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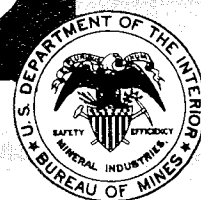
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Large-Scale Studies of Spontaneous Combustion of Coal

By Alex C. Smith, Yael Miron, and Charles P. Lazzara

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES



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UNITED STATES DEPARTMENT OF THE INTERIOR
Manuel Lujan, Jr., Secretary

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Btu/lb	British thermal unit per pound	m ³	cubic meter
°C	degree Celsius	min	minute
°C/d	degree Celsius per day	mm	millimeter
°C/h	degree Celsius per hour	μm	micrometer
cm	centimeter	pct	percent
ft ³ /min	cubic foot per minute	ppm	part per million
g	gram	st	short ton
g/cm ³	gram per cubic centimeter	V	volt
h	hour	vol pct	volume percent
kg	kilogram	vol pct/vol pct	volume percent per volume percent
L	liter	W	watt
L/min	liter per minute	wt pct	weight percent
m	meter	Ω	ohm

LARGE-SCALE STUDIES OF SPONTANEOUS COMBUSTION OF COAL

By Alex C. Smith,¹ Yael Miron,² and Charles P. Lazzara³

ABSTRACT

The U.S. Bureau of Mines constructed a large-scale facility to study the self-heating of a large coal mass under conditions that simulate a gob area of a mine. The insulated coal chamber can hold up to 13 short tons (st) of coal and is provided with a forced ventilation system and computer-controlled temperature and gas measurement systems to monitor the heat and mass transfer phenomena that occur in the coalbed.

Three experiments were completed with high-volatile C bituminous coals that exhibited high spontaneous combustion potentials in laboratory-scale tests. In the first two tests, a sustained heating was not achieved. In the third test, temperatures throughout the coalbed increased steadily from the start, with thermal runaway occurring near the center of the coalbed after 23 days. The thermal reaction zone then moved toward the front of the coalbed.

The results of these tests showed that the self-heating of a large coal mass depends not just on the reactivity of the coal, but also on the particle size of the coal, the freshness of the coal surfaces, the heat-of-wetting effect, and the availability of O₂ at optimum ventilation rates.

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INTRODUCTION

Approximately 20 pct of underground coal mine fires in the United States are caused by spontaneous combustion (1).⁴ This number is expected to increase with greater consumption and utilization of lower rank coals, deeper mines, and the growth of longwall mining practices. A spontaneous combustion fire presents a serious hazard to mine personnel and is often difficult to extinguish by direct fire-fighting methods. Sections of the mine, or the entire mine, must then be sealed, resulting in severe economic losses to the owners, miners, and surrounding community.

The spontaneous combustion of coal is due to the oxidation of coal surfaces, a heat-producing reaction. The rate at which heat is generated depends on variables such as the type of coal, particle size, O₂ concentration of the air, moisture content of the coal and surrounding atmosphere, and ambient temperature. The U.S. Bureau of Mines has evaluated several of these variables in the laboratory, and an empirical expression has been derived that predicts the self-heating potential of a bituminous coal based on the coal's dry ash-free oxygen content (2).

Although laboratory results are valuable, their extrapolation to the mining environment has not been completely successful because of complicated scaling effects that cannot be reproduced in small-scale experiments. In actual self-heating events in coal mines, much larger coal masses are involved. Mathematical models suggest that the critical mass of coal in which spontaneous combustion may develop varies from 1 to 5 st, depending on the coal (3).

Hundreds of publications on the spontaneous combustion of coal are available, but few pertain to large-scale tests. Early Bureau investigations were conducted on aboveground stockpiles and open-pit storage bins of low rank coal to determine satisfactory storage conditions for the prevention of spontaneous combustion (4-6). The data showed that self-heating resulted from air circulation within the coal mass and that even the most reactive coals could be stored safely by avoiding particle segregation effects, which increase pile permeability to air, and by thorough compaction to reduce or eliminate air circulation.

Other researchers conducted tests on three 2,500-st storage piles of Australian steam coal of different degrees of compaction, exposed to a forced ventilation flow, to evaluate the role of bed porosity on the spontaneous combustion process (7). Maximum temperature rise was found to depend on the bed porosity, which determines the degree of ventilation through the bed, with the highest temperatures occurring in the least compacted bed.

Other large-scale tests include bunker tests on 1- and 10-st quantities of coal (8-9). In the 1-st tests, the minimum self-heating temperatures (SHT), the minimum initial temperatures that produced thermal runaway, of three pulverized bituminous coals (80 pct less than 80 μ m) of different rank were determined. The temperatures ranged from 67° to 83° C. Another coal, a lignite, did not self-heat at temperatures up to 90° C, and its minimum SHT was not determined. The failure of the lignite to self-heat to thermal runaway was attributed to the greater quantities of CO₂ and H₂O evolved during oxidation at the active sites, thereby preventing the access of O₂ to these sites. The results were used, along with kinetic data obtained in a laboratory-scale adiabatic heating experiment, to validate a two-dimensional mathematical model that predicts the variables that lead to spontaneous combustion (8).

In the 10-st tests, run-of-mine coal was exposed to an airflow at ambient temperature, and the temperature of the coal was monitored. Several coals were evaluated, and the results were used to classify coals ranging from safe to unsafe. The safe coals exhibited temperature increases less than 5° C over a 3- to 6-week period. The unsafe coals showed temperature increases of 30° to 40° C over much shorter time periods. All tests were stopped at 70° C. The results were used to develop a mathematical approximation of a coal's self-heating potential under actual storage conditions, based on its temperature history and the experimental conditions of the test. The extrapolation of the mathematical approximation to actual coal piles requires temperature measurements to obtain the necessary values to predict the potential of the coal pile to go to thermal runaway (9).

Many factors that can affect the self-heating process in large coal piles have been examined using theoretical models. Recent models have examined the factors affecting the storage of lignite coals (10), the role of natural convection in O₂ transport in a pile (11), and the effect of temperature and O₂ concentration on self-heating in a pile (12).

The self-heating of coal in mines often occurs in a gob (worked-out) area and is not easily detected. Of 16 reported fires attributed to spontaneous combustion in the United States between 1978 and 1986, 14 occurred in gob areas (1). A survey of more than 100 reported cases of spontaneous combustion in French coal mines between 1960 and 1972 showed that 64 pct occurred in gob areas (13). The amount of coal that accumulates in these areas and the degree of ventilation can combine to give optimum conditions for spontaneous combustion.

The Bureau designed and constructed a large-scale test facility to better understand the self-heating of a large coal

⁴Italic numbers in parentheses refer to items in the list of references at the end of this report.

mass under conditions that might be encountered in a gob area of a mine. This report describes the design and physical structure of the facility, as well as its temperature and gas measurement systems, ventilation and heater systems, and data acquisition and analysis systems.

Three experiments were completed in the facility with high-volatile C bituminous coals that had exhibited high spontaneous combustion potentials in the Bureau's adiabatic heating oven. In the first two experiments, a sustained self-heating was not achieved. These

experiments were divided into two phases: (1) the self-heating phase, during which the effect of ventilation and moisture on temperature and gas evolution rates were examined, and (2) a stimulated heating phase, in which electrical heaters were used to stimulate a heating and the subsequent heat and mass transport processes that occurred in the coalbed were studied. In the third test, a thermal runaway did develop in the coalbed and the stimulated heating phases was not necessary.

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contributions to the design and construction of the large-scale facility.

LARGE-SCALE SPONTANEOUS COMBUSTION FACILITY

The large-scale spontaneous combustion facility was designed to simulate several conditions that might be found in a gob area of a mine. The facility consists of an insulated chamber, ventilation and heater systems, temperature and gas measurement systems, and a computerized data acquisition network. The control and measurement systems were designed to be flexible, allowing for variation of parameters and data acquisition, depending on the objectives and needs of each test.

COAL CHAMBER

The coalbed chamber was designed to provide an insulated, airtight enclosure, capable of holding approximately 13,000 kg of coal, and to allow for easy loading and unloading of the coal. Figure 1 is a cross section of the coalbed chamber, showing the radial location of the thermocouples and heaters. Figure 2 shows the dimensions of the coalbed and plenum areas, the longitudinal and radial locations of the thermocouples and gas sampling ports, and the inlet air and exit gas stack.

The coalbed chamber is 1.8 m high by 1.8 m wide by 4.5 m long and is preceded and followed by two 1.8-m-high by 1.8-m-wide by 1.2-m-long plenum areas. The sidewalls and floor of the structure are ceramic firebrick, 6 cm high by 11 cm wide by 23 cm long, providing good insulation. The front and rear walls and the roof of the structure are constructed of 0.16-cm-thick sheet steel, supported by angle iron attached to the walls of the structure. The interior surfaces of the front and rear plenum walls and the plenum roofs are covered with 10 cm of fiberglass blanket insulation.

A 1.8-m-high by 1.8-m-wide 0.6-cm-mesh wire screen, reinforced by a 10-cm-mesh wire screen, which is welded to angle iron, separated the coalbed from the rear plenum area. The coalbed and front plenum were separated by two 0.9-m-wide by 1.8-m-long 0.6-cm-mesh wire screens, reinforced by 10-cm-mesh wire screen, also welded to angle iron. The two front screens are hinged to open out, allowing access to the coalbed from the front of the enclosure, once the front sheet steel wall is removed, for

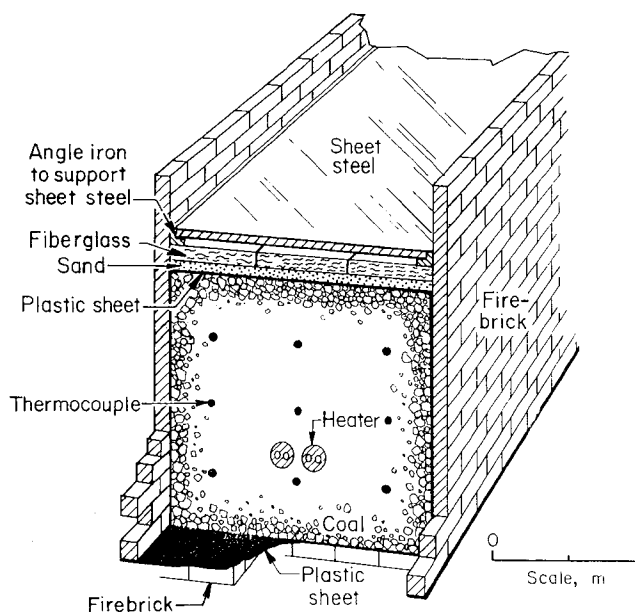


Figure 1.—Cross section of coalbed chamber.

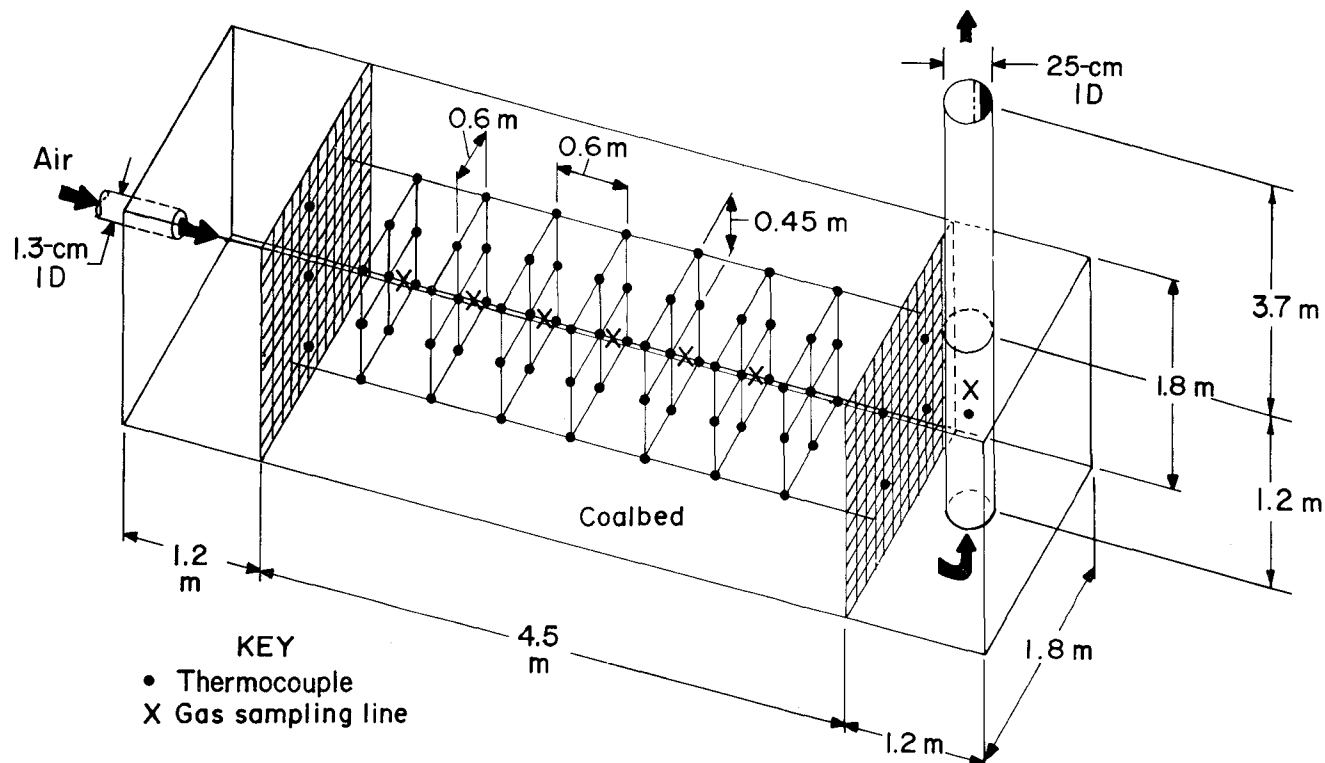


Figure 2.—Schematic of coalbed chamber and plenum areas.

easy unloading of the coal after a test is completed. For the third test, the coalbed was separated by two additional 0.6-cm-mesh wire screens, reinforced by 10-cm-mesh wire screen, located 1.7 and 2.8 m into the coalbed. These screens allowed for the placement of segregated sizes of coal into the bed, as described in the "Coals Used in Experiments" section.

Prior to the first test, the floor of the enclosure was lined with 0.6-mm-thick plastic sheet. The coal was then loaded into the chamber from the top and covered with another plastic sheet. For the second and third tests, the ceramic walls were also lined with plastic sheet, prior to coal loading, because of indications from the first test that air leakage occurred through the walls. The coal was loaded and covered with another plastic sheet, thereby creating a leak-free environment in the coalbed. In all three experiments, a 5-cm-thick layer of sand was placed on top of the plastic covering the coal, to eliminate voids between the coal and the roof of the enclosure, ensuring that the airflow would pass through the coal and not over it. Finally, a 10-cm-thick fiberglass insulation blanket was placed on top of the sand, and the steel sheet roof was installed.

VENTILATION

The ventilation air to the coalbed was provided by one air compressor in the first two tests and by two air compressors in the third test. The maximum airflow that could be supplied to the coalbed by this system in the first two tests was 150 L/min. With the addition of the second compressor, the capacity was raised to 200 L/min. Figure 3 is a schematic of the air supply system. The compressed air was regulated and filtered to remove particulates, oil, and water, and passed through a valve and flowmeter, which were used to control the flow rate. Air entered the coal chamber through a 1.3-cm-ID copper tube in the front plenum area, passed through the coalbed into the rear plenum area, and exited via a 25-cm-ID duct, which extended 1.2 m down into and 3.7 m out of the rear plenum. A 140-L drum, partially filled with water, which can be put on-line by two three-way valves, was located between the flowmeter and the front plenum to provide humidified air to the coalbed. When in line, the air was bubbled through the water. The humidity level of the inlet air was not monitored.

