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Diagnostics of Sealed Coal Mine Fires

By J. M. Kuchta, A. L. Furno, L. E. Dalverny,
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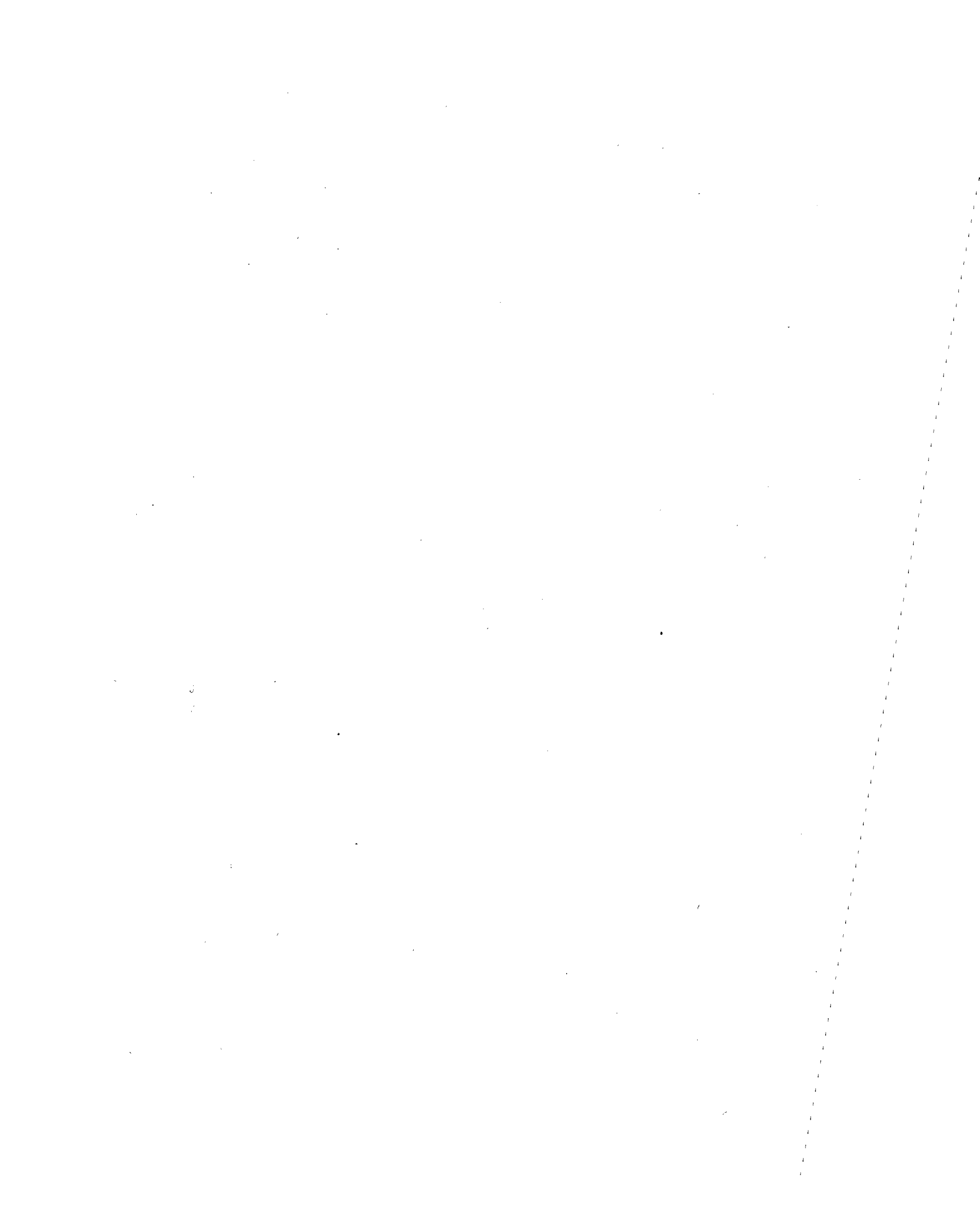
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DIAGNOSTICS OF SEALED COAL MINE FIRES

by

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ABSTRACT

The Bureau of Mines investigated four simulated coal gob fires to obtain a more reliable data base for defining the state of a sealed mine fire and to evaluate the performance of various fire detectors. The fires were conducted in a multiple-entry section of the Bruceton Experimental Mine by heating 4,000 to 21,000 pounds of rubblized bituminous coal to ignition and monitoring the temperature, gas emissions, and smoke under ventilated and sealed combustion conditions. Product gas concentrations depended upon the coal bed size, coal temperature, heating rate, and oxygen concentration or ventilating condition but varied little after the fires were

sealed. Expressions are given that define the temporal variation of CO and O₂ after sealing when the coal temperature decreased rapidly. The CO/CO₂ ratio is a more sensitive fire indicator than the CO/ΔO₂ ratio, although the latter is universally used for detecting the incipient state of a coal fire. In comparison, the Jones-Trickett ratio $\frac{CO_2 + 3/4 CO - 1/4 H_2}{\Delta O_2}$ is less reliable for this purpose. The best detector for determining the state of a mine fire after it has been sealed was a prototype submicrometer smoke particulate sensor. Limitations of the various detector systems are also discussed.

INTRODUCTION

An uncontrolled fire in an underground coal mine frequently can only be attacked by sealing off the fire zone, or the entire mine in the more drastic situations. The sealing operation itself can pose a high risk to the miners, although this risk can be greatly reduced by use of the remote-sealing technique developed

under a Bureau of Mines contract (11).⁶ Nevertheless, once a mine fire has been sealed, the problem then arises as to when and under what conditions can the sealed area be opened without the risk of reignition or explosion. The possibility always exists that restoration of the mine ventilation air may rekindle an extinguished fire, which in turn could ignite pockets of flammable mine gas-air mixtures that have accumulated in the immediate area. Reignitions have been known to occur even after the mine fire areas were flooded with water (10). Prudent decisions in mine fire recovery and

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⁶Underlined numbers in parentheses refer to items in the list of references at the end of this report.

rescue operations are not always possible because of the complexities of sealed mine fires and the uncertainties of available data for making such decisions.

The state of a coal mine fire is normally determined by analysis of mine air samplings taken inby and outby the fire zone. If the fire is only in the incipient stage, that is, self-heating with no incandescence, the main gaseous products are expected to be CO, CO₂, and CH₄ (5). If the fire is in a glowing or flaming combustion stage, the products will be mainly CO, CO₂, CH₄, and H₂. Generally, the fire condition is predictable from the ratios of these gaseous products and the consumed oxygen. In either case, continuous monitoring of the mine air composition is necessary to define the transitory fire and explosion conditions and to reveal any significant trends. The Bureau has demonstrated the utility of continuous-gas-monitoring systems in detecting spontaneous combustion in a coal mine (1) and in facilitating the sealing, reventilation, and recovery of a mine fire area (3). However, these and other field experiences indicated that a reliable interpretation of mine fire gas data requires not only a good data base but also a broad understanding of the diagnostics of sealed mine fires.

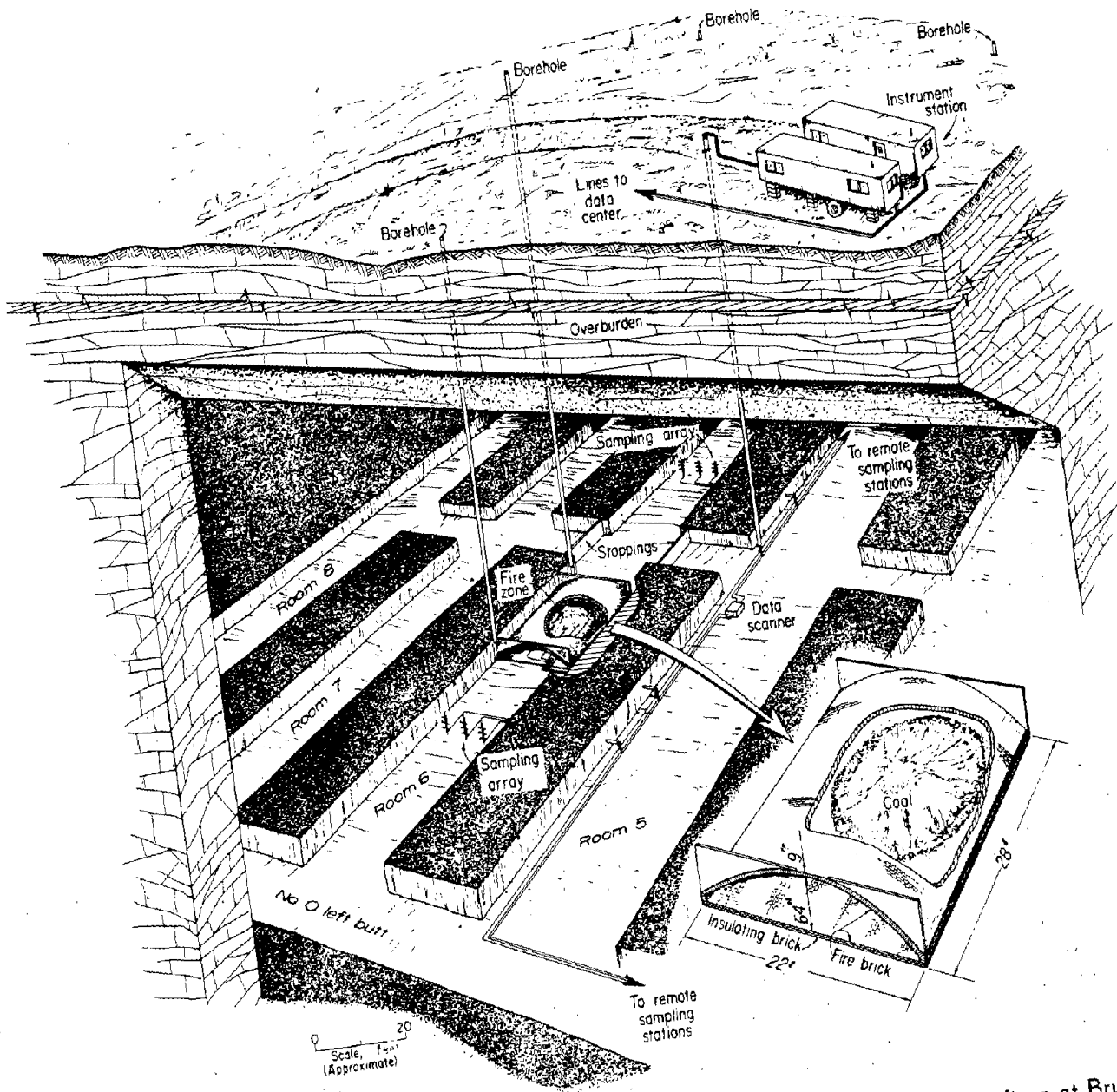
To develop improved guidelines for fighting mine fires, the Bureau's ongoing

research has included both laboratory-scale and full-scale fire studies. Of particular interest in such studies have been the variation of mine fire gas compositions with temperatures and propagation rates, effects of ventilation air, response of the fire to sealing, and effects of scaling factors. Such information has been documented for relatively small tunnel-type fires in which model ducts were lined with coal (2). The present work extends these data to full-scale fires in which various size piles of a bituminous coal (Pittsburgh seam) were ignited to simulate a gob fire. These experiments were conducted in the Bureau's Experimental Mine at Bruceton, Pa., and monitored by a new remote instrumentation facility which was equipped with a video system and various data acquisition systems. Mine fire temperature and gas composition data were defined temporally and spatially for four different size coal rubble fires (2 to 10.5 tons) that were sealed after the burning became fully developed. Different criteria for predicting the initiation, propagation, and extinction of such mine fires are discussed, and performance data are compared for thermal- and combustion-product-type detectors. A more complete report on the performance evaluation of the fire detectors used was published in 1980 (9).

