic calorimeter (6).

The major factors that contribute to the occurrence of spontaneous combustion in coal mines are (1) the intrinsic reactivity of the coal, (2) the geometry and configuration of the seam (or seams), (3) the geological conditions and structure of the seam and its surroundings, and (4) the mining method and ventilation conditions. Current Bureau research has been concerned with mostly the first factor; however, mining engineers who may be concerned with the development of new mines would do well to study all the factors involved.

The intrinsic activity of the coal can usually be studied in laboratory-scale systems. However, since coal is not a pure chemical substance, its activity can be a strong function of its past history. Various methods are used to measure this intrinsic tendency. Some relate it to the CO generation rate (2), others to the rate of absorption of oxygen (11), some to the pyritic content of the coal (5), and others argue that the low temperatures self-heating properties are dominated by the thermodynamics of the moisture absorption-desorption equilibrium (10). Since the central parameter of interest is the rate of self-heating, the Bureau of Mines approach is to directly measure this property in an adiabatic calorimeter. The calorimeter data show that these various methods of evaluating relative reactivities correlate reasonably well with one another (6). The rate of temperature rise correlates well with the rate of production of CO and CO_2. Coals with high rates of CO production per unit volume of oxygen absorbed also have high self-heating rates in the adiabatic calorimeter. The CO index correlates well with the initial oxygen content of the coal. Some recent data, table 4, show the relative tendencies of various eastern and western coals to self-heat. The minimum self-heating temperature for a fixed sample mass and particle size is the lowest initial temperature at which the coal will self-heat to ignition in the Bureau's adiabatic calorimeter.

TABLE 4. - Incipient combustion tendencies for eastern and western coals

Coal type	Heating value, Btu/lb	CO index, $CO/\Delta O_2$ ppm/vol-pct	Minimum self-heating temperature, ° C
Pocahontas, No. 3, W. Va...	14,400	[1]65	[1]90
Pittsburgh, (Bruceton), Pa.	14,500	[2]75	[1]85
Sahara, No. 20, Ill........	12,700	[2]75	[1]60
Somerset, Colo.............	13,500	[2]120	[1]60
Sarpy Creek, No. 2, Mont...	9,500	[2]215	[2]30
Dravo, No. 80, Wyo.........	11,200	[2]285	[2]30
Jim Bridger, Wyo...........	10,700	[2]190	[2]30
Alaskan....................	7,000	[2]200	[2]30

[1]Undried.
[2]Dried.

The western coals, particularly the lignite and subbituminous coals, show a markedly greater tendency to self-heat. There is a clear consensus (11), supported by these Bureau studies, that the intrinsic activity of the coal is usually directly related to its rank. High rank anthracites present a small hazard; intermediate rank bituminous coals present a moderate hazard; whereas, lignites or brown coals present the greatest hazard.

But there are complications. For example, recent studies with dried coals subjected to moist air confirms the view that the low temperature, self-heating region (20° to 60° C) seems to be dominated by the energetics of the moisture absorption-desorption processes (10).

Does the Somerset mine case discussed earlier represent an isolated occurrence, or is it a foreboding of increasing spontaneous combustion hazards as mining shifts westward to drier areas, lower rank coals, thicker seams, and the more prevalent use of longwall methods? It is difficult to determine, but figure 5 suggests that the problem may not be uncommon. It is of a spontaneous fire in an open pit mine in Wyoming; the freshly uncovered seam is burning spontaneously. While this may not be serious in this open pit situation, it can develop into a very hazardous fire in the confining geometry of a mine.

Finally, there is the question of cost. For this first system at Somerset, equipment costs for tubing, sensors, pumps, and solenoids were approximately $80,000. For a typical coal mine, benefiting from the Somerset

FIGURE 5. - A spontaneous combustion fire in a strip mine in Wyoming. The freshly uncovered seam is burning spontaneously.

experiences, a realistic cost estimate for a similar system would be well under \$50,000. Generally, for large installations involving many sampling points, the tube system is by far less expensive than a system in which each point has a separate detector. Generally, the costs of the pneumatic tubing are comparable with the wiring costs for electronic sensors; however, the electronic system requires a detector at each point, whereas the tube bundle system uses only one sensing station. This can reduce the cost substantially, or alternately one can afford to invest much more in the accuracy, reliability, and degree of sophistication of the sensor. For fire detection, there is generally a trade-off between the traveltime delay imposed by the sampling tube and the enhanced sensitivity one can achieve at the sensing station. Maintenance costs for a single sensor and pumping station should be much lower than for a system containing many individual sensors, each of which must be periodically checked, cleaned, or adjusted for sensitivity. There is also the multiple use potential. For example, the same tube system, once installed, could be used to monitor the methane content throughout the mine in active areas, returns, sealed areas, and gobs.

For a more limited system, for example, one that would involve sampling points every 500 to 1,000 feet along a belt haulageway plus several sampling points in key intake and return roadways, one is dealing with equipment costs of \$10,000 to \$20,000.

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