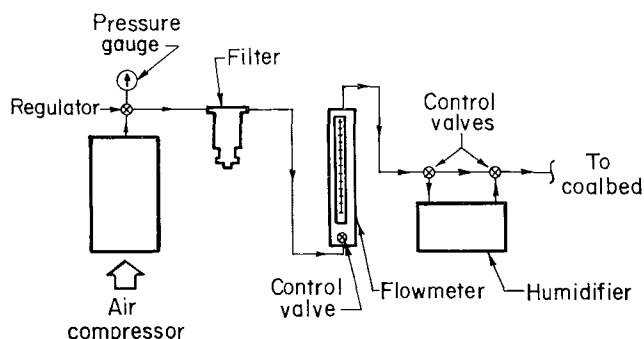


Figure 3.—Schematic of ventilation system.

TEMPERATURE MEASUREMENT

The temperature measurement system is a flexible, computer-linked network of 80 type K thermocouples located throughout the coalbed and plenum areas. The system enables the user to continuously obtain a three-dimensional view of heat development and movement through the coalbed. The coalbed was instrumented with 63 thermocouples. In addition, there were eight thermocouples located on two cylindrical heaters embedded in the coalbed that measured heater surface temperatures. Eight thermocouples were located in the plenum areas, three in the front plenum and five in the back plenum, to monitor the inlet and outlet gas temperature. Finally, one thermocouple outside the coal chamber monitored the ambient air temperature.

The three thermocouples in the front plenum were located 15 cm in front of the screen, 0.9 m from the walls, and 0.3, 0.9, and 1.5 m from the floor. In the rear plenum, four of the thermocouples were 15 cm into the plenum from the screen, in a square configuration, 0.6 m from the floor, walls, and roof; one thermocouple was placed in the center of the exit gas duct, 0.9 m from the floor.

For the first experiment, the thermocouples in the coalbed were positioned in 7 vertical arrays of 9 thermocouples, 0.3, 0.9, 1.5, 2.1, 2.7, 3.4, and 4.0 m from the front of the coalbed, and 3 horizontal arrays of 21 thermocouples, 0.45, 0.9, and 1.35 m above the coalbed floor. Across the width of the coalbed, the thermocouples were located 0.3, 0.9, and 1.5 m from one wall. For the second and third experiments, the thermocouples were again placed in 7 vertical arrays of 9 thermocouples, and

3 horizontal arrays of 21 thermocouples, at the same distances from the front of the coalbed and from the coalbed floor as in the first test. However, across the width of the coalbed, the thermocouples were located 0.45, 0.9, and 1.35 m from the wall.

The thermocouple positions can be varied for each test, with minor changes in the computer data acquisition display program, allowing for flexibility in temperature measurement, depending on the experimental conditions.

GAS ANALYSIS

The gas analysis system for the first experiment in the large-scale facility consisted of two separate subsystems. The first subsystem continuously monitored the exit gas stream for CH_4 , CO , CO_2 , and O_2 concentrations, via a 0.9-cm-ID stainless steel gas sampling tube (10 L/min) located 0.9 m up into the rear plenum exhaust duct. The second subsystem monitored six locations in the coalbed for O_2 and CO concentrations. Stainless steel 0.9-cm-ID gas sampling tubes were installed 0.6, 1.2, 1.8, 2.4, 3.1, and 3.7 m into the coalbed from the inlet air side along the longitudinal axis. The tubing was converted to plastic when it exited the enclosure. The gas lines were filtered and connected to a microprocessor-controlled solenoid valve system that sequentially sampled each tube (8 L/min) at specified intervals. The data were then logged to a computer via the computerized data acquisition system.

Several modifications to the gas analysis system were made for the second and third experiments. The gas sampling tubes in the coalbed were relocated to 0.3, 0.9, 1.5, 2.1, 2.7, and 3.4 m from the front of the coalbed, and an additional sampling tube was added 4.0 m from the front, so that their positions coincided with the locations of the thermocouples along the longitudinal axis of the coalbed. The two subsystems from the first test were combined, so that in addition to O_2 and CO , CH_4 and CO_2 concentrations could be obtained from the sampling locations in the coalbed, as well as from the exit gas stream. In addition, an H_2 analyzer was added to the gas analysis system. Again, the sampling system was controlled by a microprocessor-controlled solenoid valve system, which sequentially sampled (10 L/min) each of the seven locations in the coalbed and the exit gas stream at specified times and logged the data to a computer. A description of the gas analyzers is found in table 1.

Table 1.—Description of gas analyzers

Gas analyzer	Detector	Range, pct
Experiment 1:		
Exit gas analysis:		
CH ₄	Infrared	0 to 10, 0 to 50.
CO	.. do.	0 to 2, 0 to 20.
CO	.. do.	0 to 0.1, 0 to 0.5.
CO ₂	.. do.	0 to 5, 0 to 25.
O ₂	Paramagnetic	0 to 5, 0 to 10, 0 to 25.
Coalbed gas analysis:		
O ₂	Electrochemical	0 to 10, 0 to 25.
CO	Infrared	0 to 1, 0 to 5.
Experiments 2 and 3:		
CH ₄	.. do.	0 to 10, 0 to 50.
CO	.. do.	0 to 2, 0 to 20.
CO	.. do.	0 to 0.01, 0 to 0.05.
CO ₂	.. do.	0 to 5, 0 to 25.
O ₂	Paramagnetic	0 to 5, 0 to 10, 0 to 25.
H ₂	Thermal conductivity	0 to 10, 0 to 20.

HEATERS

The electrical heaters provide the capability of initiating a heating in the coalbed if the coal does not self-heat, or if the purpose of the test requires a rapid heating, such as in the evaluation of extinguishment methods. The heater system is comprised of two resistance-type heaters (22.6 Ω), each 1.2 cm diam by 1.1 m long, bent into a U-shaped configuration and each inserted into separate 17-cm-OD steel cylinders constructed from steel pipe. Both ends of the cylinders are capped, with the electrical wiring entering through one end. The maximum power that each heater can provide is 2,700 W, controlled by a 220-V variable transformer. Each heater is instrumented with four thermocouples, three on the top outside surface, spaced 0.3 m apart, and one on the bottom outside surface at the center of the cylinder.

In the first test, the heaters were placed side-by-side, 0.6 to 0.8 m from the bottom, 0.7 m from the walls, and 1.1 to 2.2 m from the inlet air side of the coalbed. For the second and third tests, the heaters were moved further into the coalbed, 1.8 to 2.9 m from the inlet air side of the coalbed.

DATA ACQUISITION

The data acquisition system (fig. 4) is capable of recording up to 96 channels of data. Analog signals from the thermocouples and gas analyzers are received by a 96-channel microprocessor, digitized, and transmitted to a minicomputer. Upon completion of the experiment, the data are transferred to a larger minicomputer for analysis.

Programs on the smaller minicomputer communicated with the microprocessor to control the rate of data acquisition, as well as the duration and sequence of gas sampling in the coalbed. Other programs controlled the display of the data on video terminals.

The data acquisition program is an interactive program that starts the data acquisition system and prompts for data sampling and logging intervals. It also prompts for the duration of sampling and time intervals between gas samples from the coalbed and exit gas stream and controls the solenoid valve sampling system. Subroutines in this program allow the user to change time intervals, terminate any of these tasks, or to stop the data acquisition system. The system has the capability of logging data as often as every second. However, typical logging intervals during these experiments ranged from 30 min to 4 h during periods of heating, because of the slow nature of the self-heating process, to 24 h during cooling phases.

Another program controls the display of the data on video display terminals. The data can be viewed on any terminal that is tied into the on-site computer network, or on a remote personal computer via a modem hookup. Because of the large quantity of data generated by these experiments, the program has several options available that allow the user to view selected portions of the data. The user can specify from 1 to 48 channels, see all 96 channels of data at once, view only thermocouple or gas data, or see specific vertical or horizontal arrays of thermocouples. The data are updated on the video terminal at time intervals specified by the user.

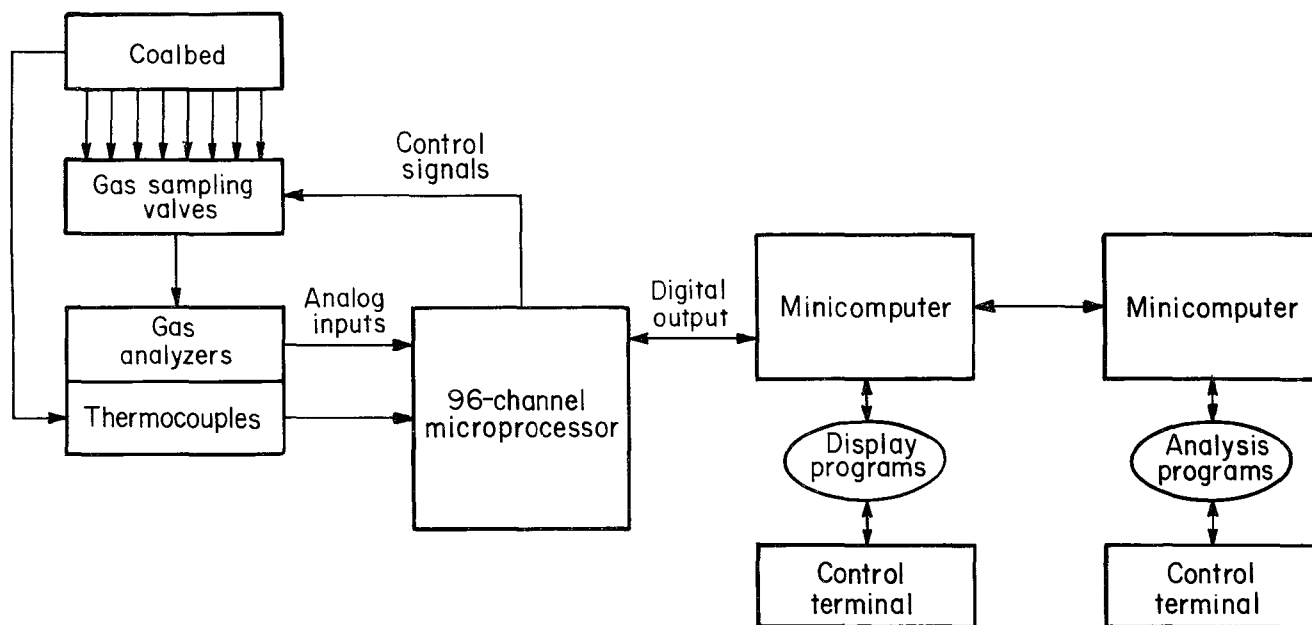


Figure 4.—Schematic of data acquisition system.

COALS USED IN EXPERIMENTS

The coals used in the three experiments were from the Colorado D seam, the Colorado F seam, and the Wyoming No. 80 seam, respectively. All three coals were high-volatile C bituminous coals. The three coals were freshly mined, loaded directly at the mine into a truck, covered, and transported to the experimental facility. Transport time was approximately 2 days. The D seam coal was 15 cm by 0, with a bulk density of 0.88 g/cm³. The F seam coal was 20 cm by 0, with a bulk density of 0.82 g/cm³.

The No. 80 seam coal was 15 cm by 0 as received. Prior to loading into the test chamber, the coal was screened and the plus 5-cm lumps were crushed to 2 cm by 0. The minus 5-cm coal was also used. A size analysis showed that 77 pct of the composite sample was less than 2.5 cm diam, with a bulk density of 0.87 g/cm³. Also in this experiment, approximately 1,100 kg of minus 2-cm coal was dried in a steam-jacketed rotary dryer under a flow of N₂, prior to loading into the test chamber.

Moisture analysis of this coal showed an average moisture content of 3.1 pct, compared with 9 pct as received, a 66-pct drying efficiency.

Table 2 shows the as-received proximate and ultimate analyses, heating values, and dry ash-free oxygen contents of representative samples of the three coals. The moisture content of the No. 80 seam coal differs from that mentioned above, because table 2 shows the analysis of the coal received by truck, just prior to the start of the third experiment. Also shown in the table are the coals' minimum SHT's as determined in the Bureau's adiabatic heating oven. The minimum SHT is the minimum initial temperature that produces a sustained exothermic reaction, or thermal runaway, under a set of standard conditions, and has been used to rank a coal's relative self-heating tendency (2). Coals with minimum SHT's less than 70° C are considered to have high spontaneous combustion potentials. Based on these results, all three coals have a high self-heating tendency.

Table 2.—Analyses of as-received coals

	Colorado D seam	Colorado F seam	Wyoming No. 80 seam
Proximate analysis, wt pct:			
Ash	11.0	8.7	4.8
Fixed carbon	42.2	42.1	46.8
Moisture	10.8	10.3	7.3
Volatile matter	36.0	38.9	41.1
Ultimate analysis, wt pct:			
Carbon	60.4	61.8	67.4
Hydrogen	5.4	5.7	5.6
Nitrogen	1.2	1.3	1.5
Sulfur	0.5	0.3	0.5
Oxygen	21.5	22.2	20.1
Dry ash-free oxygen	15.2	16.0	15.6
Heating value	Btu/lb ..	11,350	10,861
Minimum SHT	°C ..	45	35
SHT Self-heating temperature.			

RESULTS

EXPERIMENT 1

The first experiment, with Colorado D seam coal, ran for a total of 147 days from the time that the airflow was started. The experiment was divided into two phases: (1) a self-heating phase, from 0 to 93 days, and (2) a stimulated heating phase, from 93 days until the end of the test, at 147 days.

Coal Loading and Sealing

For the first experiment, the coal was unloaded onto the ground and covered with plastic overnight. Approximately 13 st of the coal was then loaded into the test chamber; the thermocouples, gas lines, and heaters were placed in the coalbed; and the coalbed was sealed. The loading and sealing procedure took approximately 7 h. The coalbed remained sealed for 3.8 days prior to the start of the airflow. During this period, CO and O₂ concentrations across the bed, and the CH₄, CO₂, CO, and O₂ concentrations in the rear plenum were monitored. The O₂ concentration fell to about 10 pct near the center of the coalbed and to 16 pct in the rear plenum, while the CO concentration rose to about 600 ppm across the coalbed and 50 ppm in the rear plenum. The CH₄ and CO₂ concentrations in the rear plenum reached 3.6 and 0.5 pct, respectively. The O₂ depletion and presence of CO and CO₂ in the coalbed and rear plenum, along with slightly elevated temperatures relative to the ambient temperature when the airflow was introduced, indicated that coal oxidation occurred during this period.

Self-Heating Phase

The self-heating phase of the experiment with D seam coal started with the introduction of the airflow and lasted 93 days. Figure 5 shows the temperature histories of the thermocouples located along the center axis of the coalbed, 1.35 m (A), 0.9 m (B), and 0.45 m (C), from the floor, as well as the ambient air temperature, from 0 to 90 days. Temperatures at the other thermocouple locations closely resembled these traces. Temperature data from the data acquisition system were not available from day 25 to day 28, and from day 41 to day 50, but several manual temperature measurements were made and the curves interpolated for these timespans. Figure 6 shows the O₂ concentration at six locations along the central axis of the coalbed and in the rear plenum. O₂ data were not available from day 25 to day 28 and from day 41 to day 50.