DESCRIPTION OF SEALED MINE FIRE TESTS

The four sealed mine fire tests were performed in a multiple-entry section of the Bruceton Experimental Mine. A perspective drawing of the mine test section appears in figure 1, together with a detailed drawing of the fire zone. The multiple-entry section consisted of five parallel rooms that were connected to a common intake airway and a common return or exhaust airway; all rooms were cement lined to protect against ignition of the mine coal seam. A section of one room (No. 6) was modified to form a

circular-archshaped tunnel and lined with fire or insulating brick. This resulted in a fire zone that measured 20 feet wide at the floor, 5-1/3 feet high at the center, and 28 feet long; total length of a room passageway was approximately 200 feet with each coal pillar a nominal 90 feet long. Temporary stoppings were erected at appropriate points to direct the ventilating air into the fire zone and to restrict the flow patterns of the mine fire gases throughout the multiple-entry test section (fig. 2).



SEALED COAL MINE FIRE TEST AREA

FIGURE 1. - Perspective drawing of multiple-entry test section in sealed mine fires at Bruceston Experimental Mine.

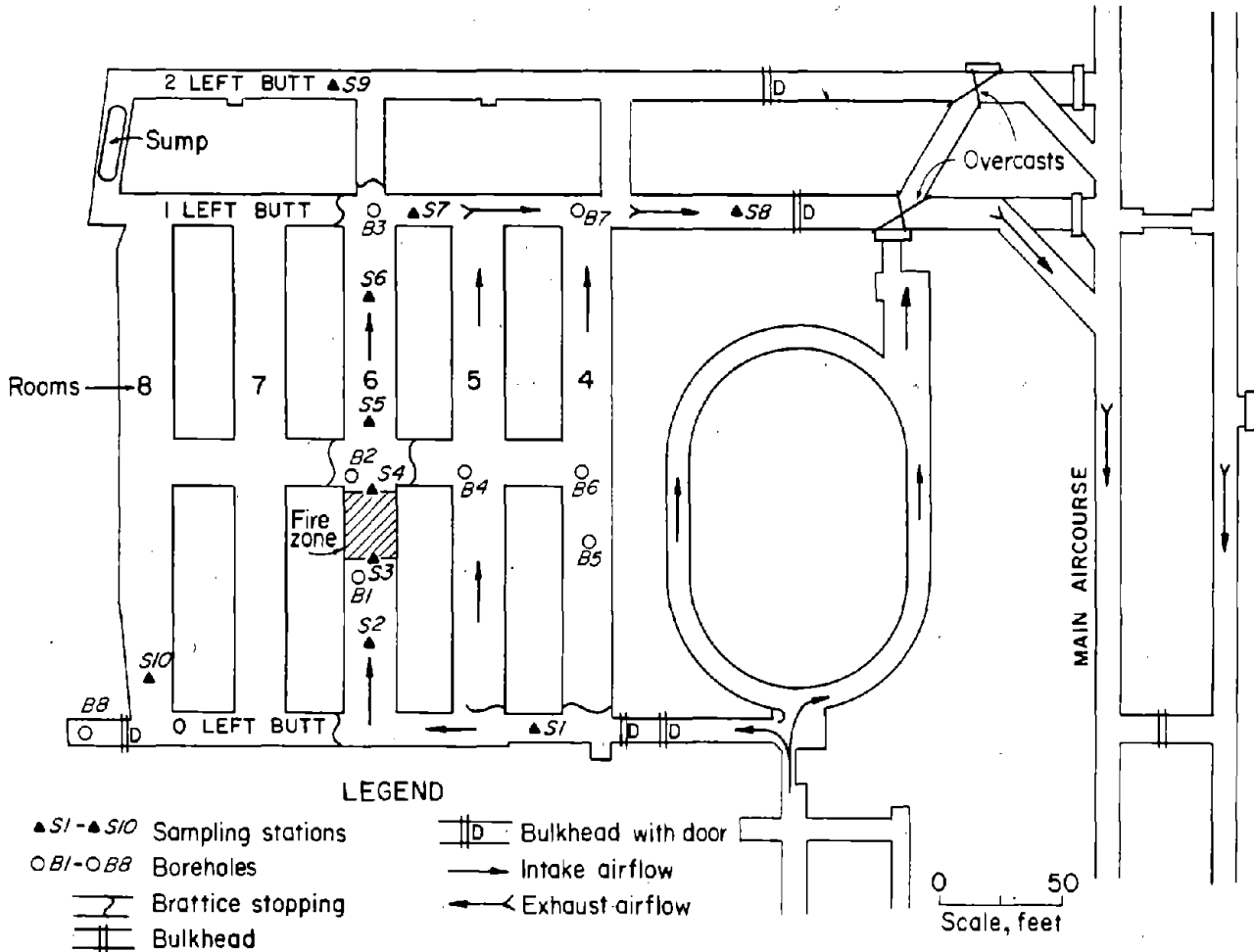


FIGURE 2. - Diagram of multiple-entry test section showing gas-sampling stations and ventilation stoppings in sealed mine fires.

Run-of-the-mine bituminous coal from the adjacent Bruceton Safety Research Mine was used in these experiments. Proximate and ultimate analyses of the coal are given in table 1. The coal was loaded in the fire zone to simulate a gob pile of some predetermined shape and size, then ignited under a ventilating condition to produce a fully developed fire, and subsequently sealed for a week or more. The mass of the coalbed ranged from 4,000 to 21,000 pounds and was ignited by 11-inch-diameter ring heaters and/or 48-inch elongated tube heaters that were centrally positioned in the coalbed, generally near the top surface; the number of heaters used in each fire

is given in table 2. Both slow and rapid ignition conditions were investigated. The first three fires (SCMF-1, 2, and 3) involved relatively rapid ignition (5 to 6 hours) and coalbed sizes ranging from 4,000 to 16,500 pounds; the fourth fire (SCMF-4) involved very slow ignition (65 hours) and a 21,000-pound bed. Table 2 summarizes the different test conditions used for the four fire scenarios, including the times for sealing and reopening the mine test entry; the indicated shapes for the coalbeds represent gross descriptions of their actual geometrical configurations. The first fire provided preliminary data for checking out the instrumentation.

TABLE 1. - Proximate and ultimate analyses of Bruceton Safety Mine coal (Pittsburgh bituminous seam),¹ percent

	As received	Moisture free	Moisture and ash free
PROXIMATE ANALYSIS			
Moisture.....	1.5	None	None
Volatiles.....	38.9	39.5	41.1
Fixed carbon....	55.8	56.6	58.9
Ash.....	3.8	3.9	None
ULTIMATE ANALYSIS			
Hydrogen.....	5.6	5.5	5.7
Carbon.....	79.7	81.0	84.3
Nitrogen.....	1.8	1.8	1.9
Oxygen.....	7.9	6.6	6.9
Sulfur.....	1.2	1.2	1.2
Ash.....	3.8	3.9	None

¹Heating value, 14,500 Btu/lb (calculated from ultimate analysis).

TABLE 2. - Test conditions and scenarios for simulated coal mine gob fires in Bruceton Experimental Mine

	SCMF-1	SCMF-2	SCMF-3	SCMF-4
Coal bed:				
Shape.....	¹ Conical	² Hemiellipsoidal	² Rectangular prism	² Rectangular prism
Size.....feet..	~8 × 6-1/2	~13 × 9 × 4-1/2	~18 × 14 × 1-1/2	~18 × 14 × 2-1/2
Mass.....pounds..	4,000	8,400	16,500	21,000
Ventilation rate before sealing				
ft/min..	100	100	100-200	50
Ignition source:				
Ring heaters, 11-inch diameter	1	1	2	2
Tube heaters, 42-inch length, 12 inches apart	2	2	2	2
Mine fire scenario, hours:				
Ignition time....	6	5	6	65
Sealing time.....	24	23	27	94
Reopening time...	387	313	190	427
Resealing time...	None	316	None	None
2d reopening time	None	529	None	None

¹Dimensions refer to maximum base diameter and height of bed, respectively.

²Dimensions refer to maximum length, width, and height of bed, respectively.

Fire growth or decay was monitored by temperature and combustion product sensors. The coal temperatures were measured by a vertical array of thermocouples at the center of the coalbed and by a horizontal array at various distances from the vertical axis of the bed; thermocouples were equally spaced at 1- or

2-foot intervals, depending upon the dimensions of the coalbed. Mine gas temperatures were also measured during the fires. However, these data are not included in this report since they displayed little variation with time at remote distances from the fire zone.

The gaseous combustion products were measured by an array of detectors at each of the sampling stations shown in figure 2. Samples of the gases at each station were taken at fixed time intervals by programmed sampling valves and analyzed by specific detectors for CO, CO₂, CH₄, and O₂; also, grab samples were periodically taken for gas chromatographic analyses to determine H₂ formation and to check reliability of the different analyzers. The various detectors or analyzers that were used follow:⁷

CO: Mine Safety Appliance, MSA Lira model 300;
Infrared Industries, IRI model 702-002

CO₂: Beckman Instruments, model 865;
Infrared Industries, IRI model 702-054

CH₄: Beckman Industries, model 865;
Infrared Industries, IRI model 702-053

O₂: Mine Safety Appliance, MSA model 802;
Beckman Instruments, model 855;
Edmont Wilson, model 60-620;
Taylor, Servomex, model OA. 272

In addition, submicrometer smoke particulate concentrations were measured in one of the fires (SCMF-4) to compare



FIGURE 3. - Smoldering coal combustion after 5 hours of heating in sealed mine fire SCMF-1.

⁷Reference to specific trade names is made for information only and does not imply endorsement by the Bureau of Mines.



the reliability of such measurements with those of temperature and gaseous combustion products for determining the state of the mine fire. The smoke detector was a prototype model developed by Litton, Graybeal, and Hertzberg (8) and was specifically compared with a CO detector. In these comparisons an Ecolyzer detector (Series 2000) was used for low CO concentrations (<500 ppm) and IRI model 702-002 for high CO concentrations (>500 ppm). The smoke emission that can occur in such fires is shown in figure 3; this photograph was taken during the smoldering combustion stage of the SCMF-1 fire after 5 hours of heating.

Signal outputs of the temperature, gas, and smoke detectors were fed to a data logger system in the mine test entry and eventually to an instrument control center above the mine. The remote data control center was initially located in a pair of field trailers (fig. 1) but later installed in a laboratory building as a more permanent facility. Figure 4 shows the remote instrument control facility, which is equipped with various gas analyzers, recorders, a computer printout terminal, and other data acquisition instrumentation; it also has a video capability for observing the status of a mine fire.

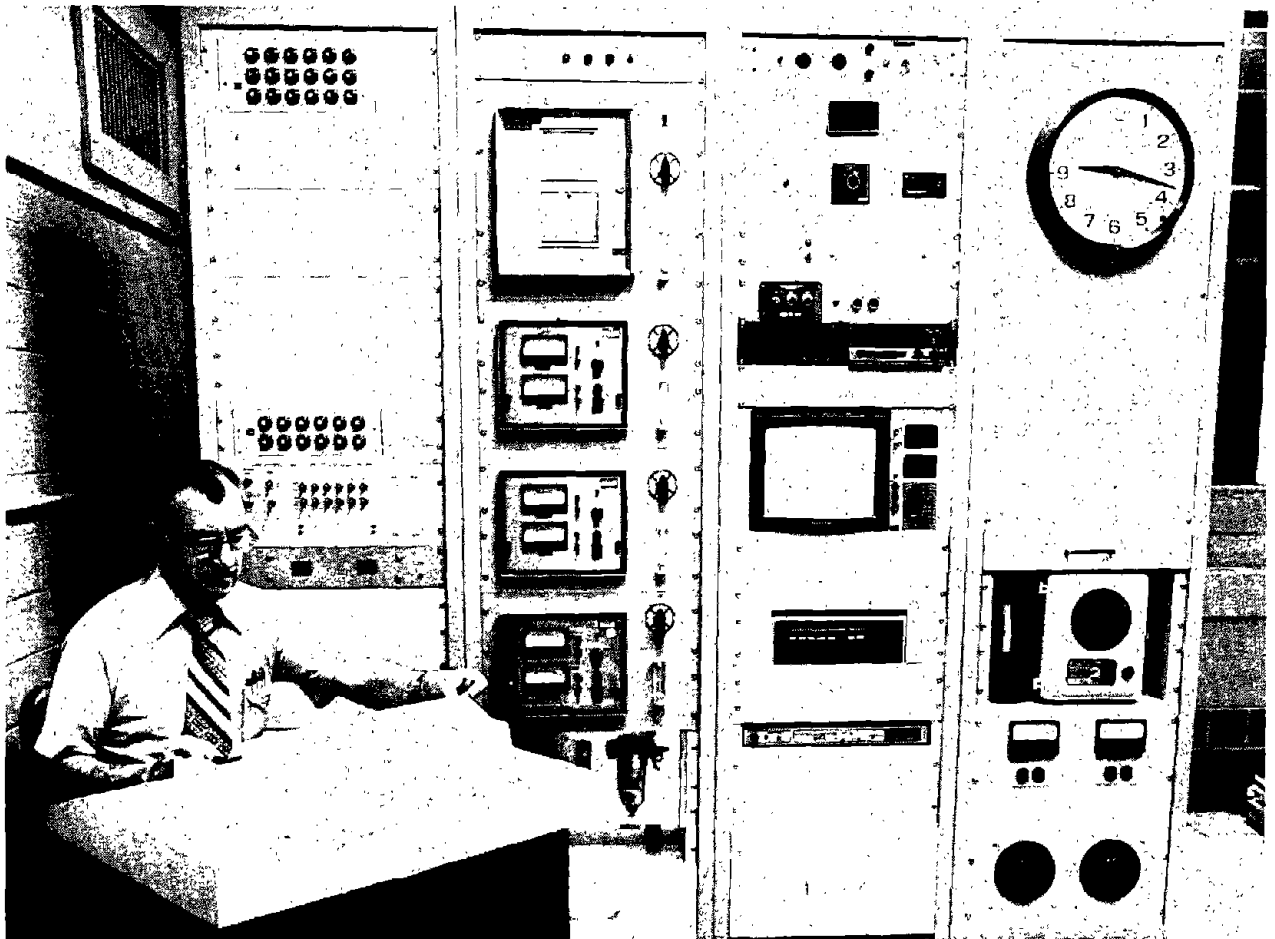


FIGURE 4. - Remote instrument control center for sealed mine fires.

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EXPERIMENTAL RESULTS

Sustained fires were achieved in each of the four fire scenarios described in table 2. Reignition after reopening the sealed mine fires occurred only in the initial scenario (SCMF-1), which was primarily intended to serve as a "shakedown test" of the monitoring systems. A brief description of each fire and the

response of the various monitoring systems is given herein. In all the fire scenarios, the initial temperature rises prior to ignition should not be construed as being due to self-heating of the coal but rather to the external application of heat.

Temperature Histories

SCMF-1.--This scenario involved the smallest quantity of coal, a 4,000-pound conical bed, and relatively early ignition (6 hours) by the electrical resistance heaters used in this work. Figure 5 shows the temperature histories obtained at three levels on the vertical, central axis of the conical coalbed. As indicated by temperature measurements closest to the top of the coalbed, the bed temperature rose rapidly to nearly 600° C prior to sealing (24 hours) and, after leveling off, increased abruptly to over 950° C because of apparent flaming combustion. Temperatures at both this location and the other bed locations peaked only after the test entry had been sealed for over 40 hours. Although these temperatures subsequently decreased sharply, they peaked again before the entry was reopened at 387 hours; apparently the smoldering coal became inflamed as a result of air leakage, which was indicated by the gas analyses. Since the middle and bottom coalbed temperatures were still above 300° C when the mine was reopened, it is not surprising that the temperature data indicated the coalbed reignited upon being reventilated.

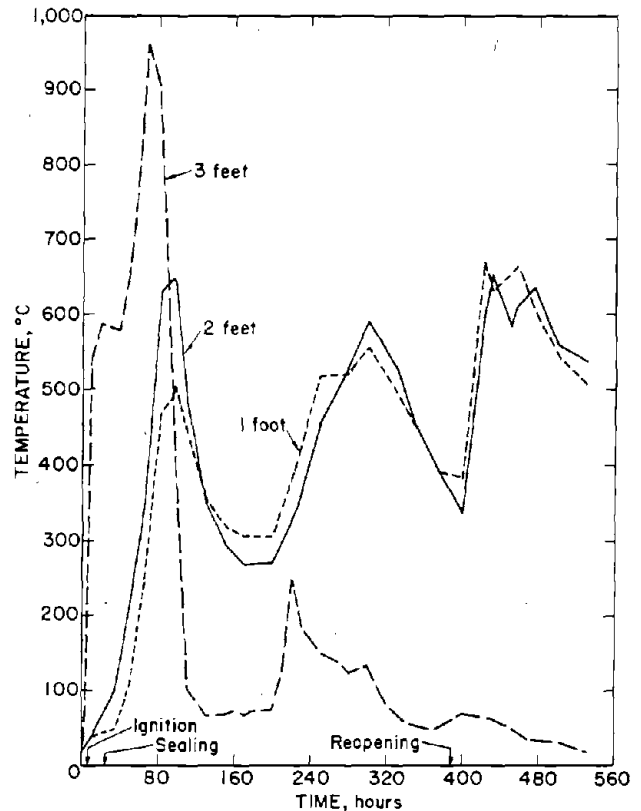


FIGURE 5. - Temperature histories at three levels on vertical axis of conical coalbed (4,000 pounds) for fire SCMF-1.

SCMF-2.--The second scenario utilized a shallow hemiellipsoidal coalbed (8,400 pounds) that was roughly twice as large in mass as that used in SCMF-1; it had similar times for igniting (5 hours), sealing (23 hours), and reopening

(313 hours). Temperature histories in the central region of the coalbed for this fire are shown in figure 6. As in the initial fire, the coal bed temperatures near the surface rose rapidly after ignition and peaked (>600° C) at the time of sealing or after sealing, depending upon their location. However, in this experiment, all three bed temperatures eventually fell to below 100° C ~150 hours after sealing and did not rise after reventilation of the test entry at 313 and 529 hours.

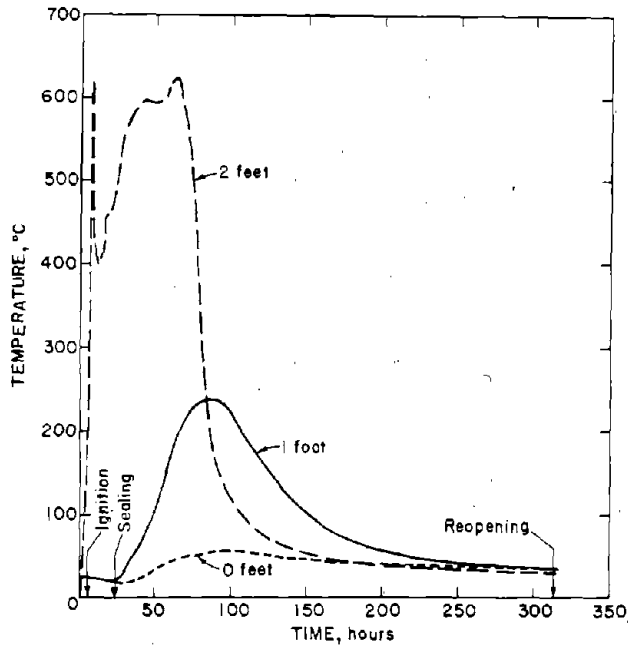


FIGURE 6. - Temperature histories at three levels on vertical axis of ellipsoidal coalbed (8,400 pounds) for fire SCMF-2.

SCMF-3.--In this fire, the igniting (6 hours) and sealing (27 hours) times were essentially the same as in the first two fires, but the reopening time (190 hours) was much earlier and the coalbed mass (16,500 pounds) and shape (rectangular prism) were different. Figure 7 shows the temperature histories of the coalbed for this fire, in which peak temperatures were about 750° C. Although the top thermocouple indicated some evidence of reignition ~70 hours after sealing, the coalbed temperature remained below 100° C after reventilation, similar to the SCMF-2 fire.

SCMF-4.--The final fire was also made with a rectangular coalbed. It differed from SCMF-3 in that the bed was

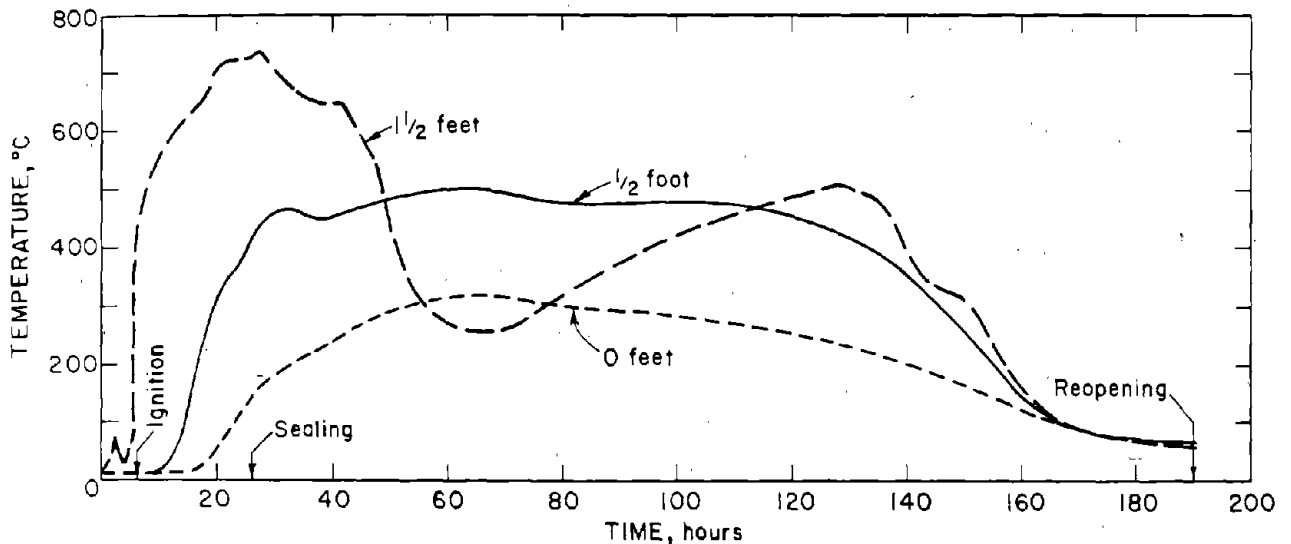


FIGURE 7. - Temperature histories at three levels on vertical axis of rectangular coalbed (16,500 pounds) for fire SCMF-3.

larger (21,000 pounds) and the igniting (65 hours), sealing (94 hours), and re-opening (427 hours) times were much later. Prior to ignition, the maximum temperature measured in the coalbed was approximately 70° C, near the surface (fig. 8). The top and middle bed temperature peaked at slightly over 800° and

550° C, respectively, before sealing. Burning appeared to be sustained in the middle of the bed for about 250 hours after the test was sealed, after which bed temperatures fell to below 100° C and did not rise after reventilation of the entry.