At the start of the airflow, most of the temperatures in the coalbed were between 27° and 30° C. The thermocouples located 2.1 m from the inlet air side of the coalbed, 0.9 and 1.45 m from the floor, and 2.7 m from the inlet air side, 0.45 m from the floor, were above 30° C. Over the first 9 days, temperatures across the coalbed rose 2° to 5° C, with the exception of the thermocouples 0.3 m into the coalbed. This area of the coalbed was probably influenced by the inlet air temperature, which was dependent on the ambient air temperature, by heat losses to the plenum area, and by moisture loss, an endothermic reaction. The O₂ in the coalbed was replenished quickly from the depleted levels observed prior to the start of the airflow and continued to rise over the first 9 days of the

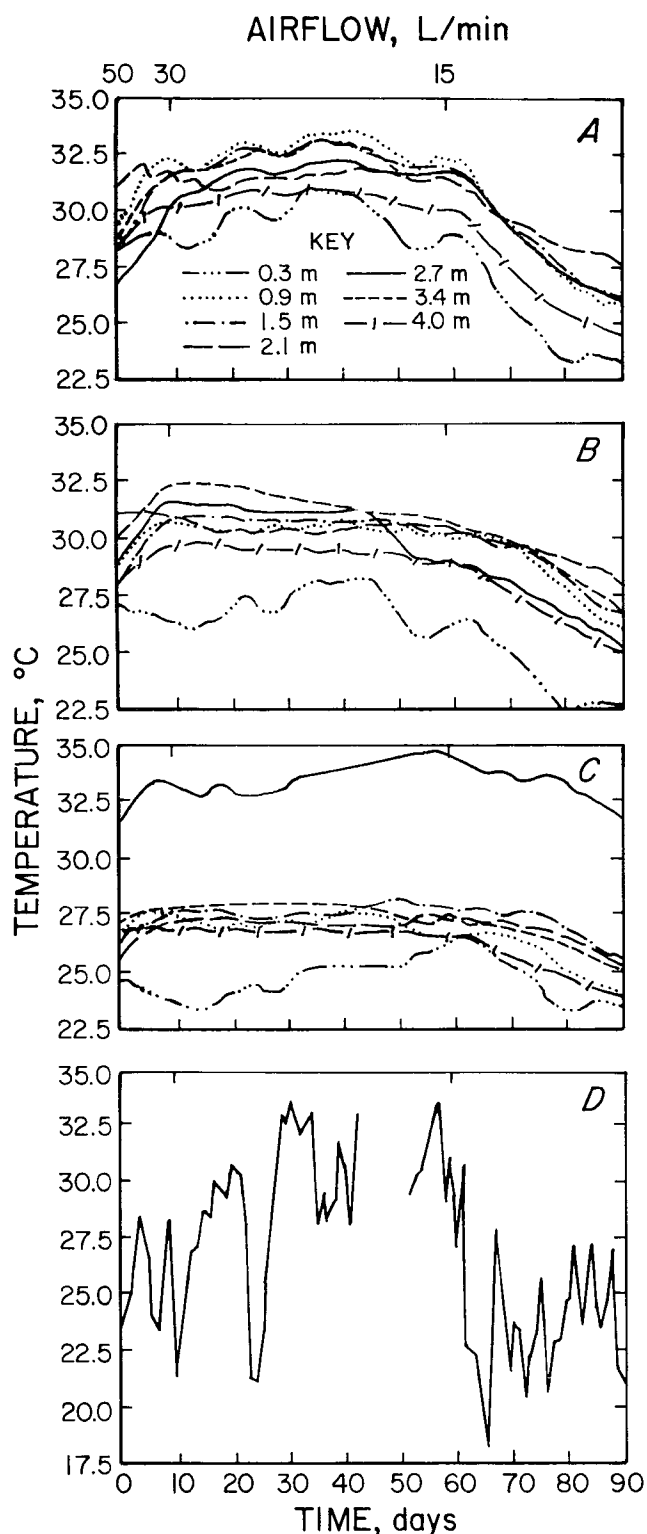


Figure 5.—Temperatures of thermocouples located 1.35 m (A), 0.9 m (B), and 0.45 m (C) above coalbed floor and ambient air temperature (D) during self-heating phase of experiment 1.

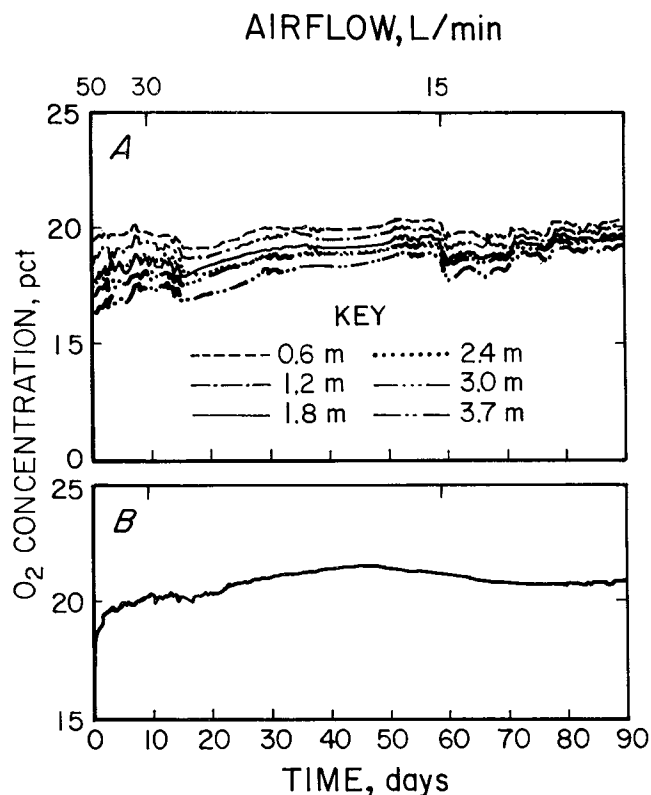


Figure 6.—O₂ concentration profiles in coalbed (A) and rear plenum (B) during self-heating phase of experiment 1.

test. The O₂ concentration decreased across the bed, indicating O₂ adsorption by the coal, from about 20 pct, 0.6 m into the coalbed, to 16 pct, 3.7 m into the coalbed. CO concentrations were approximately 200 ppm across the coalbed.

At 9 days, the airflow was reduced to 30 L/min, since the O₂ was slowly increasing throughout the coalbed and there appeared to be adequate O₂ to support self-heating. The O₂ concentrations fell off slightly from day 9 to day 18, indicating that the coal was still oxidizing, then climbed again to the levels seen prior to the airflow change. CO levels over this period remained between 50 and 100 ppm.

Temperatures across the coalbed leveled off, and over the next 50 days, either remained stable or slowly fell, with the exception of the thermocouple located 2.7 m from the front of the coalbed, 0.45 m from the floor, which continued to increase during this time. Thermocouples near the top of the coalbed showed the highest maximum temperatures, ranging from 30° to 33° C, with typical temperature increases from the start of the experiment of

4° to 6° C. Temperature fluctuations at this level were more pronounced, probably because of influences from the outside air temperature. Indeed, the trend of the peaks in the temperature traces closely resembles the ambient temperature trace.

Temperatures in the middle of the coalbed, 0.9 m from the floor, ranged from 28° to 32° C, with the exception of the thermocouple 0.3 m into the coalbed, which remained near 27° C, with average temperature increases from the start of the experiment of about 3° C. Little temperature change was observed at the lower thermocouple level, where temperatures increased just 1° to 3° C. Maximum temperatures in this region ranged from 26° to 35° C, with all but one thermocouple showing temperatures less than 28° C. This raises some doubt as to the validity of the 35° C reading, however, since the entire temperature trace was considerably higher than the other temperatures observed along that longitudinal plane of the coalbed. Also, the thermocouple located directly above the 35° C reading showed a maximum temperature of just 31.5° C. However, self-heating can develop in a small, localized area, and a hot spot may have been present.

The airflow was reduced to 15 L/min at day 58, since temperatures in the coalbed were falling and O₂ levels were increasing. As occurred after 9 days, the O₂ levels fell off slightly, then rose back up to their previous levels over the next 30 days. The rate of temperature drop increased significantly, but this may have been because of the coincidental drop in ambient temperature. This is supported by the higher rates of temperature drop near the top of the coalbed.

The O₂ concentration in the plenum area followed the same trends as in the coalbed, but concentrations were higher than were observed at the sampling locations in the coalbed. This means that either there were gas channeling effects through or over the coalbed and/or that significant diffusion down the exit stack occurred. The temperature and gas data at the locations in the coalbed closest to the rear plenum, however, indicate that the higher O₂ concentration in the plenum had no significant effect on the self-heating process in the coalbed.

Stimulated Heating Phase

At 93 days, the two heaters buried in the coalbed, 0.6 to 0.8 m from the floor and 1.1 to 2.2 m from the inlet end of the coalbed, were turned on to stimulate a heating event. The initial objective was to raise the heater temperatures to 100° C. Figure 7 shows the temperature-time traces of the thermocouples located in the center of the coalbed, 1.35 m (A), 0.9 m (B), and 0.45 m (C) from the floor, and a heater surface thermocouple (D), from

93 days until the end of the experiment. The power input values in figure 7 represent the total power supplied to both heaters. Figure 8 shows the O₂ concentrations at points 0.9 m from the floor, 0.6, 1.2, 1.8, 2.4, 3.0, and 3.7 m from the front of the coalbed. The gas concentrations in the rear plenum are shown in figure 9. No temperature data were recorded from day 115 to day 127, but manual temperature measurements were made and the curves were interpolated from these. Also shown in figures 7 through 9 are the airflows during this phase of the test.

The power to the heaters was adjusted several times from day 93 to day 97 to achieve the desired heater surface temperature of 100° C. The thermocouple 15 cm above the heaters, 0.9 m from the floor and 1.5 m into the coalbed, exhibited the highest temperature rise, to 86° C, before leveling off, while the two located 15 cm below the heaters, 0.3 m from the floor and 1.5 and 2.1 m into the coalbed, reached 69° C. Temperatures just 1.2 m downstream of the heaters remained near 30° C, giving no indication that heating was occurring in the coalbed.

O₂ and CO measurements across the coalbed indicated that some localized oxidation occurred in the region near the heaters from day 93 to day 129. O₂ concentrations fell to 19, 16, and 18 pct, 1.2, 1.8, and 2.4 m into the coalbed, respectively, while CO measurements made at these points ranged from 1,000 to 1,500 ppm. The O₂ concentration in the plenum also fell, but the concentration remained near 20 pct. Small amounts of CO and CO₂ were detected in the rear plenum at day 99, when the heater temperature increased above 100° C, but disappeared when the power to the heaters was reduced to 50 W. At day 110, some CO was observed again, as the heater temperature rose slightly.

By day 129, it was apparent that the coalbed was not heating. O₂ and CO concentrations in the bed had stabilized, and temperatures were not increasing. The power to the heaters was then increased to 100 W. An immediate temperature rise was observed above and below the heaters, and the O₂ concentration near the heaters fell rapidly. The power was reduced to 80 W on day 131 and to 50 W on day 133, but the temperature of the coal near the heaters continued to rise, indicating thermal runaway in the coalbed.

The power to the heaters was turned off on day 134, at which time the heater surface temperature was 165° C, the temperature directly above the heaters, 140° C, and the temperature below the heaters, 113° C. The temperature of the coal 15 cm above the heaters and 1.5 m from the front of the coalbed leveled off at 147° C over the next 3 to 4 days and then fell. Temperatures in the coal below the heaters continued to rise, peaking at 225° C at

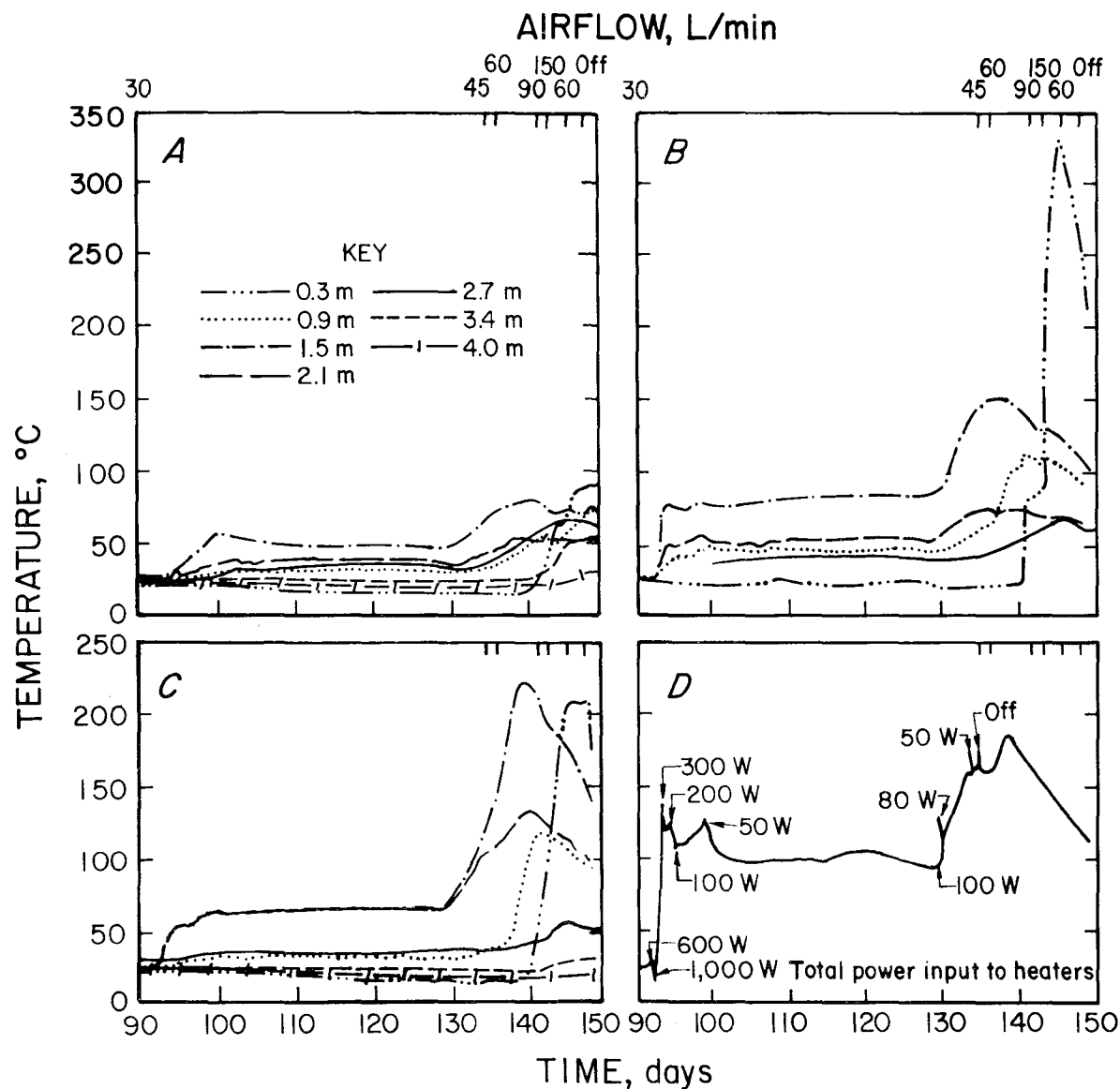


Figure 7.—Temperatures of thermocouples located 1.35 m (A), 0.9 m (B), and 0.45 m (C) above coalbed floor and on heater surface (D) during stimulated heating phase of experiment 1.