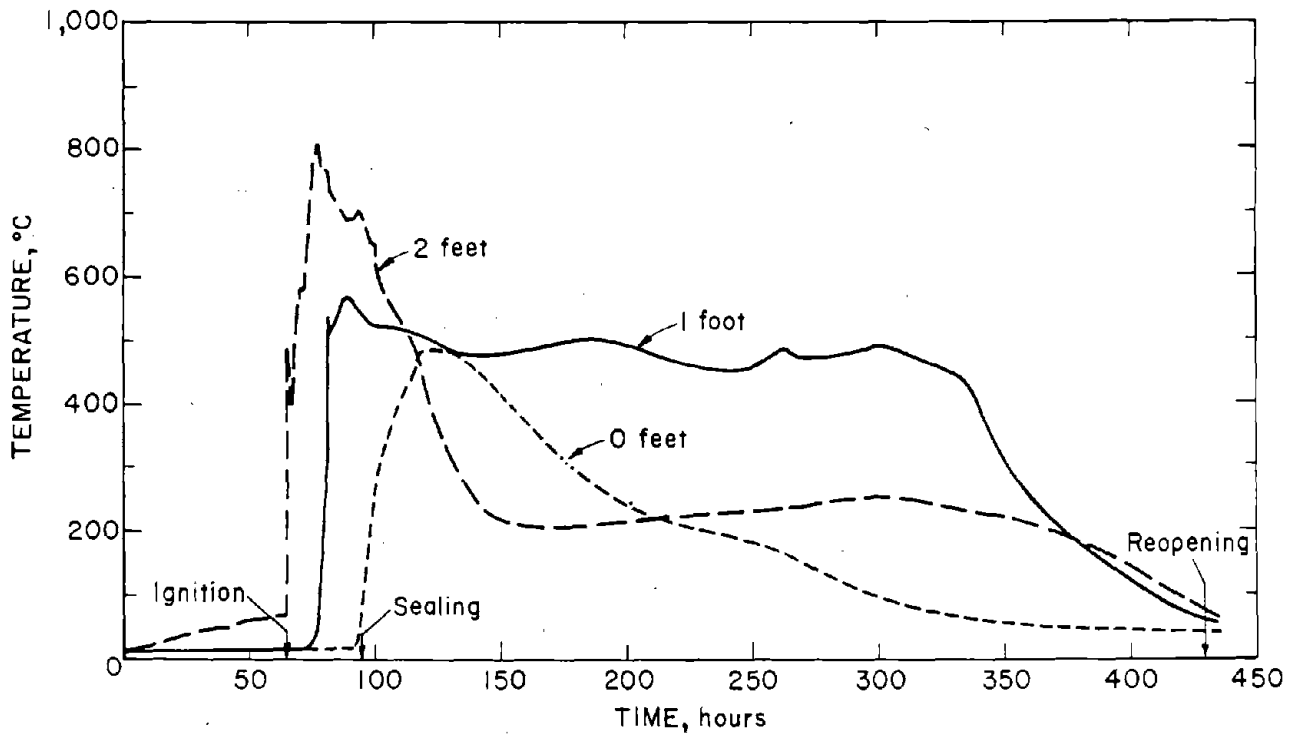


FIGURE 8. - Temperature histories at three levels on vertical axis of rectangular coalbed (21,000 pounds) for fire SCMF-4.

Generally, the fires spread more rapidly horizontally than vertically down through the coalbed. Also, the propagation tended to extend farther upstream than downstream of the ignition sources(s) apparently because of the greater availability of fresh oxygen at the upstream end, particularly during the ventilation stage, that is, prior to sealing; this assumes the ventilation air becomes more vitiated in passing across the burning coalbed. Figure 9 shows the horizontal temperature histories obtained at four upstream positions in SCMF-4. Note that the 100° C level was reached at the 6-foot horizontal station in

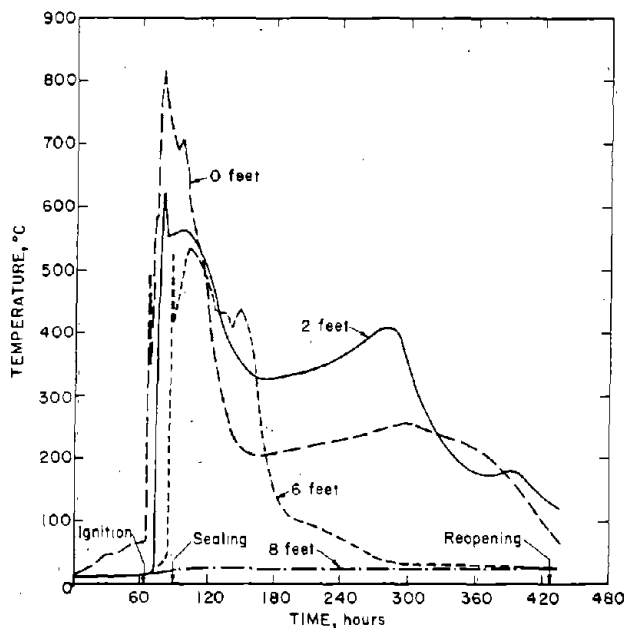


FIGURE 9. - Temperature histories at four locations on horizontal axis of rectangular coalbed for fire SCMF-4.

approximately 85 hours, whereas in figure 8, this temperature was not realized at the 2-foot vertical station until 95 hours had elapsed. The other fires gave a similar trend to that displayed by SCMF-4.

Thermal Wave Velocities

Propagation of the fires after ignition was greater with the larger coalbeds, which were relatively shallow (1-1/2 or 2-1/2 feet). This was largely attributable to the greater bed ventilation expected with the shallower beds and the fact that an additional ring heater was used for their ignition. Table 3 summarizes the average thermal wave velocities that were deduced from the temperature-time profiles found at various vertical (central axis) and horizontal (major axis) stations in the bed. The downward thermal velocities at 100° and 200° C temperature levels were between 0.25 and 0.55 in/hr for SCMF-1 and 2 and between 0.66 and 0.80 in/hr for SCMF-3 and 4. These values roughly approximated the maximum linear burning rates of the coalbeds. Generally, the horizontal thermal wave rates were about four times greater than the vertical rates, but the former could not be precisely defined for the conical or ellipsoidal coalbeds (SCMF-1 and 2). The vertical rate data for these coal gob fires were not greatly different from those reported for small coal tunnel fires (2); however, the horizontal rates were much lower than those found in the tunnel fires because the latter involved noticeably higher ventilation rates and much lower radiative heat losses.

TABLE 3. - Average thermal wave velocities along vertical and horizontal axis of coalbed in sealed mine fires

Test	Height (nominal) of bed, feet	Weight of coal, pounds	Thermal wave temperature, ° C	Thermal wave velocity, ¹ in/hr	
				Downward	Horizontal
SCMF-1	6-1/2	4,000	100	0.55	NA
			200	.41	NA
SCMF-2	4-1/2	8,400	100	.25	NA
			200	.40	NA
SCMF-3	1-1/2	16,500	100	.73	2.5
			200	.66	2.4
SCMF-4	2-1/2	21,000	100	.80	3.7
			200	.78	3.5

NA Not available.

¹Average rates inferred from temperature measurement along central vertical axis (downward) and major horizontal axis of the coalbed. Rates for SCMF-1 and SCMF-2 achieved after sealing; rates for SCMF-3 and SCMF-4 achieved prior to sealing.

Product Gas Analyses in Fire Zone

The main gaseous products evolved in the mine fires were CO, CO₂, CH₄, and H₂. Their formation and oxygen consumption in the fire zone of each experiment are compared in figures 10-13. These data were obtained at the upstream end of the coalbed (station S3) and near the mine roof. Corresponding data at the downstream end or at other vertical sampling levels did not differ greatly because of the high degree of convective mixing that was induced by the fires. Also, the CO, CO₂, CH₄, and O₂ data largely represent continuous analyzer samples, while the H₂ data refer to grab samples taken at regular time intervals; an exception are the SCMF-2 data which refer to grab samples for all the gases because of an analyzer malfunction. Although the continuous analyzer and grab sample data for CO agreed reasonably well, the former data tended to be noticeably higher (>10 pct) in many instances for CO₂ and CH₄. Sampling uncertainties could account for this discrepancy. The variations of the mine fire gases are summarized in the following paragraphs:

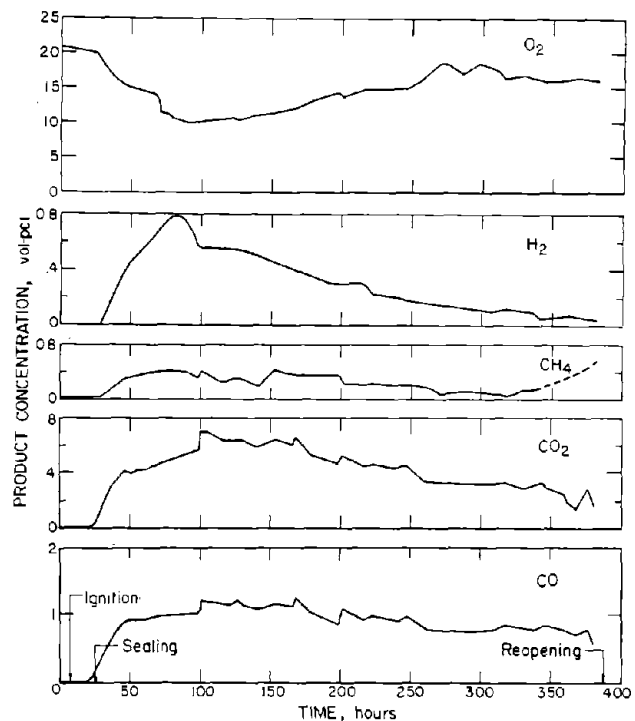


FIGURE 10. - Product gas concentrations versus time in fire zone (station S3) for fire SCMF-1. Dashed portion of CH₄ curve gives approximate trend; data were ill-defined owing to electronic malfunction.

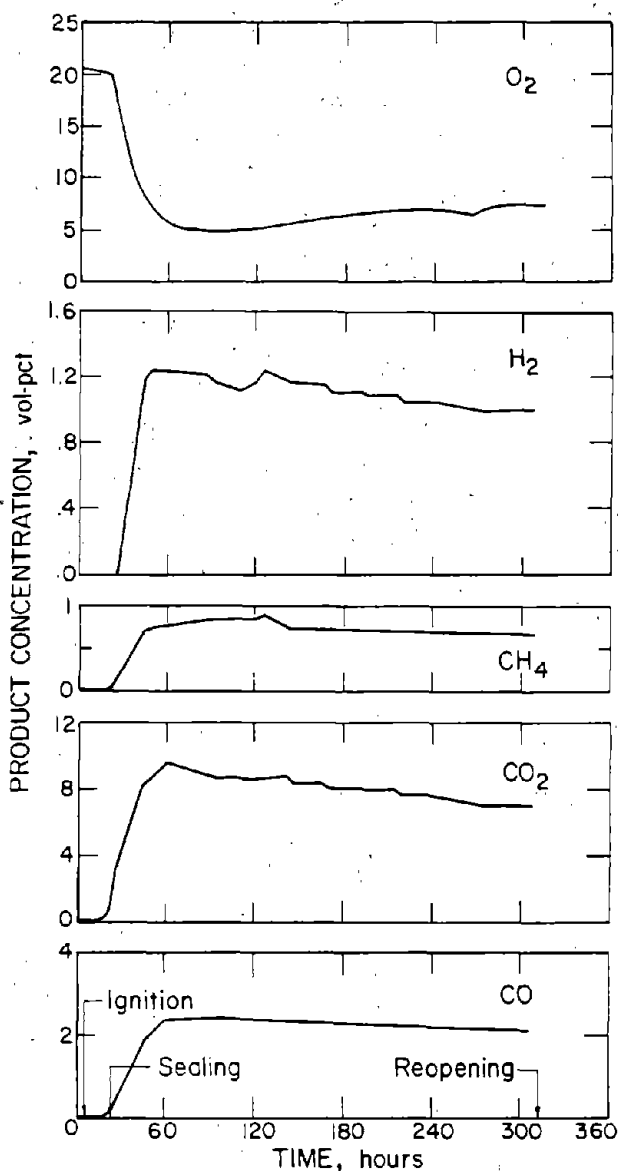


FIGURE 11. - Product gas concentrations versus time in fire zone (station S3) for fire SCMF-2.