140 days. The airflow was increased to 45 L/min at day 135 and to 60 L/min at day 136 because of the decrease in the O_2 concentration observed in the plenum, but the additional O_2 was quickly used up. The thermal reaction then moved toward the front of the coalbed, and the O_2 concentration across the entire coalbed fell rapidly. The airflow was increased to 90 L/min at 141 days, but the O_2 concentrations did not change significantly, except for a short time at the sampling location 0.3 m into the coalbed.

The temperature reached 121° C at the thermocouple 0.45 m from the floor and 0.9 m from the front of the coalbed at 142 days. The airflow was increased to 150 L/min, the limit of the supply system, at 143 days, in an attempt to move the reaction deeper into the coalbed, but the airflow change had little effect on the O_2 concentration in the coalbed. By day 145, the maximum temperature peaked at 340° C, at the thermocouple 0.3 m from the wall, 0.9 m from the floor, and 0.3 m from the

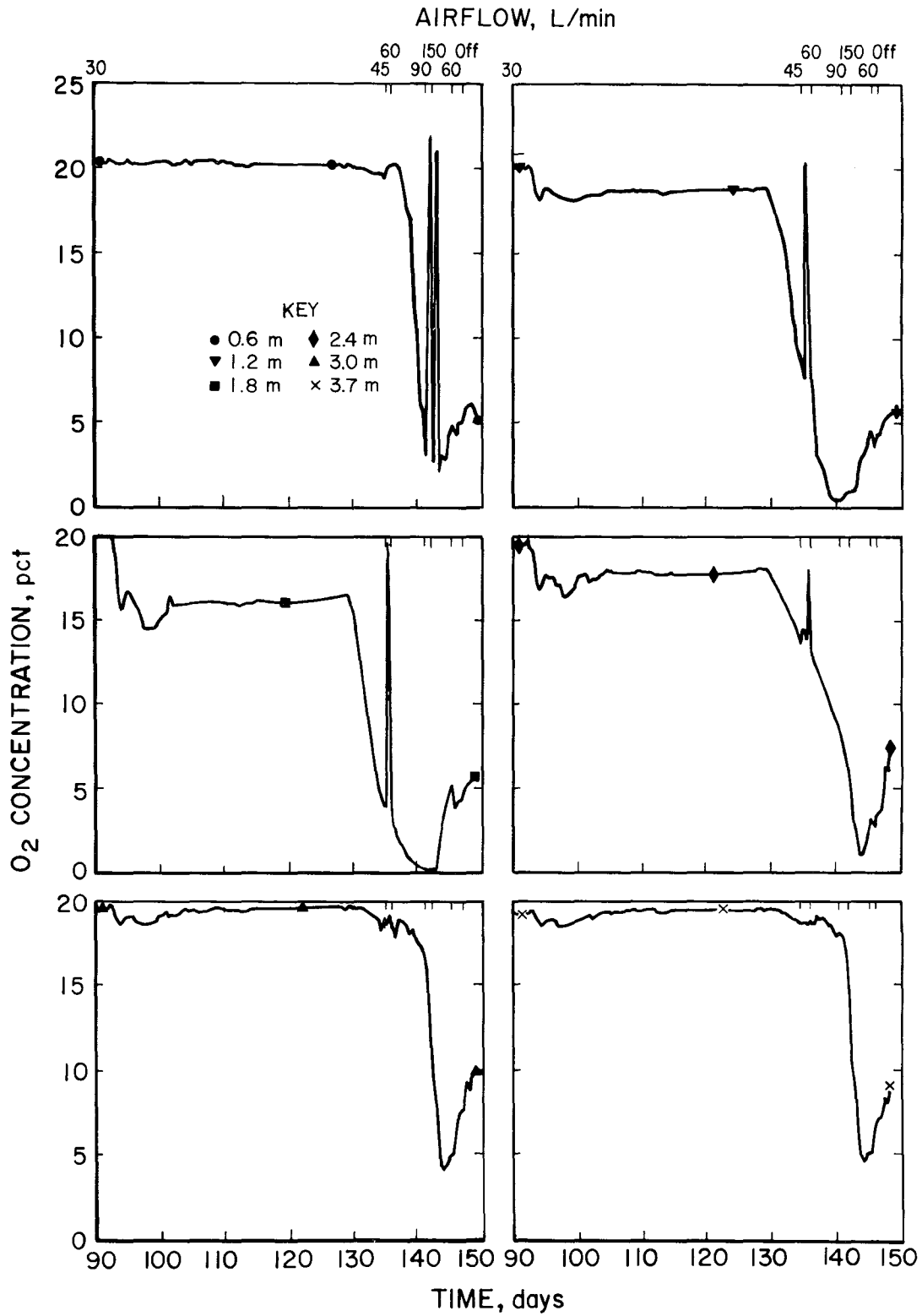


Figure 8.—O₂ concentration profiles in coalbed during stimulated heating phase of experiment 1.

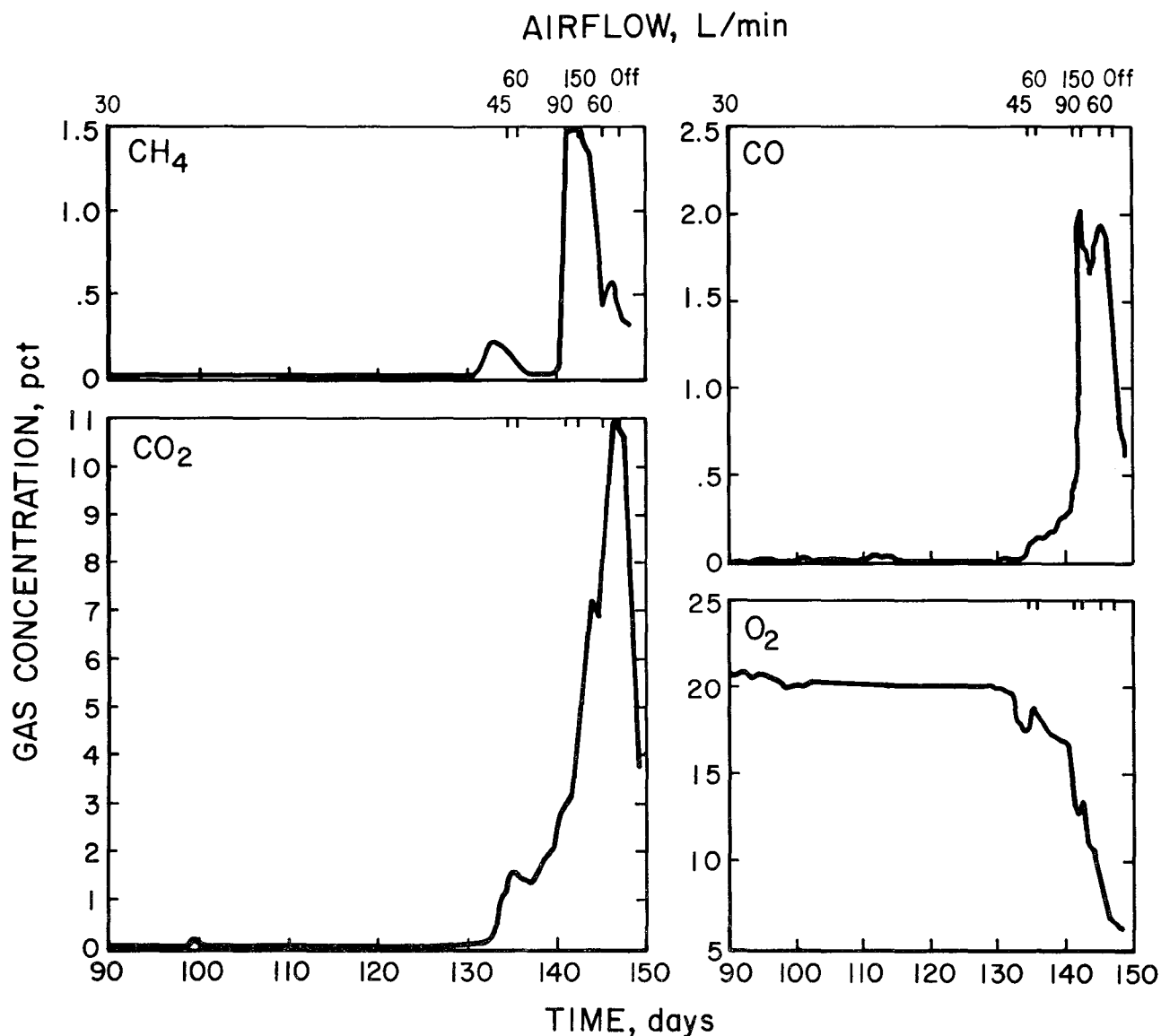


Figure 9.—Gas concentrations in rear plenum during stimulated heating phase of experiment 1.

front of the coalbed, and smoke was observed in the exit gas stream. The airflow was reduced to 60 L/min, since coal temperatures nearby the hot spot were increasing at rate of 4° C/h and the reaction was occurring only near the front of the coalbed. At day 147, temperatures 0.3 m into the coalbed near the wall were near 300° C and the airflow was stopped. Temperature increases downstream of the heating lagged behind, with the thermocouple 4.0 m from the front of the coalbed increasing just 3° to 5° C.

Gas concentrations in the rear plenum reached high levels as the heating developed. The CH₄ concentration reached 1.5 pct at 143 days and the CO₂ concentration reached 11 pct at 146 days, while the maximum CO concentration was 2 pct at 143 days. The O₂ concentration fell from day 129, with small peaks due to increases in the airflow.

The coal was unloaded several months after the test was completed. A large ashed section was found near the front of the coalbed (fig. 10), indicating high temperatures.

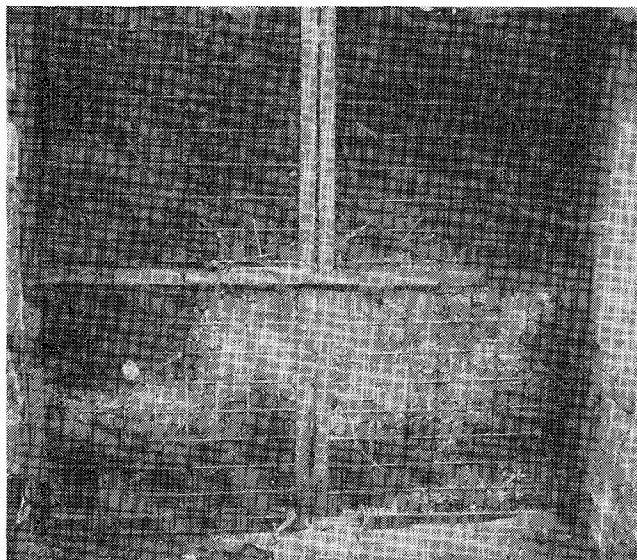


Figure 10.—Front of coalbed showing ashed section prior to unloading coal from coal chamber following experiment 1.

EXPERIMENT 2

The second experiment, with Colorado F seam coal, ran 167.7 days from the time the coal was loaded into the enclosure and the coalbed was sealed. This experiment was also divided into two phases, a self-heating phase, from day 0.9 until day 84.8, and a stimulated heating phase, from day 84.8 to day 167.7. Temperatures were also monitored for an additional 27 days as the coalbed cooled, and these data are included in the description of the stimulated heating phase of the test.

Coal Loading and Sealing

The F seam coal was unloaded from the truck onto the ground, and approximately 13 st was loaded into the test chamber. For this experiment, the heaters were moved back into the coalbed, equidistant from the front and rear of the coalbed. Their exact location was 1.8 to 2.9 m from the front of the coalbed, 0.6 to 0.8 m above the floor. The thermocouples and gas lines were then placed into the coalbed, the remainder of the coal was loaded, the coalbed was sealed, and the data acquisition system was started. The loading and sealing procedure took approximately 10 h.

Continuous data acquisition was begun for this experiment immediately after the coalbed was sealed, but the airflow was not started until 0.9 days later. Thus, the figures include the period from the time the coalbed was sealed until the start of the airflow, which was not included in the figures for the first test.

Table 3 shows the gas concentrations at the sampling locations across the coalbed and in the rear plenum area just prior to the introduction of the airflow to the coalbed. The values show a uniform gas distribution across the coalbed, with a slight dilution effect in the coalbed near the front and rear plenum areas. The gas concentrations indicate that oxidation, as well as CH_4 and H_2 desorption, was occurring in the coalbed over the 0.9-day period. Temperatures near the bottom of the coalbed, 0.45 m from the floor, increased 1° to 2° C during this phase, while temperatures 0.9 and 1.35 m from the floor remained stable or dropped slightly, responding to the ambient temperatures.

Table 3.—Gas concentrations in coalbed and rear plenum prior to start of airflow during experiment 2, volume percent

Sampling location, distance from coalbed front, m	CH_4	CO_2	CO	H_2	O_2
0.3	2.3	0.65	0.23	0.3	12.8
0.9	2.6	.69	.18	.4	11.8
1.5	2.6	.68	.24	.5	11.6
2.1	2.6	.82	.41	.5	10.0
2.7	2.6	.76	.33	.5	10.6
3.4	2.6	.75	.23	.6	10.9
4.0	2.4	.70	.25	.5	11.5
Plenum	2.0	.56	.26	.4	13.2

Self-Heating Phase

Figure 11 shows the temperature histories of the thermocouples located along the center axis of the coalbed, 1.35 m (A), 0.9 m (B), and 0.45 m (C) from the floor, along with the ambient outside air temperature (D), for the first 80 days of the test. As in the first experiment, these temperatures are representative of temperatures observed at other locations. Figure 12 shows the O_2 concentrations at the sampling locations in the coalbed (A) and rear plenum (B). These figures include the 0.9-day period prior to the start of the airflow.

At day 0.9, a 30-L/min airflow was introduced to the coalbed, and at 1.8 days, the airflow was increased to

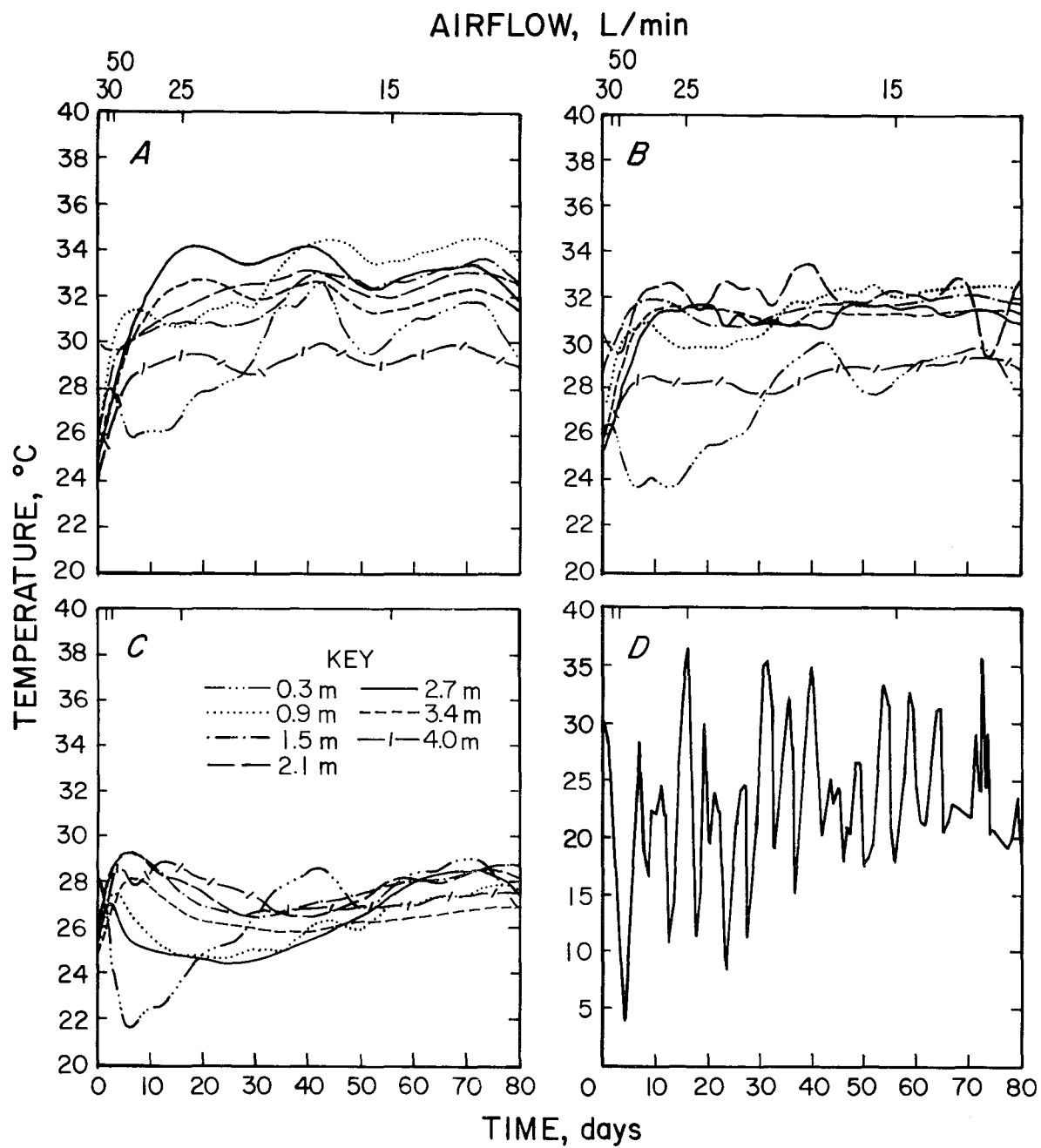


Figure 11.—Temperatures of thermocouples located 1.35 m (A), 0.9 m (B), and 0.45 m (C) above coalbed floor and ambient air temperature (D) during self-heating phase of experiment 2.

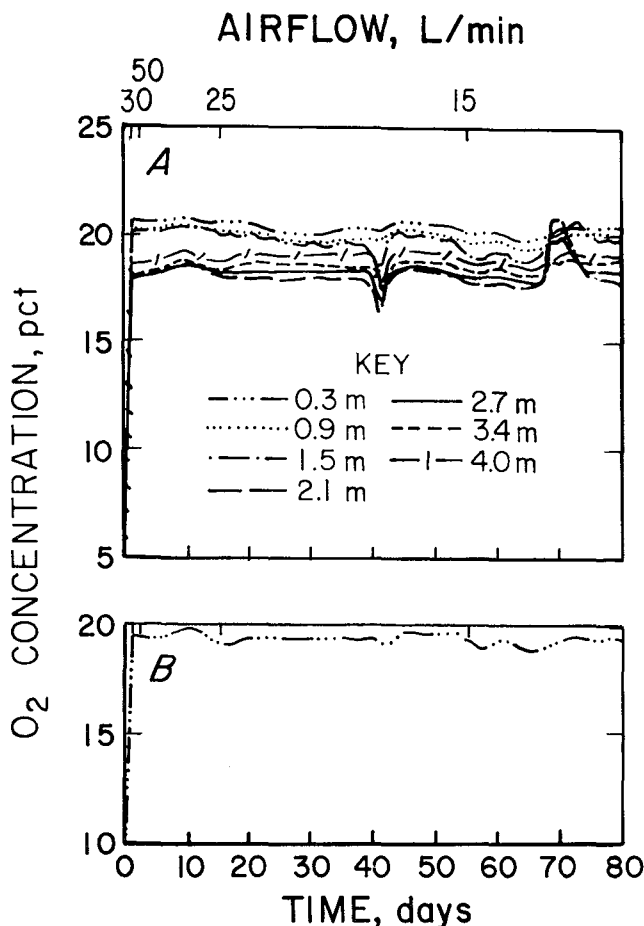


Figure 12.—O₂ concentration profiles in coalbed (A) and rear plenum (B) during self-heating phase of experiment 2.

50 L/min because of the decreasing O₂ concentration near the front of the coalbed. At 15.7 days, the O₂ concentrations across the coalbed were all above 17 pct, and either stable or increasing, so the airflow was reduced to 25 L/min. At 22 days, the humidifier was placed on-line, providing a moist airflow to the coalbed. A power outage stopped the airflow from 43.6 to 44.5 days, which resulted in a drop in O₂ concentration in the middle of the coalbed of about 2 pct. O₂ levels were quickly restored upon resumption of the airflow. The airflow was reduced to 15 L/min at 57 days, where it remained for the duration of the self-heating phase of the test. In addition, a 10 L/min airflow was introduced through the gas sampling lines at the center of the coalbed at 71.6 days, 2.1 m from the inlet air side. This flow was reduced to 5 L/min at 71.7 days and to 3 L/min at 72.7 days, where it remained until 78.8 days, when this flow was stopped. The O₂ concentration increased sharply, to above 20 pct, in that region during that time, with slight increases seen at the

other locations across the coalbed. A drop in temperature, from 33° to 29° C, was also observed during that time at the thermocouple 2.1 m from the front of the coalbed, a result of the cooling effect of the airflow.

Little variation was observed in O₂ concentration across the coalbed and in the rear plenum during the self-heating phase of the test. There was a decrease in O₂ concentration from the front to the rear of the coalbed, from approximately 20 pct, 0.3 m into the coalbed to 18 pct, 2.1 m from the front of the coalbed, indicating that some O₂ was being used up as the air flowed through the coal. The O₂ concentration was slightly higher at the locations 3.4 and 4.0 m from the front of the coalbed, indicating that some back diffusion from the rear plenum area was occurring. The O₂ concentration in the rear plenum remained near 20 pct for the duration of the self-heating phase of the test. CO and CO₂ levels throughout this phase of the experiment ranged from 50 to 80 ppm and 0.6 to 0.8 pct, respectively, in the rear plenum.

Initially, temperature increases were observed over most of the coalbed, with the exception of the thermocouples 0.3 m into the coalbed, 0.45 and 0.9 m above the floor. Temperatures along the center axis of the coalbed, 0.45 m from the floor (fig. 11C) increased 3° to 4° C over the first 7 days of the test, reaching maximums of 27° to 29.5° C. The highest temperature recorded at that level, 29.5° C, occurred at the thermocouple 1.5 m into the coalbed, 5 days after the start of the experiment. The temperature 0.3 m into the coalbed dropped to 22° C over the first 5 days before rising, but this thermocouple appeared to be strongly affected by the outside air temperature. Temperatures near the floor fell over the next 20 days, with the exception of the thermocouple located 0.3 m into the coalbed, apparently unaffected by the decreased airflow or the introduction of humidified air at day 22. From day 30 to near day 70, temperatures on the bottom level rose slightly, again with the exception of the thermocouple 0.3 m into the coalbed. The largest increase occurred 0.3 into the coalbed, where the temperatures rose 6° C, with the highest rate occurring at 22 days when the humidified air was introduced.

Temperatures 0.9 m from the floor (fig. 11B) followed the same trend as at the lower level, but the temperature increases over the first 7 to 10 days were greater, while the decreases from 10 to 30 days were less pronounced. The highest temperature observed along this level in the coalbed was 33.5° C, 2.1 m into the coalbed at 39 days, but this area was above 30° C at the start of the test. The largest temperature increase was 7° C, 2.7 m into the coalbed, which occurred over the first 10 days. The additional airflow to the center of the coalbed at day 71 had a pronounced cooling effect at the thermocouples located 2.1 and 2.7 m into the coalbed.

of the thermocouples located in the center of the coalbed, 1.35 m (A), 0.9 m (B), and 0.45 m (C) from the floor, and a heater surface thermocouple (D), from day 80 until the end of the test. Figure 14 shows the O₂ concentrations across the coalbed, while figure 15 shows the gas concentrations in the rear plenum for the stimulated heating phase of the experiment.

In the first experiment, an attempt was made to bring the coal near the heaters to a temperature of 100° C. In this test, the objective was to supply just enough power to maintain a steady temperature increase in the coal near the heaters. At day 84.8, the power input to each heater was set at 20 W, for a total power input of 40 W. The temperature of the heaters increased, reaching 100° C by day 120. The temperatures in the coal 15 cm below (fig. 13C) and above (fig. 13B) the heaters, 2.1 m and 2.7 m into the coalbed, followed the same trend, reaching 56° and 60° C, respectively, by day 120. The coal temperatures just upstream and downstream of the heaters, 1.5 and 3.4 m from the front of the coalbed, increased slightly, while those nearest the plenum areas, at 0.3, 0.9, and 4.0 m decreased during this time. The O₂ concentrations 2.1 and 2.7 m into the coalbed decreased from 18 to about 15 pct over this time, while the CO and CO₂ concentrations increased from preheater concentrations of 50 ppm and 0.6 pct to 500 ppm and 1.3 pct, respectively, indicating that oxidation was occurring in those areas. Gas concentrations in the rear plenum for the period from day 84 to day 120 showed a slight decrease in O₂ concentration, a small increase in CO₂, a trace of CH₄ near day 100, and no detectable levels of CO or H₂.

Temperatures near the heaters continued to climb, and on day 130, the airflow was increased to 25 L/min. With little effect seen on the rate of temperature increase or O₂ depletion, the flow rate was again increased on day 133, to 50 L/min. By day 149, the coal near the heaters appeared to be in thermal runaway. The temperature of the heaters had reached 147° C and was increasing at a rate of 3.5° C/d, while the coal 15 cm above the heaters was 102° C and increasing 2° C/d. The O₂ concentrations 2.1 and 2.7 m into the coalbed were decreasing rapidly, falling to 9.9 and 12.0 pct, respectively, while the CO concentration at those locations reached 1.5 pct. The power to the heaters was turned off at that point, and the temperatures of the heaters and the nearby coal fell immediately.

At 154 days, power to the heaters was restored to the previous level of 40 W. Over the next 11 days, temperatures increased at the heater surfaces and in the coal. At day 164.9, the heaters were turned off. The heater surface temperature at that time was 176° C, and the highest coal temperature was 117° C, 15 cm below the heaters, 2.1 m into the coalbed. The heater surface temperature and the temperature of the coal 15 cm above the heater again fell

at that time. However, temperatures in the coal below and to the side of the heaters continued to rise.

The thermal reaction moved radially to near the wall, 0.45 m from the floor, 0.45 m from the wall, and 2.1 m from the front of the coalbed, where the temperature increased from 93° to 435° C (not shown in figure 13) from day 166.5 to day 167. The reaction zone was very localized, with a temperature of just 34° C, 0.45 m upstream of this point, and 82° C, 0.45 m downstream of the hot spot. During this rapid heating period, the O₂ concentrations throughout the coalbed fell to very low levels, CH₄, CO, CO₂, and H₂ concentrations downstream of the hot zone increased dramatically, and smoke was observed in the exit gas stream. The rear plenum gas concentrations, shown in figure 15, were typical of concentrations found at locations 2.1, 2.7, 3.4, and 4.0 m into the coalbed. The CH₄, CO, CO₂, and H₂ concentrations upstream of the hot zone were 40 to 60 pct of those found downstream. The CH₄, CO, CO₂, and H₂ concentrations in the rear plenum reached maximums of 5.5, 2.9, 17.2, and 4.0 pct, respectively, at 167.6 days. Because of the high concentrations of explosive gases at that time, the airflow was stopped and the coalbed was sealed and inerted with 1,000 m³ of N₂.

Temperatures and gas concentrations were monitored for the next 27 days. Temperatures near the hot reaction zone fell rapidly, as did the CH₄, CO, CO₂, and H₂ concentrations, while the O₂ concentration rose, apparently because of leakage through the plenum walls. During the unloading of the coalbed, no ashed coal was found, as was observed in the first test. A portion of the plastic used to line the coalbed was melted and charred in the area where the highest temperatures were observed. This indicates that a very small, localized hot spot developed and produced the high CH₄, CO, CO₂, and H₂ concentrations observed in this experiment.

EXPERIMENT 3

The third experiment in the large-scale facility, with Wyoming No. 80 seam coal, reached thermal runaway and the airflow was stopped at 26.6 days. Thus, this test had only one phase, the self-heating phase. Temperature and gas concentrations were monitored for an additional 21 days.

Coal Loading and Sealing

Approximately 13 st of the as-received No. 80 coal was crushed to minus 2 cm at a nearby coal preparation plant approximately 3 h before loading. Initially, the coal was loaded into the test chamber to a height of 0.6 m across the length of the coalbed. Next, the coal that had been dried prior to the test was placed in the area between

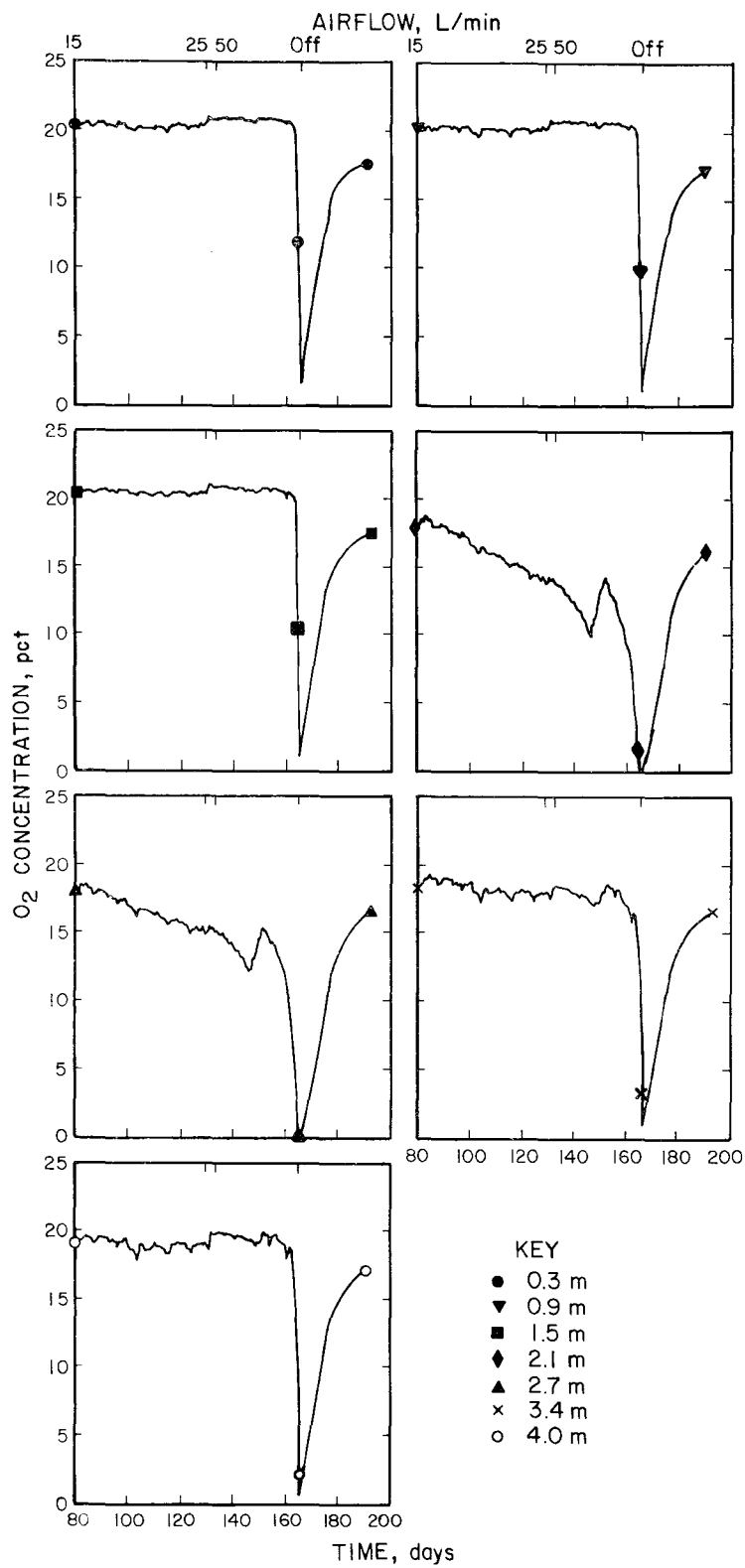


Figure 14.—O₂ concentration profiles in coalbed during stimulated heating phase of experiment 2.