Oxygen (O_2).--Before the mine fires were sealed, the O_2 concentration in the fire zone decreased only slightly, from 20.9 percent to approximately 20 percent, indicating the mine ventilation rate was more than adequate to sustain burning of each coal bed. Most of this O_2 reduction occurred after the coalbeds were brought to ignition. After sealing, the O_2 concentrations fell sharply and tended to level off at some minimum value, except in the smallest size fire (SCMF-1), where the O_2 increased substantially after falling to a minimum (fig. 10).

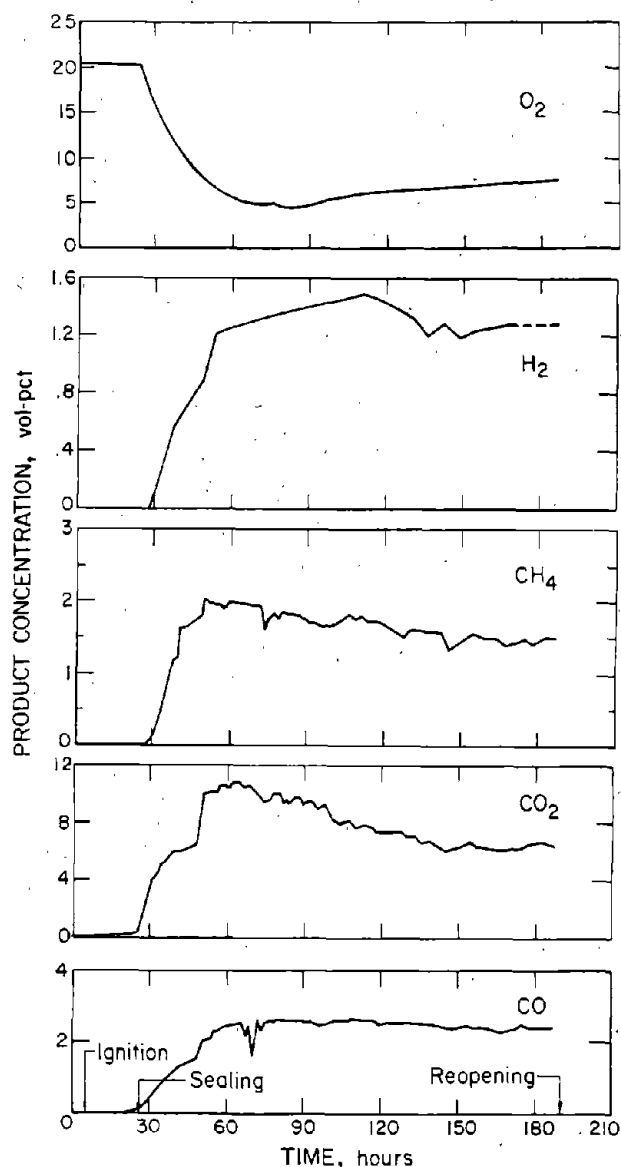


FIGURE 12. - Product gas concentrations versus time in fire zone (station S3) for fire SCMF-3. Dashed portion of H_2 curve gives approximate trend; data were ill-defined owing to electronic malfunction.

The minimum O_2 after sealing was about 5 percent in three of the fires (SCMF-2, 3, and 4) but not less than 10 percent in the initial fire (SCMF-1). Although the latter result was consistent, since this fire was the smallest (4,000 pounds of coal), the fact that the subsequent O_2 concentrations increased substantially in this same fire indicated that noticeable air leakage into the entry had occurred; air leakage after sealing was also apparent in SCMF-2 (fig. 11)

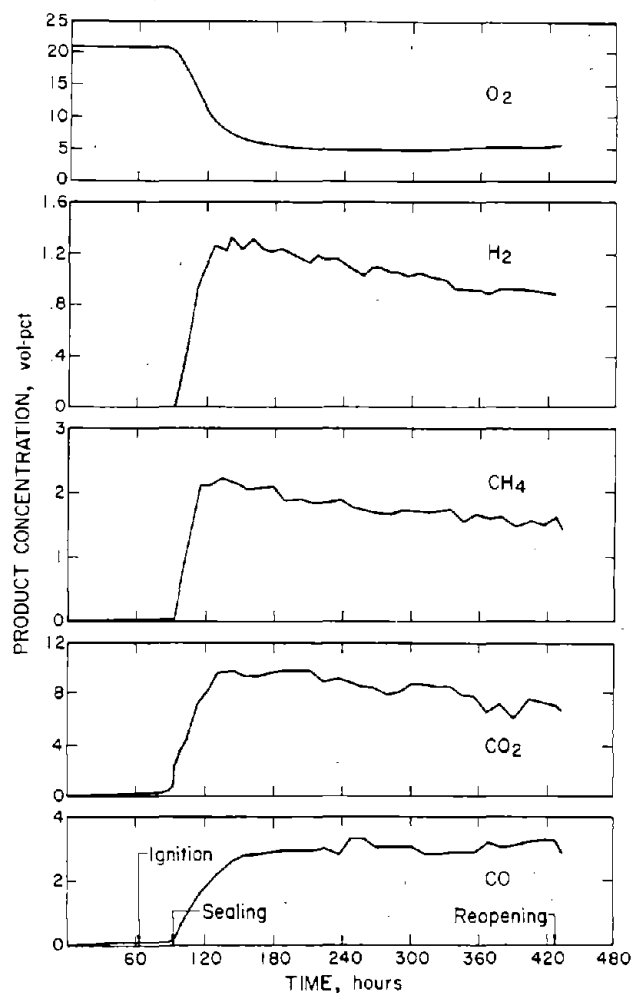


FIGURE 13. - Product gas concentrations versus time in fire zone (station S3) for fire SCMF-4.

Furthermore, without any air leakage, the sealed fires involving at least the larger coalbeds (figs. 12 and 13) would have been expected to consume practically all of the initially available O₂. Confirming evidence of air leakage was found in examination of barometric pressure records, which correlated with many of the small excursions of the O₂ concentration histories.

Carbon Monoxide (CO).--The early formation prior to sealing was at a relatively low level (<0.10 percent) for each fire and required the use of a more sensitive range of the detector than those used to obtain the data shown in figures 10-13. The low level of CO concentrations observed during the initial

stage of these fires was obviously due to the great dilution of the combustion products by the ventilating air. A discussion of the low-level CO emissions is given later in this report.

After sealing, the CO increased to some maximum value and then tended to level off as combustion diminished to a low and relatively constant rate. The peak CO levels varied consistently with the size of the burning coalbed, increasing from about 1.2 percent to 3.5 percent as the coalbed size was increased from 4,000 to 21,000 pounds. Air leakage into the sealed entry appeared to have little or no effect on the CO formation; the peak CO levels decreased during sealing only in the two smallest fires (figs. 10-11) and these decreases were small. Generally, the CO formation varied with the O₂ consumption.

Carbon Dioxide (CO₂).--Like CO, the CO₂ emissions prior to sealing were relatively small, although their levels were much greater than that of CO. These early data are discussed later together with the corresponding CO data.

The CO₂ concentrations peaked shortly after sealing and then decreased at a relatively slow rate because of the apparent air leakage. The peak CO₂ levels were much greater than the CO levels, as would be expected in most coal mine fires. Here, the peak CO₂ level increased from about 7 percent to 10 percent when the coalbed was increased from 4,000 pounds to 8,400 pounds or more. In all four fires, the peak CO₂ level subsequently decreased by one-third or more, indicative of air leakage effects. The CO₂ formation was generally consistent with the O₂ reduction.

Methane (CH₄).--This gas is ordinarily a major constituent of the gases found in coals and is largely consumed as a result of combustion, although its concentration level will vary with the coal temperature. Thus, the CH₄ emissions of a given coal should largely depend upon the temperature and loading density of the coal. Because of the ventilation

rate, this gas was barely detectable prior to sealing. In the present experiments, the peak CH_4 level increased from about 1/2 percent to slightly over 2 percent when the coalbed weight increased from 4,000 to 21,000 pounds. These concentrations were substantially below the lower limit of flammability of CH_4 -air mixtures (5 percent). In fact, the combined fuel emissions of CH_4 , CO , and H_2 were never high enough to form a flammable mixture in any of the fires. This is not to imply that flammable mixtures would not form if larger heated coalbeds were involved. Explosions are known to have occurred after some mine fires.

Hydrogen (H_2).--Hydrogen is formed primarily during the combustion of the coal but was not detected until after sealing because of dilution by the air ventilation. The peak H_2 values were nominally between 0.8 and 1.5 percent for these fires and also decreased subsequently because of air leakage. The air leakage effect was pronounced in the smallest size fire (fig. 10), which was consistent with the O_2 data. As mentioned earlier, these data were obtained solely by grab samples that were analyzed by gas chromatography.

Product Gas Analyses Beyond Fire Zone

Corresponding gas samples taken at other locations in the sealed mine section did not vary greatly from those found in the fire zone. This can be explained by the fact the fire induced great mixing of the mine gases upstream and downstream of the fire zone. Flow probe data indicated that flow reversal in the fire zone occurred even prior to sealing the fires and thereby effected a high degree of mixing; air leakage into the mine test section would also help the mixing process. Figure 14 is based on gas-sampling data obtained at one of the most remote stations (S10) from the fire zone for the largest size fire (SCMF-4). These data varied little from those obtained in the fire zone (fig. 13). The minimum O_2 level and peak CO , CO_2 , CH_4 , and H_2 (not shown in fig. 14) levels were

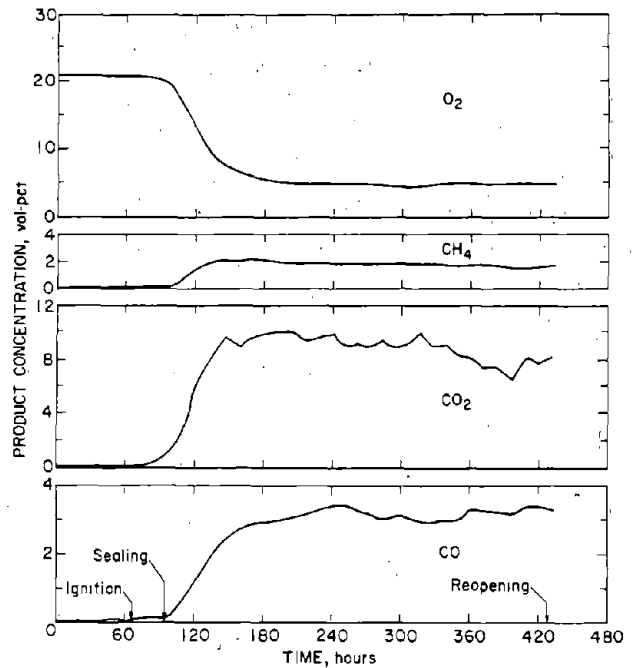


FIGURE 14. - Product gas concentrations versus time at remote station (S10) from fire zone for fire SCMF-4.

essentially the same at the S3 and S10 sampling locations. The main difference, although small, was that the gas concentration levels were observed somewhat later at the remote station. Obviously, a greater difference would be expected if the data comparisons were made for substantially shorter sampling time intervals than used in these tests (~1 hour). Remote-sampling data obtained in the other fires displayed similar trends to that observed in SCMF-4.