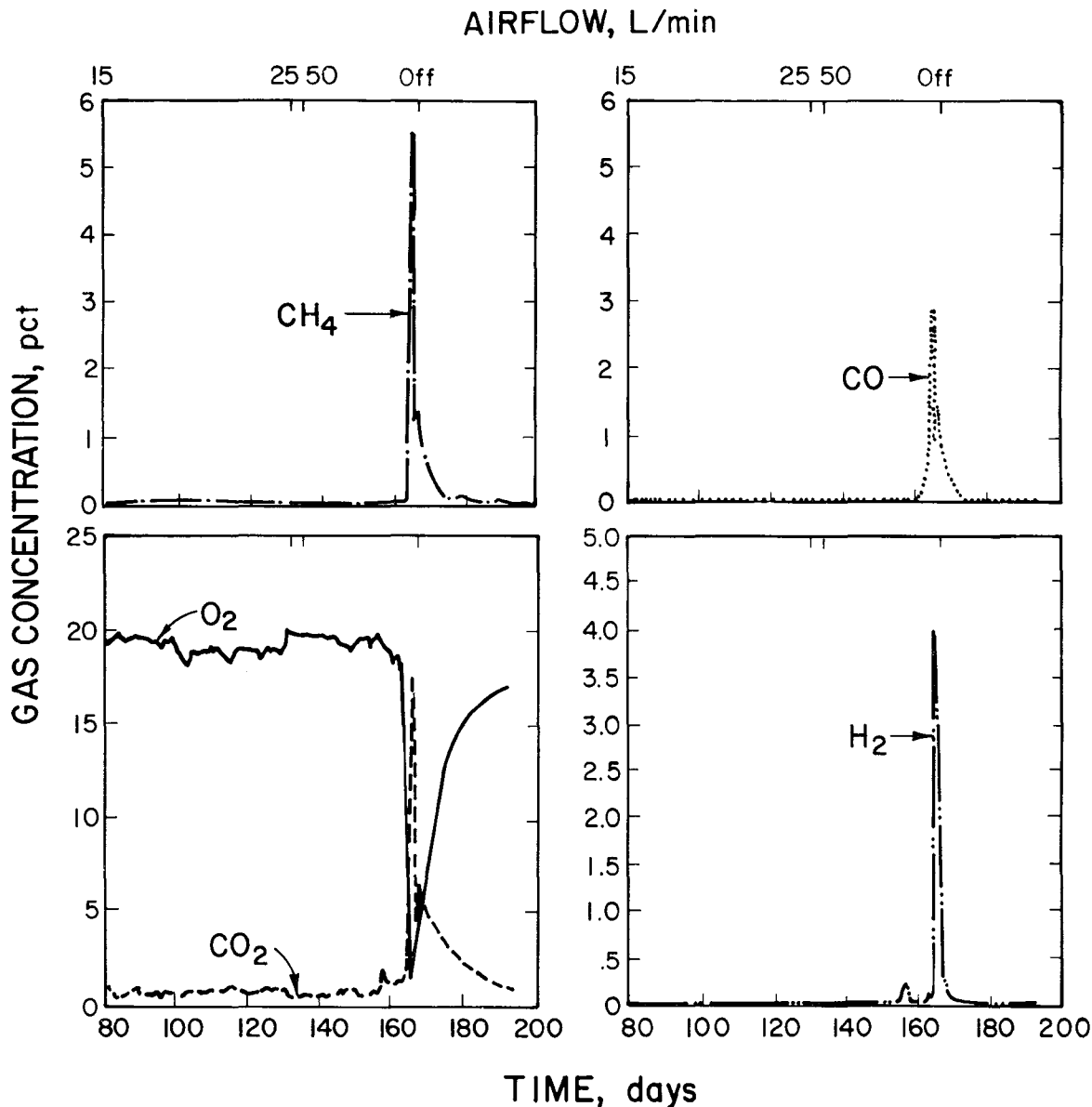


Figure 15.—Gas concentrations in rear plenum during stimulated heating phase of experiment 2.

the two wire mesh screens located 1.7 and 2.8 m into the coalbed. This coal filled that area from a height of 0.6 to 1.5 m above the floor of the coalbed and occupied a volume of 1.5 m³. The as-received coal was then used to fill the test chamber. During the coal loading, the heaters were placed into the coal, 1.8 to 2.9 m from the front of the coalbed, and 0.6 to 0.8 m above the floor, and the thermocouples and gas lines were installed. The loading and sealing procedure took just over 4 h, and the airflow was started immediately after sealing.

Self-Heating Phase

In this experiment, the entire coalbed showed indications of heating immediately after the airflow was started. Figure 16 shows the temperature histories of the coalbed thermocouples, arranged in vertical arrays 0.3 m (A), 0.9 m (B), 1.5 m (C), 2.1 m (D), 2.7 m (E), 3.4 m (F), and 4.0 m (G) from the front of the coalbed. The thermocouples 2.1 m from the front and 0.9 and 1.35 m from the floor are in the predried coal, while those 2.7 m from the

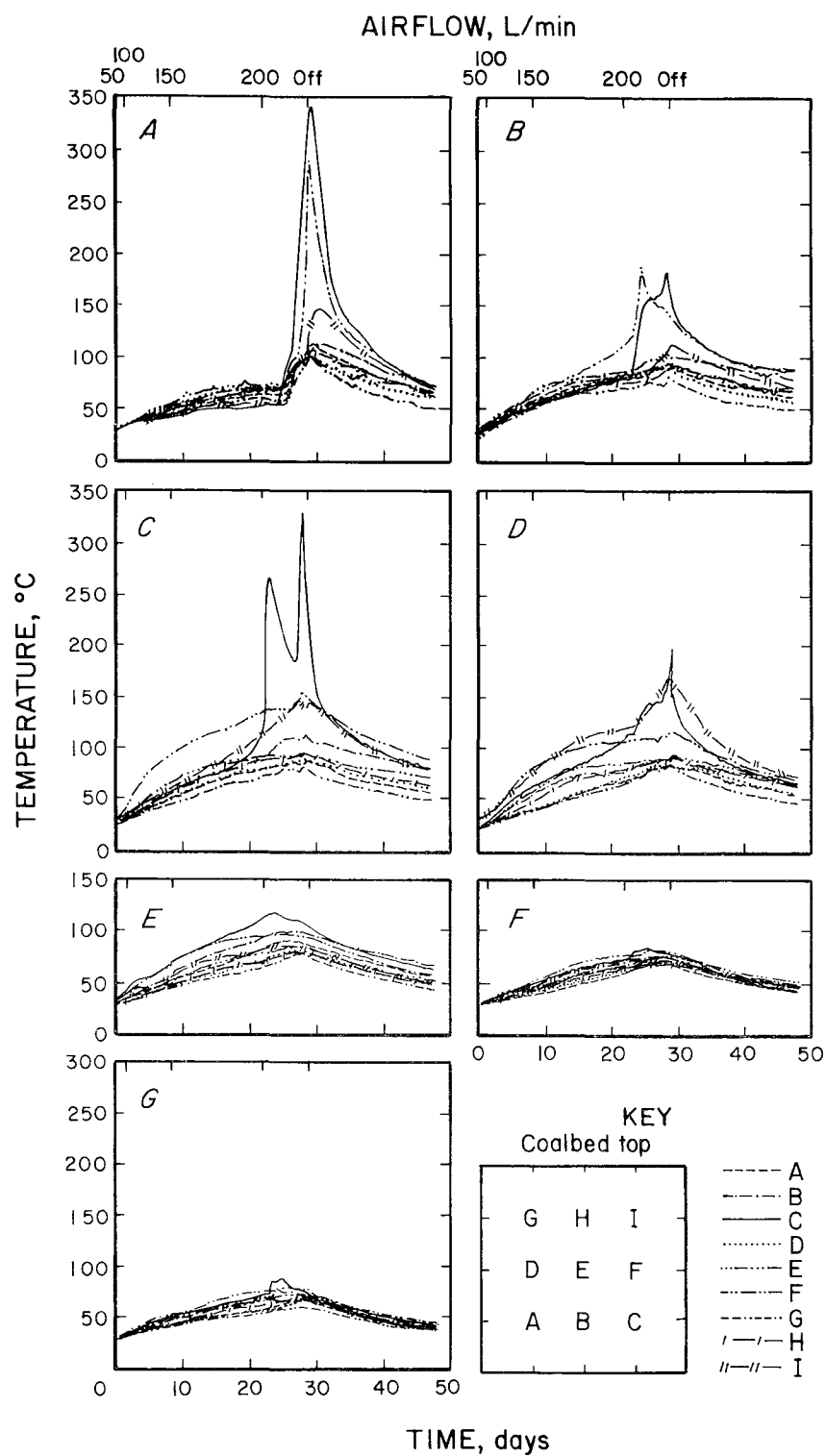


Figure 16.—Temperatures of thermocouples located 0.3 m (A), 0.9 m (B), 1.5 m (C), 2.1 m (D), 2.7 m (E), 3.4 m (F), and 4.0 m (G) from front of coalbed during experiment 3.

front at the same heights are at the dried-as received coal interface. Figure 17 shows the CH_4 , CO , CO_2 , O_2 , and H_2 concentrations in the rear plenum.

Initially, a 50 L/min airflow was established. O_2 concentrations quickly fell to less than 2 pct in the center of the coalbed and to 15 pct near the front of the coalbed. Corresponding increases in CO across the coalbed ranged from 0.1 to 0.3 pct. The airflow was increased to 100 L/min at day 0.8. O_2 concentrations in the coalbed rose slightly, but still remained below 4 pct in the center of the bed. Temperatures rose steadily over the entire coalbed, with the highest temperatures and heating rates occurring near the wall, 0.9 m from the floor.

By day 7.6, the highest temperature was 88° C, 0.45 m from the wall, 0.9 m from the floor, and 1.5 m from the front of the coalbed (fig. 16C), while the temperatures just downstream of that thermocouple, 2.1 and 2.7 m from the front of the coalbed, were 80° and 63° C, respectively. Other areas of the coalbed ranged from 40° and 60° C. Temperatures were still increasing, but the rates of increase appeared to be falling. The O_2 concentrations in the coalbed and rear plenum were decreasing slowly, while the CO and other gas concentrations in the rear plenum appeared stable or decreasing.

At day 7.6, the airflow was increased to 150 L/min. Temperatures continued to rise, but the airflow increase

had no apparent effect on the rate of coal reaction in the coalbed. The O_2 concentrations in the coalbed and rear plenum continued to decrease, while a slight increase in the CO_2 concentration was observed, and CO concentrations in the coalbed were stable or slightly decreasing.

At day 17, an increase in the reaction rate was observed at the thermocouples 0.45 m from the floor, 0.45 m from the wall, and 1.5 and 2.1 m from the front of the coalbed, where temperatures were 78° and 92° C, respectively. The highest temperature in the coalbed at that time was 117° C, along the same wall, 0.9 m from the floor and 2.1 m from the front of the coalbed, but the rate of temperature increase at that location remained steady. O_2 concentrations near the center of the bed were already less than 1 pct, and at that time, the O_2 concentration 1.5 m into the coalbed began to fall from 2.5 pct to less than 1 pct. The O_2 concentration in the rear plenum began to decrease more rapidly, and the CO_2 concentration began to increase.

At day 20, the rate of temperature rise increased rapidly at the thermocouple located near the wall, 0.45 m from the floor, and 1.5 m into the coalbed, and increases in the rate of temperature rise at nearby thermocouples were seen. Rates of production of CO and CO_2 also increased at the sampling locations 0.9, 1.5, and 2.1 m into the bed, while changes in the O_2 levels in the coalbed were less pronounced, since the areas near where the heating developed were already less than 1 pct. At day 21.7, the airflow was increased to 200 L/min. This resulted in slight increases in the O_2 concentrations and slight decreases in the CO concentrations across the coalbed, while the change had minimal effect on the gas concentrations in the plenum area. Thermal runaway occurred shortly afterward at the thermocouple 0.45 m from the wall, 0.45 m from the floor, and 1.5 m from the front of the coalbed, where the temperature reached 264° C at day 22.5. Corresponding sharp increases in the combustion gas concentrations and a drop in O_2 concentration were observed in the rear plenum, and smoke was observed in the exit gas stream. Concentrations of CH_4 rose to 2 pct, CO_2 to 5.5 pct, CO to 1.4 pct, and H_2 to 1 pct, while O_2 fell to about 11 pct. The O_2 concentration in the center of the coalbed was less than 1 pct, but was still 12 pct at 0.3 m into the coalbed, because of the high airflow rate. The reaction zone was localized, possibly because of O_2 deficiency in the center of the coalbed. Coal temperatures across the rest of the coalbed also continued to rise, but indications of thermal runaway were not evident in other areas. Maximum temperatures 0.9 and 1.5 m upstream of the hot spot were 119° and 71° C, respectively, at that time, while 0.9 and 1.5 m downstream of the hot area the maximum temperatures were 117° and 111° C, respectively.

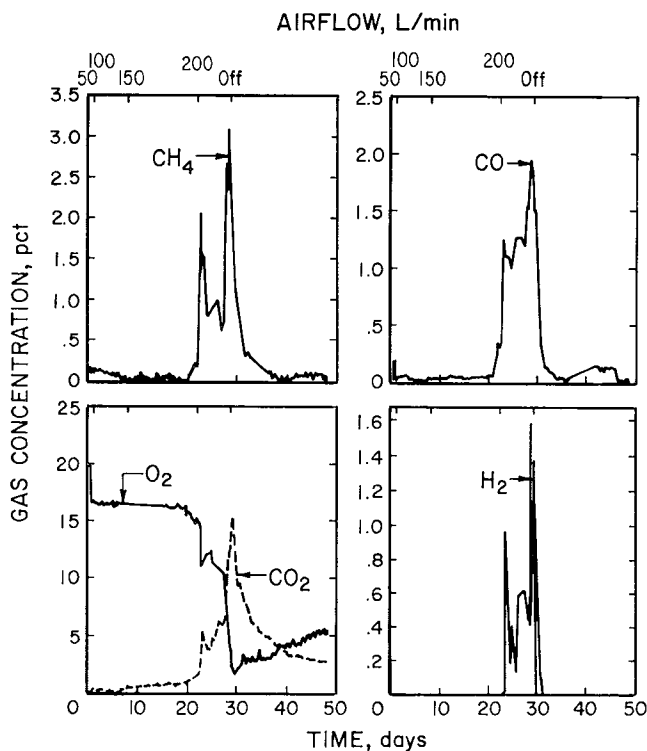


Figure 17.—Gas concentrations in rear plenum during experiment 3.