Relative Performance of Analyzers

The greatest uncertainty in the gas analytical data was in the SCMF-1 mine fire, in which reliability of the data was questionable because of analyzer deficiencies. Table 4 summarizes the relative performance of the gas analyzers used in the four fires. In SCMF-1, the analyzers for monitoring CO , CO_2 , and CH_4 suffered from the fact that their response was nonlinear and affected by the concentration of the background gases that were present; also, one of the

analyzers for monitoring O₂ had a rather slow response, which could present undue constraints in programming the sampling frequency. For these reasons, other analyzers were substituted in the larger fires for monitoring these gases. Overall, the IRI analyzers for CO, CO₂, and CH₄ gave satisfactory performance; the Beckman O₂ analyzer also performed satisfactorily. Accuracy of these analyzers compared favorably with that obtained by gas chromatographic (GC) analyses of selected samples and indicated that such

analyzers should be suitable for field use under similar mine fire conditions. However, since the concentration range of each analyzer was selected to include the maximum concentration expected in these mine fires, the reliability of each analyzer at very low concentrations in the parts-per-million range was not determined. No problems were encountered in monitoring the H₂ formation, which was determined solely by GC analyses of grab samples.

TABLE 4. - Relative performance of gas analyzers in sealed mine fires

Gas	SCMF-1	SCMF-2	SCMF-3	SCMF-4
CO.....	MSA (Lira)-- nonlinear.	IRI-- satisfactory.	IRI--satisfactory.	IRI--satisfactory.
CO ₂	Beckman--nonlinear.	IRI-- satisfactory.	IRI--satisfactory.	IRI--satisfactory.
CH ₄	Beckman--nonlinear.	IRI-- satisfactory.	IRI--satisfactory.	IRI--satisfactory.
H ₂	GC--satisfactory.	GC-- satisfactory.	GC--satisfactory.	GC-satisfactory.
O ₂	Taylor-- satisfactory. MSA--slow response.	Taylor-- malfunction. Edmont Wilson-- satisfactory.	Beckman-- satisfactory.	Beckman-- satisfactory.

DISCUSSION

Rate of O₂ Consumption

If the burning coal mass in a sealed mine fire is relatively large compared with the available oxygen, the rate of reaction will be controlled by the oxygen concentration (O₂) of the mine atmosphere. In such fires, the reaction should follow a first-order rate law for the rate of oxygen consumption ($\frac{dO_2}{dt}$):

$$\frac{dO_2}{dt} = -k O_2 \quad (1)$$

which upon integration yields

$$\ln O_2 = -k t + \text{constant} \quad (2)$$

or

$$(O_2)_t = (O_2)_{t=0} \exp(-kt) \quad (3)$$

where t is time and k is the reaction rate constant. This implies that a semi-log plot of O₂ versus t should give a straight line with a negative slope of k . A change in the slope would reflect a change in the rate-controlling step, as governed by chemical or physical factors.

In the present simulated fires, the O₂ reduction generally displayed an exponential time dependence from the time the fire was sealed until the O₂ concentration began to level off at a minimum value. The semilog plots of the O₂ data obtained in the fire zone for these fires are given in figure 15. These data show that the O₂ depletion rate after sealing was least for the smallest fire (SCMF-1) and greatest for the two intermediate-size fires (SCMF-2 and 3); the data for the largest fire (SCMF-4) fall in between. The low depletion rate

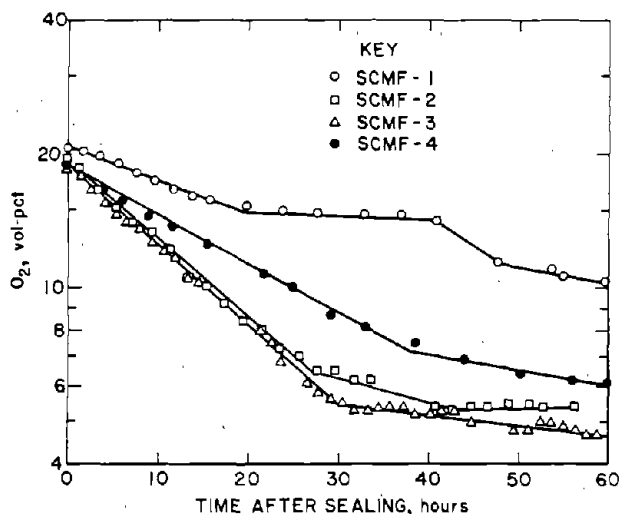


FIGURE 15. - Semilog plots of the variation of O_2 consumption with time in fire zone (station 53) for sealed mine fires.

in SCMF-1 is most likely attributable to the small size of this fire and the relatively great amount of air leakage that occurred (see also fig. 10), note that the O_2 concentration leveled off at approximately 15 percent within 20 hours after sealing and did not fall below 10 percent subsequently. The fact that the O_2 consumption rate in SCMF-4 was less than that observed in SCMF-2 and 3 is more difficult to explain since the former fire was made with a larger coalbed. However, the SCMF-4 fire also involved different ignition and presealing conditions, a lower ventilation rate (~50 versus 100 ft/min), a longer heating time before ignition (65 versus 5 to 6 hours), and a longer burning time before sealing (29 versus 18 to 21 hours). Apparently, these differences were sufficiently significant to result in less complete or extensive burning of the largest coalbed used, at least during the early stage (< 30 hours) of the sealing period.

Expressions were derived from the data in figure 14 to define the temporal variation of the O_2 concentration for each fire after sealing. These expressions are given below and represent the straight lines of best fit

(95-percent confidence level) drawn in figure 15 up to the time where the O_2 levels off:

$$\begin{aligned} \text{SCMF-1} \quad O_2 &= 21.02 \exp(-mt); \\ &t < 20; m = 0.0185 \\ &\pm 0.0015 \end{aligned} \quad (4)$$

$$\begin{aligned} \text{SCMF-2} \quad O_2 &= 18.90 \exp(-mt); \\ &t < 30; m = 0.040 \\ &\pm 0.002 \end{aligned} \quad (5)$$

$$\begin{aligned} \text{SCMF-3} \quad O_2 &= 18.47 \exp(-mt); \\ &t < 30; m = 0.0405 \\ &\pm 0.001 \end{aligned} \quad (6)$$

$$\begin{aligned} \text{SCMF-4} \quad O_2 &= 18.17 \exp(-mt); \\ &t < 40; m = 0.024 \\ &\pm 0.001 \end{aligned} \quad (7)$$

where O_2 is in volume percent, t is in hours, and the coefficients before the exponential terms represent the initial O_2 concentrations, that is, the y-axis intercepts in figure 15. The m coefficients represent the reaction rate constants as reflected by the initial slopes of the curves in figure 15 in units of percentage per hour. Thus, in these fires, the initial oxygen consumption rates ranged from a minimum 1.85 percent initial concentration per hour (SCMF-1) to a maximum of 4.05 percent per hour (SCMF-3).

Rate of CO Formation

The CO formation did not follow an exponential time dependence like that observed for the O_2 consumption, nor should one expect such an agreement. Figure 16 shows a semilog plot of the CO versus time observed in the fire zone after the fires were sealed. As noted, the slopes of the curves change greatly from the onset of sealing to the time the CO level tends to be maximum. The changing slopes are consistent with the fact that the chemical kinetics will vary with great variation in temperature or oxygen concentration, which in turn affects the ratio of CO and CO_2 products. In the present experiments, both temperature and

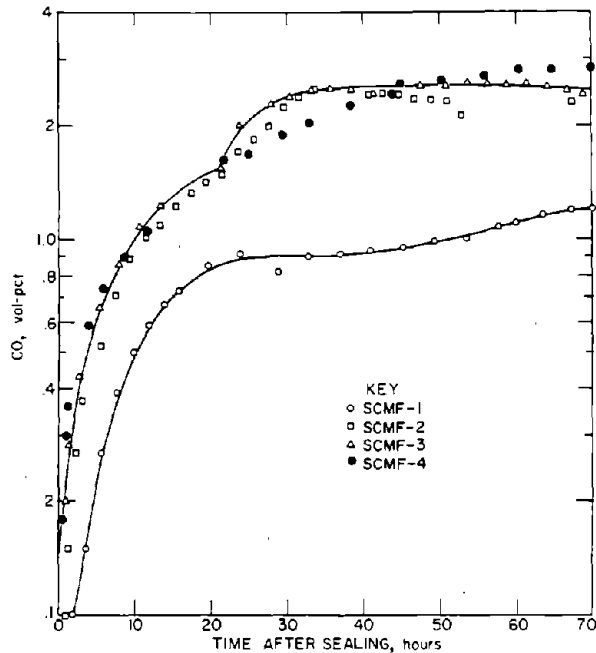


FIGURE 16. - Semilog plots of the variation of CO formation with time in fire zone (station S3) for sealed mine fires.

oxygen concentration decreased drastically during sealing; in addition, the rate of CO formation was complicated by the fact that the surface area of burning was continuously changing and not a controlled variable in any of the fires.

A log-log plot of CO versus time was found to describe these data best, as illustrated in figure 17. The log-log plots for each fire approximated a linear dependence upon time between the instant of sealing and the time at which the CO formation peaked and leveled off. These data show that the rate of CO formation in the SCMF-1 fire was practically the same as in the SCMF-2 fire and somewhat higher than in the SCMF-3 and 4 fires. However, the level of CO formation generally increased with the size of the coalbed, although the data were not entirely consistent, particularly those involving the largest coalbed (SCMF-4). Under normal and uniform burning conditions, the CO level would have been expected to be highest in SCMF-4 before and after the sealing periods. Nevertheless, these CO data are consistent with the gross trends of the O₂ data.

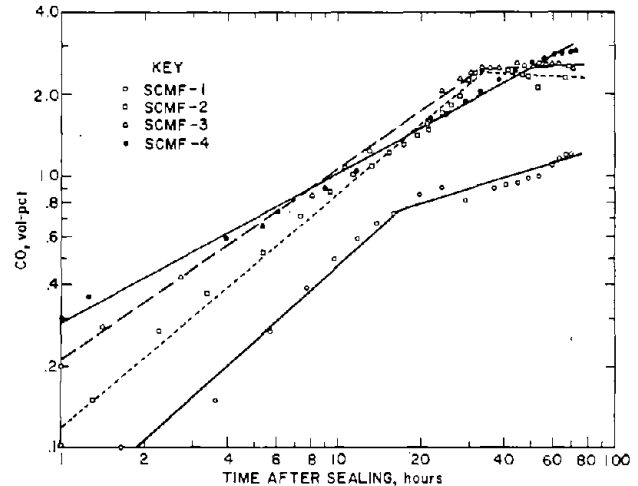


FIGURE 17. - Log-log plots of the variation of CO formation with time in fire zone (station S3) for sealed mine fires.