The temperature at the hot spot then began to decrease, and the reaction zone moved toward the front of the coalbed, seeking O_2 . CO , CO_2 , H_2 , and CH_4 concentrations in the rear plenum also decreased, while the O_2 concentration increased slightly. Temperatures 0.9 m into the coalbed, 0.45 m from the wall, and 0.45 and 0.9 m from the floor appeared to be in thermal runaway at day 24, but peaked or leveled off at day 25, at 160° and 190° C, respectively. Gas production rates again slowed, and the O_2 consumption in the bed leveled off. CO , CO_2 , H_2 , and CH_4 concentrations in the rear plenum were 1.3, 6, 0.6, and 1 pct, respectively, while the O_2 concentration was near 12 pct. Concentrations across the coalbed for these gases ranged from 1 to 2.5 pct CO , 2 to 11 pct CO_2 , 0.2 to 1 pct H_2 , 0.3 to 1.5 pct CH_4 , and 0 to 15 pct O_2 . Concentrations were highest for the combustion gases near the reaction zone, decreasing downstream of that area, with the lowest concentrations found 0.3 m into the coalbed before the reaction zone. O_2 concentrations followed the same trend, but the relative concentrations were reversed.

At day 25.3, thermal runaway occurred near the front of the coalbed and again in the hot region 1.5 m into the coalbed. Temperatures 0.3 m into the coalbed increased rapidly over the next 3 days, rising at a rate of about 3.3° C/h, at the locations 0.45 m from the floor and 0.45 and 0.9 m from the wall, where temperatures had reached 333° and 268° C, respectively, while the temperature 1.5 m into the coalbed was 330° C. Combustion gas concentrations in the coalbed and rear plenum were also increasing, with the CO , CO_2 , H_2 , and CH_4 concentrations in the rear plenum reaching 2.2, 16, 1.6, and 2.8 pct, respectively. O_2 concentration in the rear plenum was 4 pct. The airflow was stopped and the coalbed sealed at 26.6 days. Temperatures in the coalbed continued to rise for a short period of time, using up the remaining O_2 available in the front plenum area before falling, as did the CH_4 and CO_2 concentrations, while the H_2 and CO concentrations fell immediately. Temperatures and gases were monitored for an additional 21 days.

DISCUSSION

The self-heating rate of a coal mass may be expressed as the sum of the heat release reactions, the heat of oxidation, and the heat of wetting, and the heat losses, by conduction and convection. It is generally agreed that the oxidation rate of coal is a temperature-dependent reaction that obeys an Arrhenius type rate law of the form of rate = $A[\exp](-E/RT)$, where the rate coefficient A includes the heat of reaction, the specific rate constant, and the specific heat of the coal; E is the activation energy; R is the molar gas constant; and T is the temperature. The reaction rate has been shown to be dependent on particle size (14-15), increasing with decreasing particle size, because of the increased accessibility of O_2 to the internal surfaces, and on O_2 concentration, decreasing with decreasing O_2 concentration (15).

The adsorption of moisture on dried coal surfaces is a heat-producing reaction known as the heat of wetting. The heat generated raises the coal temperature, thereby increasing the oxidation reaction rate, and at low temperatures, the heat of wetting can cause greater temperature increases in a coal mass than the heat of oxidation. In addition, moisture has been shown to have a synergistic effect on the oxidation process (2, 16-17). The subsequent evaporation of moisture from coal surfaces at higher temperatures is an endothermic process. During this phase of the self-heating process, the reaction rate usually slows.

Ventilation can affect the reaction rate in two ways. Since O_2 is a critical parameter in the oxidation rate,

adequate ventilation is required to provide sufficient O_2 for the reaction. On the other hand, convection, which is primarily a function of the ventilation rate, is a mode of heat dissipation. Thus, there is an optimum ventilation rate to promote and sustain self-heating.

Although several of these factors have been evaluated in the Bureau's adiabatic oven, extrapolation of the results to large-scale or in-mine conditions is difficult because of both the size constraints of the apparatus and the general lack of large-scale and in-mine data (2). In this study, an attempt has been made to evaluate several of these factors under large-scale conditions that simulate a gob of a coal mine.

The three coals used in this study were of similar rank (high-volatile C bituminous) and composition and exhibited similarly high self-heating tendencies in the adiabatic oven tests. The F seam coal had a minimum SHT of 35° C in the adiabatic oven, while the D and No. 80 seam coals had minimum SHT's of 45° C. Although the results indicate that the F seam coal was a slightly more reactive coal, all three coals would be classified as having a high spontaneous combustion potential (2). However, only the No. 80 seam coal underwent a sustained self-heating that led to thermal runaway in the large-scale experiments. It is clear that the conditions used in the experiment with No. 80 seam coal, relative to the other two experiments, played the major role in the self-heating of this coal.

The test conditions in the self-heating phase of the first two experiments were similar. Both the D and F seam

coals were freshly mined and delivered as received to the large-scale facility in approximately 2 days. The D seam coal was stored overnight on the ground, whereas the F seam coal was loaded directly into the test chamber. Airflow rates during the experiments were based on supplying an adequate O_2 concentration to the reacting coal mass, defined as greater than 15 vol pct. In both tests, airflow rates were comparable, ranging from 50 L/min at or near the start of the experiment and being reduced to 25 to 30 L/min and finally to 15 L/min as the experiment continued.

The small differences in the experimental conditions, namely the higher reactivity of the F seam coal based on laboratory tests and the 1-day delay in the loading of the D seam coal into the test chamber, agree with the higher temperature rise exhibited by the F seam coal. However, the assignment of these factors as the conclusive reason for the higher temperature rise is difficult because of the small magnitude of the temperature differential, 9° C compared with 6° C, and the inherent uncertainties due to the nature of the test, such as variations in the coal composition within each coal sample, the effect of ambient temperature, and size segregation effects due to loading.

In the third experiment, the No. 80 seam coal was of similar rank and composition and exhibited the same high self-heating potential as the D and F seam coals. However, there were two major differences in the conditions used relative to the first two tests: the placement of 1 st of dried coal in the center of the coalbed and the crushing of the coal just prior to the test. The resultant sustained self-heating and thermal runaway indicate that these factors played a major role in the self-heating of this coal.

The highest temperatures and heating rates over the first 20 days of the experiment with No. 80 seam coal were observed at the thermocouples located near the wall, at the boundary between the dried coal and the as-received coal (fig. 16C) and in the dried coal (fig. 16D). The shapes of the heating curves during that time are consistent with those obtained in experiments in the adiabatic oven (100-g sample) and moderate-scale apparatus (3-kg sample) with humidified air and dried coal (2). In those tests, it was shown that the heat of wetting was the dominant heat-producing mechanism at low temperatures. During this time, CO concentrations in the coalbed were stable and relatively low, near 500 ppm, indicating little increase in the oxidation rate, while CO_2 production steadily increased. This increase in the release of CO_2 has been attributed to moisture evaporation from the coal (18-19), which in this experiment could have occurred during moisture migration from the undried coal to the dried coal region. Thus, it appears that the heat of wetting was the dominant mechanism in the early part (first 20 days) of the experiment with No. 80 seam coal, that eventually led to the development of thermal runaway.

Although the development of the hot zone in the third test was attributed primarily to the heat of wetting, it is apparent that oxidation was occurring throughout the entire coalbed during this period, at rates much higher than those observed in the first two tests. Examining the temperature traces for the thermocouples located near the front and rear of the coalbed, far enough away from the hotter center of the coalbed to be unaffected by heat conduction, several temperatures in excess of 50° C were found. Although the CO concentrations across the bed remained stable during this period, the concentrations were 2.5 to 5 times higher than those observed in the tests with D and F seam coal, indicating a much higher oxidation rate. Assuming that in the experiment with No. 80 seam coal the heat-of-wetting effect was negligible in those areas, although some partial drying probably occurred during the crushing process, these higher temperatures and CO concentrations in the third experiment indicate a significantly higher coal oxidation rate. Since these three coals exhibited similar reactivities in the adiabatic oven, the enhanced reaction rate of the No. 80 seam coal is most likely due to the increased surface area and weakening of the internal coal structure because of the crushing of the coal just prior to the experiment (20).

DEVELOPMENT OF REACTION ZONE

In the first two experiments, when it was apparent that the coal was not undergoing a sustained heating, the heaters were turned on to stimulate a heating in the coalbed. The development of the heatings in these experiments and their subsequent behavior differed markedly.

In the first experiment, the heaters were turned off on day 134, at which time the temperature of the coal 0.15 m above the heaters was 140° C, and below the heaters, 113° C. However, even though the temperature was higher above the heaters, the reaction rate slowed there, peaking at 149° C on day 136, while the coal below the heaters went to thermal runaway, peaking at 225° C at day 140. The reaction zone then moved toward the front of the bed over the next 5 days, with temperatures reaching 340° C at the thermocouple 0.3 m from the wall, 0.9 m from the floor, and 0.3 m from the front of the coalbed.

The development of the hot zone below the heaters may be explained by a thermal mechanism. The buoyancy-induced heat losses from the reacting coal would be less in the region below the heaters, because of the placement of the heaters, than the heat losses from the coal above the heaters. Assuming a similar reaction rate in the coal in both regions, the conditions below the heaters were more adiabatic.

However, it is apparent from the temperature histories for these thermocouples that virtually no reaction was occurring in the coalbed above the heaters. The shape of

that curve is convex, following closely that of the heater. When the heater power was turned off, the heater temperature fell immediately, and the coal temperature above the coal leveled off and then fell after 2 days. At the same time, the shape of the temperature curve for the coal below the heaters was concave, as is usually seen in thermal runaway reactions. When the heater power was turned off, the temperature continued to increase rapidly.

Two plausible explanations exist for the behavior of the coal above the heaters. First, the area above the heaters may have been O_2 deficient. However, O_2 data from probes located 1.2 and 1.8 m from the front of the coalbed at this height showed that at 134 days, when the heaters were turned off, the O_2 concentrations at those locations were 9.7 and 4.8 pct, respectively. Thus, it appears that there was sufficient O_2 to sustain the reaction in the coalbed above the heater. Second, the reactive sites on that coal may have been used up during the period from 93 days to 129 days. During that time, the coal temperature at the thermocouple located 15 cm above the heaters hovered near 85°C , while 15 cm below the heaters, the temperature stayed near 69°C .

The movement of the reaction zone to the front of the bed was most likely due to O_2 deficiency. O_2 concentrations 0.9 and 1.5 m into the coalbed fell to less than 1 pct as the reaction zone moved through those areas. The path along or near the wall was attributed to ventilation channeling effects, created by the mode of coal loading. Top loading leads to particle size segregation, with the larger sizes falling to the sides. Thus, the least restricted airpath was along the walls.

Again, in experiment 2, a sustained self-heating was not achieved, and the heaters were used to stimulate a heating event in the coalbed. In this experiment, the thermal runaway developed somewhere between the thermocouple located directly below the heater and the adjacent thermocouple and moved radially. The temperature peaked at 435°C at the thermocouple located 0.45 m from the wall, 0.45 m from the floor, and 2.1 m from the front of the coalbed. The temperature at that location began to fall, but CH_4 , CO , CO_2 , and H_2 concentrations continued to rise in the rear plenum area, forcing the termination of the experiment and inerting of the coalbed. It is not clear whether the reaction zone moved from the hot area, as in the first experiment, or if the area burned itself out. From the gas data, it appears that the reaction rate was increasing, indicating either an increase in temperature in the reaction zone, or an increase in the amount of coal involved in the reaction. Since the temperature at the hot spot was decreasing, it would appear that the reaction zone was moving. However, the lack of a significant increase in temperature upstream of the hot spot makes this unclear. There was a slight increase in temperature downstream of the hot spot, but that was probably

convective heating, since any movement in the reaction zone would be expected to be in the direction of the air source (21).

The development of the reaction zone in the third experiment occurred near the wall, 0.45 m from the floor, and 1.5 m into the coalbed, and subsequently moved toward the front of the coalbed over a 6- to 7-day period. The reaction occurred as a result of self-heating and did not require the use of the heaters as in the first two experiments. The development of the reaction zone was described previously and was attributed to the heat of wetting at the dried-as-received coal interface. The subsequent movement along the wall to the front of the coalbed was probably due to ventilation channeling effects, as described for the first experiment.

GAS ADSORPTION AND EMISSION

Freshly mined coals both evolve and adsorb gases. The main gas adsorbed by the coal is O_2 . The adsorption of O_2 is initially a physical process. The adsorbed gas then reacts with the coal, forming new chemical bonds and groups in the coal. These new groups undergo decarboxylation, decarbonylation, and dehydroxylation at temperatures above ambient, releasing CO_2 , CO , and H_2O . At higher temperatures, coal can undergo oxidation, decomposition, pyrolysis, and combustion reactions, releasing large amounts of various volatiles and gases.

The gases released by freshly mined coal include CH_4 , CO_2 , N_2 , and trace amounts of higher hydrocarbons and H_2 , with CH_4 being the main gas. These gases form during the coalification and maturation processes in the coal. CH_4 is contained in coal either as a free gas, in the pores or fissures, or as sorbed gas, with a major portion of it being in the sorbed phase. The amount of CH_4 sorbed on the coal depends mainly on the temperature, pressure, rank of coal, and overburden thickness. The amount of CH_4 increases with the increase of the fixed carbon (dry ash-free basis) of the coal (22).

Once the coal is mined and reduced in size, evolution of the gases starts, initially at a high rate and then at exponentially lower rates (23). These rates of evolution depend, among others, on the coal, the types and proportions of the various macerals in the coal sample, and the lump or particle size (24).

The three coals used in these experiments were freshly mined and delivered to the facility in covered trucks in about 2 days. The coals were then loaded and sealed into the test chamber. During the transport, some of the gas content of the coals was released; however, large amounts were evolved after the coals were sealed. The flow of ventilation air through the coalbed carried these gases away, increasing the evolution rate by increasing the concentration gradient between the coal and the surrounding

atmosphere. Depending on the coal size, this gas release process can take many months.

At the same time, the coals adsorbed O_2 from the air and interacted with it. In the first and second experiments, which did not undergo extensive self-heating, O_2 was adsorbed. As seen in figure 6A, the level of O_2 in the coalbed in the first experiment decreased from about 20 pct near the front of the bed (0.6 m), to approximately 17.5 pct near the rear (3.7 m), and this concentration gradient remained stable during the first 90 days. The level of CO detected in the coalbed during this same period varied between 50 and 100 ppm. As seen in figure 6B, the level of O_2 in the rear plenum was higher than in the coalbed, probably due to channeling of the airflow through the coalbed, as well as diffusion of air through the exhaust duct, as mentioned earlier.

The same phenomenon is observed in figure 12, which depicts the O_2 concentration in the bed and rear plenum during the self-heating phase of the second experiment. O_2 levels varied between 20 and 17.5 pct, from 0.3 to 4.0 m, respectively. The O_2 level in the rear plenum was approximately 19.5 pct throughout this period, again suggesting diffusion from the outside.