The best-fit expressions for describing the early CO variations after sealing were simply a power function of time. These are given below for time periods that roughly correspond to those used in defining the O₂ consumption in each fire (95-percent confidence level):

$$\text{SCMF-1 } CO = 0.056 t^m; t < 20; \\ m = 0.93 \pm 0.11 \quad (8)$$

$$\text{SCMF-2 } CO = 0.120 t^m; t < 35; \\ m = 0.85 \pm 0.035 \quad (9)$$

$$\text{SCMF-3 } CO = 0.20 t^m; t < 35; \\ m = 0.70 \pm 0.035 \quad (10)$$

$$\text{SCMF-4 } CO = 0.28 t^m; t < 70; \\ m = 0.56 \pm 0.02 \quad (11)$$

where CO is in volume-percent and t is in hours. The form of these equations indicates that the rate of CO formation could not be predicted from the rate of oxygen consumption, which varied exponentially with time during roughly the same time periods. Although similar expressions were not derived for the CO₂ data, their temporal dependence also was not an exponential type; however, they were somewhat more time dependent than the CO data; that is, the m values in the above equations were slightly greater for the CO₂ formation.

Ratios of Gaseous Products

The different stages of a coal mine fire can be characterized by a knowledge of the composition and relative ratios of the gaseous products. In the incipient or spontaneous combustion stage, slow reactions are initiated at near ambient temperature (<100° C) and the main oxidation products are CO and CO₂ in rather small concentrations, depending upon the confinement. With increasing temperature, both CO and CO₂ evolution increases but the conversion to CO₂ becomes increasingly greater, particularly above the autoignition temperature (~150° C), where rapid oxidation occurs; H₂ formation also becomes noticeable at these temperatures. In the flaming combustion stage the coal reaches a maximum temperature of about 1,000° C accompanied by peak levels of CO₂ and H₂. Although the state of a coal mine fire can be ascertained in theory from analyses of the fire gases, the interpretation of the data is difficult in practice because of mine air dilution effects. Therefore, it is frequently more meaningful to rely upon the ratios of the various product gases, which are not affected by air dilution. Three different ratios were compared in the present sealed fires:

CO/CO₂.--This ratio indicates the completeness of the combustion or oxidation and is defined in terms of volume-percent concentrations of CO and CO₂ that are formed. The ratio is <<1 in a lean coal-air fire and varies with coal temperature and the oxygen concentration of the atmosphere.

CO/ΔO₂ (CO index).--This ratio indicates the amount of CO formed per unit volume of O₂ that is consumed or absorbed and is defined in terms of volume-percent concentrations. More specifically, it is defined as follows:

$$CO/wO_2 = \frac{(CO)_f - (CO)_i}{(O_2)_i - (O_2)_f} \quad (12)$$

where i and f refer to the initial and

later or final concentrations. The ratio is strongly dependent upon temperature and is 0.1 or more above the autoignition temperature (~150° C) of the coal. A recent report by Kuchta, Rowe, and Burgess (6) characterizes the CO indexes for many U.S. coals and their susceptibility to spontaneous combustion at various temperatures.

JT ratio.--

$$JT = \frac{[CO_2] + 3/4[CO] - 1/4[H_2]}{[\Delta O_2]} \quad (13)$$

This ratio (JT) was developed by Jones and Trickett (4) for determining whether methane or coal dust has been involved in a mine explosion. It has also been applied to the analysis of mine fires, although it was not intended for such complicated combustion conditions. Each of the product gas concentrations is in volume-percent. By this equation, methane would have a JT value of 0.5 for complete combustion to CO₂; the values for other hydrocarbons would be greater than 0.5, depending upon their H/C mole ratio. In comparison, the JT value can be 0.5 to 1.0 for coal and equal to or greater than 1.0 for wood (7). Thus, a ratio noticeably less than 0.5 in a coal mine fire could be indicative of extinguishment or greatly reduced coal temperatures. Tunnel coal fire data by Chaiken, Singer, and Lee (2) indicate that the JT ratio tends to decrease monotonically with temperature after sealing. However, any extrapolation to spontaneous combustion temperatures would be rather tenuous.

The CO/CO₂, CO/ΔO₂, and JT ratios derived from three of the present mine fire experiments are shown in the composite plots of figures 18 (SCMF-2), 19 (SCMF-3), and 20 (SCMF-4). Some specific values before and after sealing are given in table 5. Grab sample data were used in all cases for the sake of consistency and because they were the only available data for hydrogen, which is necessary for calculating JT ratios.

TABLE 5. - CO/CO₂, CO/ΔO₂, and Jones-Trickett (JT) ratios for sealed mine fires^c

	CO/CO ₂	CO/ΔO ₂	JT ratio ¹
SCMF-1:			
At sealing.....	0.15	0.09	0.68
At reopening.....	.34	.21	.74
SCMF-2:			
At sealing.....	.11	.08	.70
At reopening.....	.30	.15	.60
SCMF-3:			
At sealing.....	.09	.07	.69
At reopening.....	.40	.18	.55
SCMF-4:			
At sealing.....	.17	.11	.77
At reopening.....	.52	.18	.48

$$1_{JT} = \frac{CO_2 + 3/4 CO - 1/4 H_2}{\Delta O_2}$$

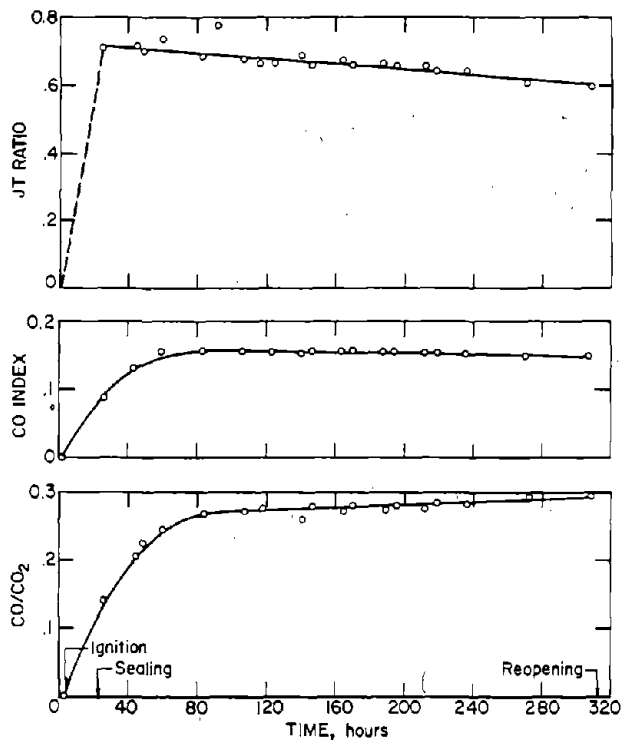


FIGURE 18. - CO/CO₂, CO/ΔO₂, and Jones-Trickett (JT) ratios in fire SCMF-2.

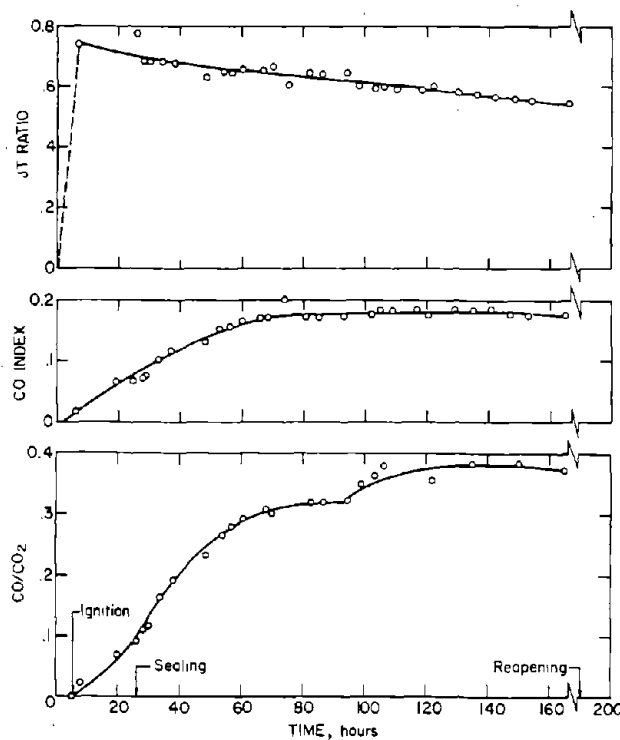


FIGURE 19. - CO/CO₂, CO/ΔO₂, and Jones-Trickett (JT) ratios in fire SCMF-3.

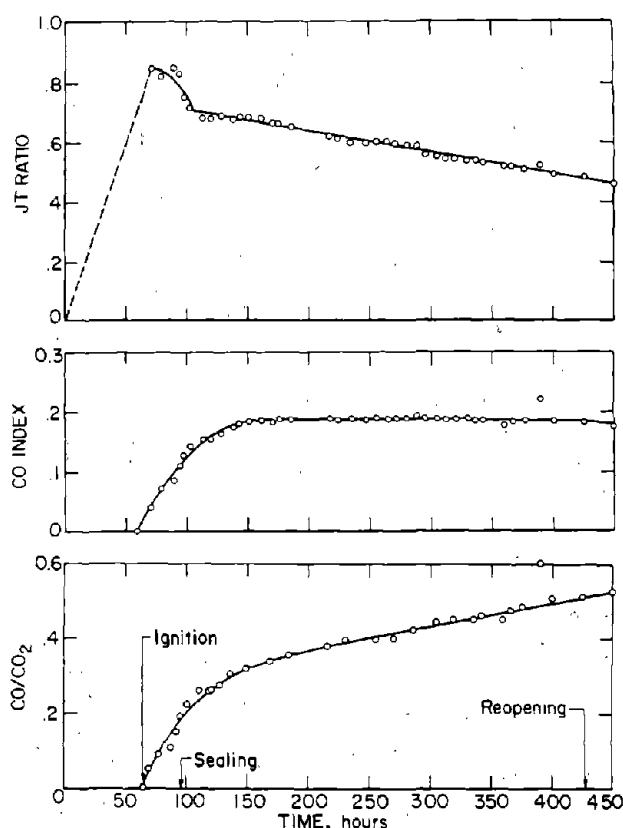


FIGURE 20. - CO/CO_2 , $\text{CO}/\Delta\text{O}_2$, and Jones-Trickett (JT) ratios in fire SCMF-4.

As observed in laboratory experiments, the CO/CO_2 and $\text{CO}/\Delta\text{O}_2$ ratios in these fires were sensitive to the coalbed temperature and increased almost linearly with time from the onset of ignition to at least the time of sealing, or when oxygen reduction became a limiting factor. Prior to sealing, both ratios rose steeply and were generally below 0.1 except for the CO/CO_2 ratios of the SCMF-1 and 4 fires, which yielded values up to 0.15 and 0.17, respectively, at the time of sealing. After sealing, these ratios rose less steeply because of the increasing oxygen reduction. However, whereas the $\text{CO}/\Delta\text{O}_2$ ratios leveled off at a maximum value, the CO/CO_2 ratios continued to increase somewhat depending upon the size of the fire; this is most evident in comparing the data for SCMF-2 (fig. 18) with those for SCMF-3 (fig. 19) and SCMF-4 (fig. 20).