Gas analysis procedures were changed for the second and third experiments, so that in addition to O_2 and CO, the concentrations of CH_4 , CO_2 , and H_2 were measured in the coalbed as well. It is interesting to observe the concentrations in the test chamber just before the airflow was started in the second experiment. CH_4 levels were at 2.6 pct, and the average CO_2 concentration was 0.7 pct. In addition, CO and H_2 were present at relatively high concentrations of about 0.2 to 0.4 pct and 0.5 pct, respectively. The CO and H_2 concentrations were highest in the center of the coalbed and lower at both ends, whereas the O_2 concentration was lowest at the center (10 to 11 pct) and higher at both ends. These values indicate that the coal readily adsorbed the O_2 and released its sorbed and occluded gases. Most of the CO was probably present in the coal even before it left the mine, while some was formed because of oxidation of the coal since it was mined.

During the first 80 days of the second experiment, levels of CO in the coalbed stayed at 50 to 80 ppm, while amounts of CO_2 were much higher, between 0.6 and 0.8 pct.

These data from the self-heating phases of the first two experiments indicate that higher flow rates might have increased the oxidation rates of the coals somewhat, but the effects of the increased oxidation rates would be balanced by the increased heat losses due to convection. In agreement with the literature, the rate of oxidation of moist coal at ambient temperature is low and the associated heat produced is small. It has been suggested that the heat that is produced when dry or partially dry coal

adsorbs moisture raises the temperature to a value where the coal oxidation rate increases enough to result in thermal runaway. The D and F seam coals used in these experiments contained relatively high amounts of moisture. The airflow through the coalbed removed some moisture from the coal, as evidenced by traps in the gas sampling lines. Most of the removed moisture was from the front of the coalbed, and this was seen in the temperature drops 0.3 and 0.9 m into the coalbed, which were attributed to ambient temperature changes and the cooling effect of the evaporation of H_2O from the coal. When the humidifier was added to the airflow at 22 days, a marked increase in temperature was noticed in the area 0.3 m into the coalbed and a smaller increase in temperature 0.9 m into the coalbed, probably because of the heat-of-wetting effect.

The coal used in the third experiment underwent self-heating from the start of the experiment, throughout the coalbed, which was evident in the decreased O_2 and increased CO concentrations in the coalbed, compared with the first two experiments, and in the increasing CO_2 concentration observed in the rear plenum (fig. 17).

Thermal runaway occurred 1.5 m from the front of the coalbed at 21.7 days. Gas concentrations in the rear plenum were indicative of an active smoldering combustion. Actual flaming combustion requires both combustible gases and a minimum concentration of O_2 of about 12.4 pct, while smoldering combustion will occur at much lower O_2 concentrations (25). The rate of smoldering combustion is slow and depends on the rate of O_2 diffusion into the smoldering area. The smoldering combustion will move along the bed of combustible material if enough O_2 is available to sustain it. This was observed in both the first and third experiment.

Ample ventilation should help in the dissipation of heat from a coal pile, but in practice it is difficult to achieve such flows in large piles or stacks. In many instances, instead of dissipating the heat, the ventilation flow will aggravate conditions that are already bad (26). In the third experiment, the increased airflow was not sufficient to dissipate the heat, and the O_2 was consumed as it reached the smoldering area.

Only twice during the experiment were temperatures higher than 300° C observed. To undergo extensive pyrolysis, in an atmosphere consisting mostly of N_2 , higher temperatures are needed, but even at the lower temperatures, from 200° to 350° C, the coal decomposes. The literature on pyrolysis of bituminous coal indicates that the major loss of volatiles takes place between 300° and 600° C. Between 200° and 350° C, loss of H_2O from phenolic structures, as well as release of CO and CO_2 from carbonyl and carboxyl groups, predominates. Primary carbonization starts at about 350° C, initially with the release of H_2 and CO_2 . With increase in temperature and the associated rupture of cross links and bonds of aliphatic and

hydroaromatic groups, more CH_4 , CO , and other gases are evolved, as well as some condensable oils and tars (27). However, the temperature at which pyrolysis occurs may depend on the heating rate of the coal. At lower heating rates, as in these experiments, these events might take place at lower temperatures.

In the stimulated heating phases of the first two experiments, the coals underwent similar pyrolysis-decomposition reactions in the heated areas, and large amounts of combustion gases (CH_4 , CO_2 , and CO) were produced. The maximum temperature in the first experiment was 340°C . However, the presence of ash in the heated area, observed after the test chamber was opened, suggests that higher temperatures were obtained near the front of the coalbed. In the second experiment, the maximum temperature observed was 435°C , 100°C higher than in the first experiment, yet ash was not found in the heated area when the chamber was opened. The high concentrations of the released combustion gases agreed, though, with the observed temperatures.

DETECTION OF SPONTANEOUS COMBUSTION

Early detection is critical in the prevention and control of fires caused by spontaneous combustion in underground coal mines. Two types of detectors are commonly used in the detection of underground mine fires: thermal and combustion gas.

The use of thermal detectors in the detection of spontaneous combustion, primarily thermocouples and infrared scanners, has limited use in underground mining situations. Most heatings occur in gob or sealed areas, where access to these areas for infrared scanning is impossible. Infrared scanning methods have been used to monitor the rib, roof, and floor of entries to detect self-heating. Remote monitoring of gobs via thermocouples has been attempted, but the destructive nature of gobs usually result in the loss of the thermocouples in a matter of days. The results of the experiments in this study emphasize another of the major drawbacks in the use of thermocouples for the detection of heatings in gobs and sealed areas: that of proximity to the heated area. In these experiments, the size of the hot spots that developed was small relative to the size of the coalbed, and nearby thermocouples were often unable to detect the hot spot. In the third experiment, as the hot spot approached 300°C in the front of the coalbed, temperatures just 2 m downstream remained near 50°C .

The analysis of gaseous products of combustion is the primary method used for the detection of spontaneous combustion in underground coal mines (28). The use of gas analysis and various fire ratios in the detection of gob fires was evaluated early in this century in British collieries (29). The information does not show clear differences

between safe conditions and the beginnings of heating events. Only in cases of advanced heating were the values from gas analysis more easy to interpret and able to identify heatings. This is understandable, considering the state of gas analysis at the time. More recently, Chamberlain (30-32) showed that CO is the most sensitive indicator of the early stages of coal oxidation and recommended that the continuous monitoring of this gas would provide the earliest detection of self-heating. Other gases have been investigated, such as CO_2 , CH_4 , H_2 , and higher hydrocarbons. CO_2 production increases with increasing temperature and is useful in determining the state of a fire. However, several sources of CO_2 are usually present in mines, making its use unreliable. CH_4 is present in large background quantities and, as with H_2 and other hydrocarbons, is not produced until much higher temperatures. These facts, combined with the low detection limits and availability of relatively inexpensive CO detector systems, have made CO detectors the most popular (33).

As stated above, many of the combustion product gases, including CO , are encountered in the normal mining of the coal seam, and their concentrations fluctuate with changes in ventilation rates, diminishing their reliability as indicators of spontaneous combustion. This was recognized early, and the use of ratios, such as the $\text{CO}-\Delta\text{O}_2$ ratio that compares the CO concentration with the O_2 deficiency, the $\text{CO}-\text{CO}_2$ ratio, and the $\text{CO}_2-\Delta\text{O}_2$ ratio, have been widely used. The Bureau evaluated the $\text{CO}-\Delta\text{O}_2$ and $\text{CO}-\text{CO}_2$ ratios for the analysis of sealed mine fires and found that the $\text{CO}_2-\Delta\text{O}_2$ ratio was a more sensitive indicator for determining the state of a fire (34).

Recently, the Bureau developed the R ratio to evaluate the atmosphere of sealed mines for safe reentry (35). This ratio compares the CO concentration with respect to the residual gas concentration (all gases except ambient air, CH_4 , and C_2H_6) to the ratio of residual gas with respect to the O_2 concentration. An R ratio value greater than 1 indicates that there is a state of higher-than-normal temperature oxidation. Although the R ratio was developed for sealed areas, it was evaluated to determine its applicability in the detection of self-heating in a flowing system.

Plots of the $\text{CO}-\Delta\text{O}_2$, $\text{CO}-\text{CO}_2$, $\text{CO}_2-\Delta\text{O}_2$, and R ratios for the third experiment in the large-scale facility are shown in figure 18. In the experiment, temperatures increased across the coalbed as the experiment progressed, with thermal runaway starting at day 20. The ratios all increased over the first 2 to 3 days, because of the initial surface oxidation that occurred when the coal was first exposed to air. The ratios then fell, and with the exception of the $\text{CO}_2-\Delta\text{O}_2$ ratio, leveled off after about 10 days. The $\text{CO}_2-\Delta\text{O}_2$ ratio started to increase at day 6 and continued to increase for the duration of the test. When the thermal runaway occurred in the coalbed at day 20, all four ratios increased rapidly, indicating a heating in the

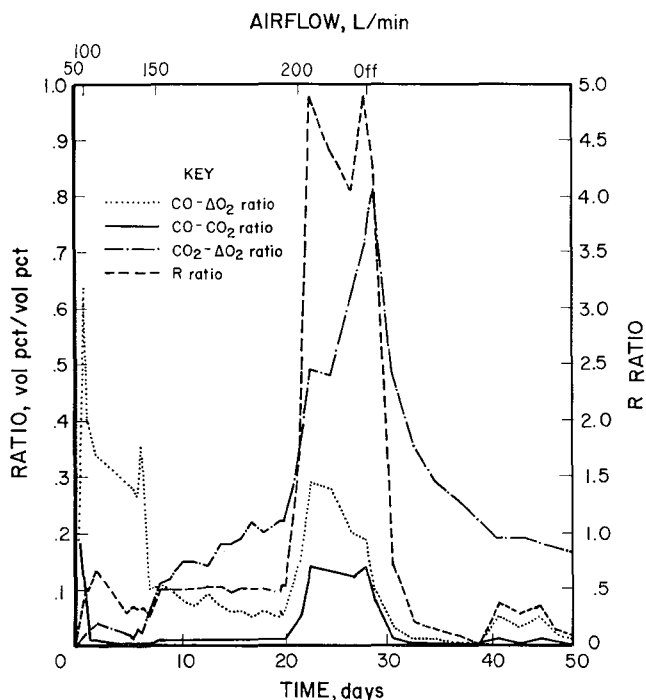


Figure 18.—Ratios for rear plenum gases during experiment 3.

coalbed. The response times to the thermal runaway were nearly the same, which would be expected, since the ratios are related to combustion product gas concentrations, which increased dramatically when the self-heating occurred.

Although all the ratios clearly indicated the development of the thermal runaway at day 20, the $\text{CO}_2\text{-}\Delta\text{O}_2$ ratio was the only ratio that gave an early warning of the heating in the coalbed. This is not unexpected, based on the gas concentration profiles in figure 17, in which only CO_2 exhibited an increase over the first 20 days of the experiment.

COMPARISON OF LARGE-SCALE TESTS WITH OTHER TESTS

Large-scale tests have been conducted over the years to study and assess the changes undergone by coal during storage. Of major importance have been changes such as lowered heating values, size degradation, and reduction of coking properties. Concurrently, spontaneous combustion in storage piles has also been carefully studied. In all these studies, the goal has been to minimize and prevent the undesirable changes and the hazardous occurrences of spontaneous combustion.

Toward this goal, the coal in these large-scale experiments was usually compacted, to exclude air as much as

possible, and size segregation in conical and pyramidal piles was avoided. In spite of such precautions, heatings developed. Reviews of large-scale tests (10, 36-38) detail these and other factors that contribute to the development of spontaneous combustion. Results from studies of coal behavior in very large open pits and with uncapped and asphalt-capped piles (5-6) led to recommendations of safe procedures for storage of thousands of tons of coal for industrial use. Likewise, tests were conducted in open and covered bins, with and without ventilation, using 3-st samples, and the best conditions for safe storage of these smaller quantities were delineated (4). During all these tests, heatings and fires frequently occurred in various locations in the piles, until careful compaction and elimination of air leakage were attained and scrupulously maintained.

Results from field tests with three topped pyramidal coal piles, each containing about 2,500 st and varying in porosity from 13 to 31 vol pct, were used for verification of a mathematical model of spontaneous combustion of coal in storage (39).

Similarly, results from field tests in three hoppers (with volumes ranging from 3.5 to 5.5 m³, accommodating roughly 1-st quantities of coal, were combined with mathematical modeling, to elucidate the development of spontaneous combustion in larger quantities (8).

These experiments and others like them vary in both size and conditions from the conditions used in the present three experiments (which utilized forced ventilation), and thus the results cannot be compared in detail. The objective in this set of experiments was to create and identify conditions favorable to self-heating and spontaneous combustion in a gob area of a mine. To this end, the size and configuration of the test chamber, coal and coal size, and ventilation rates were, at least partly, chosen based on the above-stated needs. And likewise, some of these variables were modified for each succeeding experiment, based on the results from the preceding experiments, in order to enhance the probability of achieving the objective of a heating.

Four experiments conducted in bunkers (40), in which the amounts of coal varied from 12 to 15 st, more closely resembled the experiments conducted in this study. Twenty-four thermocouples were arranged in the coal in horizontal arrays 0.3 m apart, and tubes were used to collect gas samples from each point. Forced ventilation was not supplied; however, a chimney with damper afforded a variation in the amounts of air entering the coal piles. The coals used were relatively fine (80 pct minus 4 mesh and 13 pct minus 100 mesh). The high temperature attained in the first test was 60° C, and in the third test it was 140° C. In the fourth experiment, 15 st of freshly mined coal (mined on the same morning and placed in the bunker within 6 h from the time of mining) was all less than

1.2 cm in size, but contained less of the fines than was found in the coals from the previous tests. Heating was much more rapid, and in less than 2 months the front board stopping caught fire at the top corner. With the rise in temperature, airflow increased to 69.5 ft³/min. Later, portions of the coal burned. Temperatures were high enough to destroy the thermocouples and cause much additional damage.

The fresh coal and the more uniform size of the coal contributed to the development of combustion, and in this respect, the latter experiment resembles the third experiment in this study. Thus, it is evident that each large-scale test is unique and contributes additional insight into the understanding of the phenomenon of spontaneous combustion.

CONCLUSIONS

A large-scale facility was constructed to study the self-heating of a large coal mass (13 st) under conditions that are found in the gob area of a mine. Three experiments were completed, using high-volatile C bituminous coals that had exhibited high self-heating potentials in laboratory-scale tests. In the first two tests, a sustained self-heating was not achieved, with maximum temperature increases of 6° and 9° C, respectively. In the third test, a thermal runaway developed near the center of the bed, reaching temperatures of 340° C. The results of these experiments showed that the self-heating of a large coal mass depends not just on the reactivity of the coal, but also on the particle size of the coal, the freshness of the coal surfaces, the heat-of-wetting effect, and the availability of O₂ at optimum ventilation rates. These conditions can

occur in gob areas of coal mines, where access is limited or impossible.

An analysis of the gas data showed that during the low-temperature oxidation phase (less than 50° C), the main gases emitted were CH₄ and CO₂, which occur naturally in the coal, and CO resulting from coal oxidation. As thermal runaway developed in the third experiment, the concentrations of CO and CO₂ increased at increased rates, and O₂ concentrations decreased rapidly. As temperatures reached the pyrolysis stage, substantial amounts of CH₄ and H₂ were measured.

Four gas ratios clearly indicated the development of thermal runaway in the third experiment, but only the CO₂-ΔO₂ ratio gave an early warning of the heating in the coalbed.

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