The maximum or equilibrium $\text{CO}/\Delta\text{O}_2$ values after sealing were between 0.15 and 0.20 as compared with corresponding CO/CO_2 values between 0.30 and 0.50. Since the CO/CO_2 ratio was noticeably more time dependent than the $\text{CO}/\Delta\text{O}_2$ ratio, it was a more sensitive criterion for determining the status of the coal mine fires. This observation is consistent with that suggested earlier (5). Nevertheless, since the currently available CO_2 field detectors are less sensitive than CO detectors, the latter are superior for early detection of the initiation or extinction of such fires. Field results from monitoring a spontaneous combustion condition at the Somerset Mine in Colorado (1) support this conclusion and the need to obtain the gas samples as close as possible to the fire source.

The JT ratios are least meaningful during the early stage of a coal fire; therefore, they are not extrapolated to the time of ignition in the accompanying figures. The JT values were approximately 0.7 to 0.8 at the time of sealing and decreased or remained relatively constant during the sealing period; the decrease was slightly more noticeable in the larger fires (figs. 19 and 20). The fact that the JT ratio was unusually high (0.74) at reopening of the SCMF-1 fire was not unexpected since reignition occurred in this unextinguished fire scenario. Although the JT ratios decreased after sealing in most of the fires, they still remained relatively high compared with those reported in the small-scale coal tunnel fires (2), where the ratios decreased to nearly zero after sealing. Obviously, the composition of the fire gases after sealing varied much more in the tunnel fires in which combustion conditions were supposedly more ideal before and after sealing. However, a near-zero JT ratio is unrealistic after sealing unless one assumes the CO and CO_2 combustion products disappear or are small relative to the H_2 formation (equation 13). Thus, the present data are more characteristic of what is expected in a real sealed mine fire situation.

Nevertheless, both sets of data indicate that the extinction of such fires occurs when the JT ratio falls below about 0.5.

Smoke Particulate Formation

Submicrometer smoke particulate sensors were demonstrated to be one of the most reliable means of monitoring a sealed coal mine fire. Such sensors do not necessarily provide the earliest detection of CO emission by a coal mass, but they are sufficiently sensitive to detect smoldering combustion and are superior to gas-monitoring methods for determining the status of a coal mine fire after it has been sealed.

Figure 21 compares the variation of smoke particulates and CO with time that was observed in the SCMF-4 fire at the S7 station, 125 feet from the center of the coalbed and 1/2 foot from the roof. The

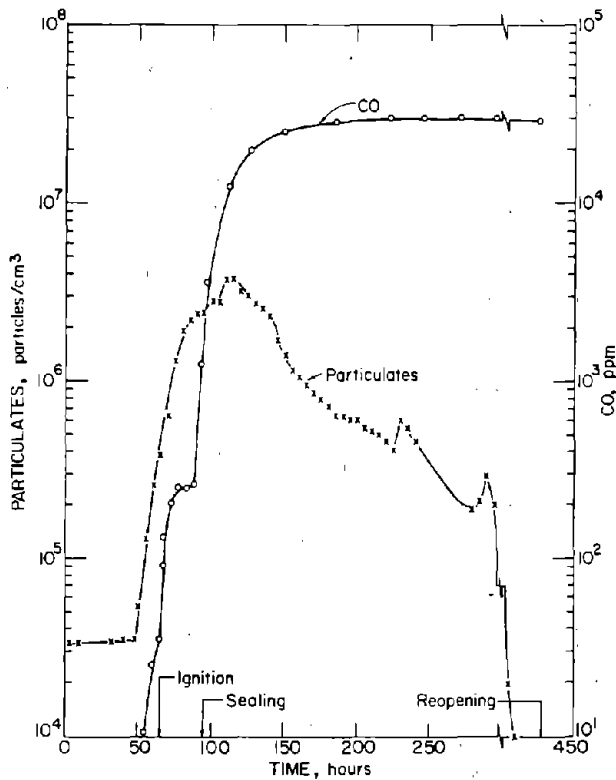


FIGURE 21. - Variation of CO and smoke particulate concentrations with time in fire SCMF-4 at a station (S7) 125 feet from the center of coalbed.

CO data prior to sealing were obtained by an Ecolyzer monitor and those after sealing by GC analysis of grab samples. Three significant trends are reflected by the curves in this figure. First, it is apparent that both CO and smoke particulate formation were barely detectable during the initial 50 hours of heating; second, they increased exponentially during the combustion prior to sealing. Essentially, both combustion product sensors used here were equally sensitive in detecting smoldering and flaming combustion. Third, peak CO and smoke particulate concentrations occurred shortly after the fire was sealed; subsequently, the smoke particulates decreased whereas the CO remained relatively constant for the duration of the sealing period. Thus, a submicrometer smoke particulate sensor should be more reliable than a CO sensor for detecting extinction of a sealed coal mine fire. Data obtained at other monitoring stations gave similar trends, although CO emission was generally detectable before the onset of smoke emission.

The smoke generation can be related to the temperature of the reacting coal, but such correlations for sealed mine fires are complicated by the changing combustion conditions and their effect on the rate and nature of the particulate formation. In the SCMF-4 fire (fig. 21), the particulate concentration was not sensitive to temperature during most of the preheat period before ignition; the maximum temperature attained at any location in the coalbed after initial 50 hours of heating was less than 150° C. Subsequently, the rate of particulate formation became sensitive to temperature as the temperature increased to produce flaming combustion, but the rate decreased after sealing since the temperature decreased. The semilog plot in figure 22 shows that the smoke particulate formation after sealing correlates roughly with the varying temperature of the coalbed. The decreased particulate concentration after sealing is not only a result of decreasing temperature but also reflects the effect of any agglomeration of the submicrometer particulates;

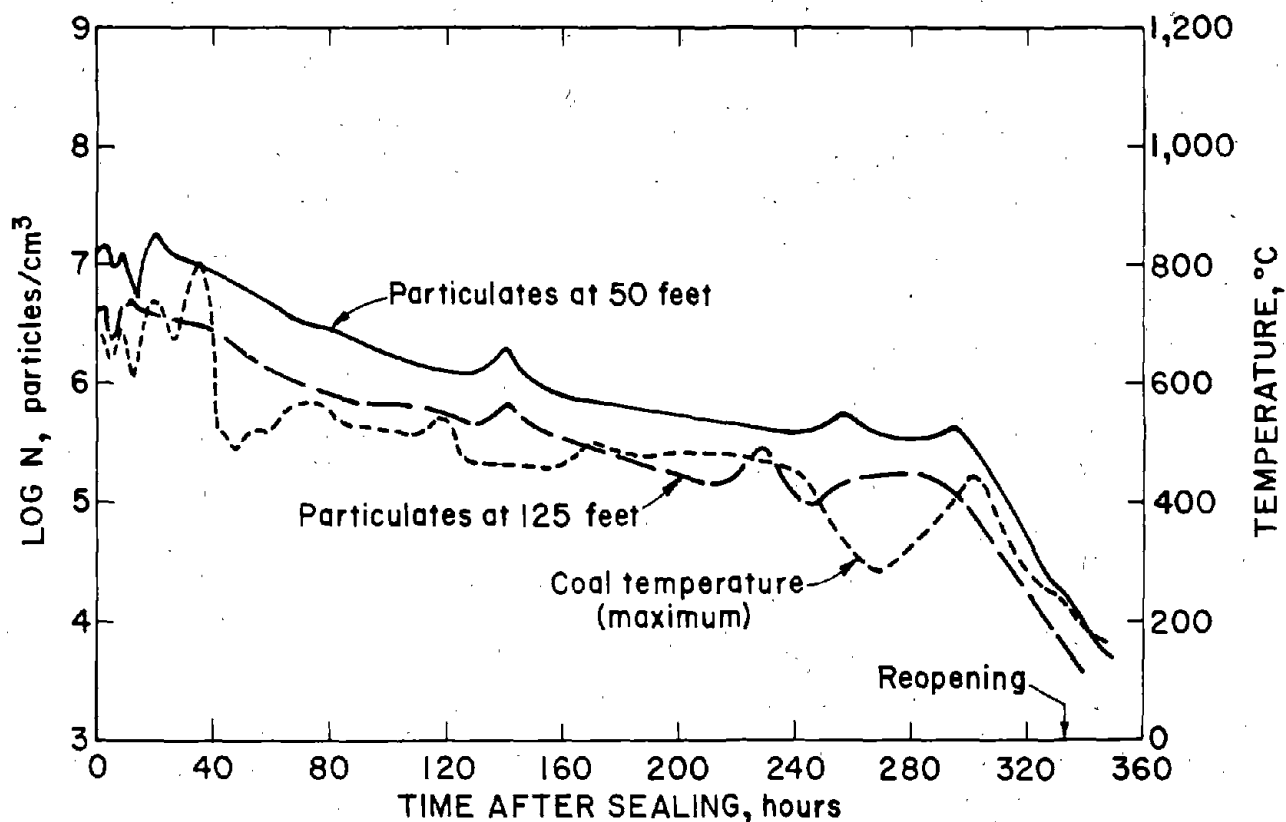


FIGURE 22. - Semilog plot of smoke particulate concentrations and maximum coalbed temperature versus time in fire SCMF-4.

furthermore, the size and/or number of smoke particles can vary when the chemical kinetics changes to produce smoke by char formation or other incomplete

combustion reaction. The effects of these uncertainties are more fully discussed by Litton, Hertzberg, and Furno (9).

CONCLUSIONS

The simulated coal gob fires show that such fires have relatively low propagation rates and that the criteria for their initiation, propagation, or extinction can vary with the ventilating and sealing conditions. Temperature data in the present fires indicate that the thermal wave velocities are nominally less than 1 in/hr into the coalbed and about fourfold greater across the longitudinal surface of the bed. The main fire gases are CO, CO₂, CH₄, and H₂, and their formation is a function of the size and temperature of the coalbed, as well as the oxygen concentration or ventilating condition in the mine. Under a sealed condition, the O₂ consumption rate tends to

follow an exponential decay until the coal temperature becomes drastically reduced, but the corresponding rate of CO formation does not display the same dependency on time or temperature.

Generally, the CO/CO₂ ratio is a more sensitive indicator than the CO/ΔO₂ ratio for determining the state of a coal mine fire, since the former is more sensitive to temperature. However, the CO/ΔO₂ ratio is more widely used for early detection of a coal fire in the incipient stage, largely because the sensitivity of available CO field sensors is greater than that of the CO₂ sensors. Neither ratio provides much useful

information after a mine fire has been sealed since the ratios vary little after most of the available oxygen in the sealed system has been consumed. In comparison, the Jones-Trickett ratio is a less meaningful value, although a value less than about 0.5 may be indicative of fire extinction.

A submicrometer smoke particulate sensor appears to be suitable for detecting a coal fire when the coal has been heated to at least about 150° C. This type of sensor is superior to any thermal or gaseous combustion product sensor in detecting extinction of a sealed mine fire at some remote distance from the fire zone. Its advantage is that the smoke particulate concentration in a sealed fire environment decreases with decreasing temperature, whereas the gaseous combustion product concentration remains relatively constant throughout the sealing period. The response time of such detection systems depends upon their spatial location and proximity to the fire zone, the intensity and amount of

combustion, and the convection produced by the fire, air leakage, or ventilating flow.

Future research should be conducted to extend these mine fire data to conditions of greater oxygen depletion, before and after sealing, which would result in greater detectable changes in the mine gas compositions at various stations in the mine. These data would provide a better opportunity to calculate mass balances from gas-sampling data (ventilation condition) and to predict the variation of combustion product gas ratios and smoke particulate concentrations with oxygen depletion (ventilated and sealed conditions). The oxygen depletion effect should relate to the coal mass effect, which appeared to be noticeable in this work on the combustion product gas ratios after sealing. In addition, research is needed to exploit the cited advantage of CO₂ analyzers for predicting smoldering combustion and to investigate the practical merits of nitrogen-inerting systems in sealed coal mine fires.

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