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Detection and Control of Spontaneous Heating in Coal Mine Pillars—A Case Study

By Robert J. Timko and R. Lincoln Derick

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

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ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Metric Units

cm	centimeter	Pa	Pascal
m	meter	pct	percent
m^3/s	cubic meter per second	ppm	part per million
ml	milliliter	$^\circ C$	degree Celsius
mm	millimeter		

U.S. Customary Units

ft	foot	in^3	cubic inch
ft^3/min	cubic foot per minute	in H_2O	inch water gage
in	inch		

Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

Detection and Control of Spontaneous Heating in Coal Mine Pillars-A Case Study

By Robert J. Timko[1] and R. Lincoln Derick[2]

ABSTRACT

This U.S. Bureau of Mines study examined spontaneous heating episodes in coal mine pillars in an active underground coal mine. The information obtained from these incidents was then analyzed to learn which sampling methods provided the earliest indication of pillar heating. The objective of this study was to discover if the location of future events of pillar spontaneous heating could be inferred from the available information.

The spontaneous heating-prone area in this evaluation involved pillars located just inby the mine portals. Several detection methods were used to determine gas levels outside as well as inside the affected pillars.

It was hoped that, by incorporating external and internal sampling methods into an organized program, locations undergoing spontaneous heating could be determined more readily. This study found that by drilling small-diameter boreholes into the pillars, then obtaining gas samples from the affected pillars, the ability to locate early spontaneous heating episodes was improved. However, the ability to accurately predict future spontaneous heating events remains in question.

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INTRODUCTION

Because of previous spontaneous combustion episodes within another Colorado mine operating in the same coal seam as the mine studied, portal pillars at the study site had to be closely monitored for signs of spontaneous heating. The purpose of this study was to document various detection methods and to show that, even when using many of these techniques, results could be difficult to interpret. This work was in support of the U.S. Bureau of Mines (USBM) program to minimize underground fire hazards by employing better ventilation methods.

Spontaneous heating in underground coal mines involves the oxidation of coal deposits. Factors affecting the likelihood of spontaneous heating include coal rank, moisture content, temperature, ventilation, oxygen concentration, particle size, impurities, friability, geological factors, and mining practices (*1-4*).[3]

All coals oxidize to some extent when exposed to the atmosphere. Since oxidation is an exothermic reaction between coal and the oxygen component of the atmosphere, heat is constantly being released. This reaction is directly related to temperature; if the heat released by the oxidation reaction is not dissipated, the temperature of the mass increases. In some reactive coals this oxidation can increase to the point that, if remedial control measures are not instituted, the heating can continue and the temperature will rise at an increasing rate until smoldering combustion occurs.

Mine operators usually know if their coal is prone to spontaneous heating. This understanding may have come from a previous heating discovered in their mine, from heatings in other nearby mines within the same coal seam, or from published USBM research that defines a coal's propensity for self-heating (*5*).

Spontaneous heating typically occurs when the quantity of air passing through the coal is sufficient to support oxidation but is inadequate to carry off the heat produced by the oxidation reaction. Some ways to generate spontaneous heating include; continuing to ventilate a heating-prone area once the mining cycle is completed, air leaking around poorly built seals, or by permitting pressure differentials across weathered or previously oxidized pillars.

If spontaneous heating is permitted to continue until smoldering combustion, it is often necessary to seal a large volume underground to control the fire. This can be an expensive decision, not only because of the loss of valuable coal reserves, but also because sealing is typically an expedited process. This usually means that all coal extraction and haulage machinery remain within the sealed volume.

When coal is prone to spontaneous heating, a problem can arise within pillars that remain after the mining cycle has been completed. This is especially true in main or submain entries where large quantities of ventilation air continually flow. Differential pressures exist across the pillars as well as across any structures, such as stoppings, that are used to separate entries. These pressure differences tend to induce air leakage not only through stoppings but also through the pillars themselves. Under certain conditions, this airflow can generate spontaneous heating within the pillar. The volume of air flowing past a pillar in a main or submain entry is sufficient to dilute combustion products being emitted. Thus, spontaneous heating in a main or submain entry pillar is more likely to continue undiscovered. At times, a strange odor is detected or "sweating" is seen on cooler surfaces near the heating. However, control procedures are normally begun only after either carbon monoxide (CO) is detected or smoke is observed.

This report is divided into four sections. The first involves an overview of the detection methods used. The second section looks at the discovery and control of the initial pillar heatings. The third studies the long-term evaluation of control method effectiveness. This section includes a description of the boreholes that were drilled into the pillars to obtain additional information on spontaneous heating. The final section documents methods developed to permanently control spontaneous heating within the pillars in question.

SPONTANEOUS HEATING IN A COLORADO COAL MINE

The D seam in Colorado's western slope coal fields is prone to spontaneous heating. Coal from the D seam contains an easily fractured vertical cleat (*6*),[4] which creates a multitude of airflow paths through it. These fractures, and their attendant heatings, are especially

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

[4]Cleat is defined as the main joint in a coal seam along which it breaks most easily. Cleat runs in two directions, along and across the seam.

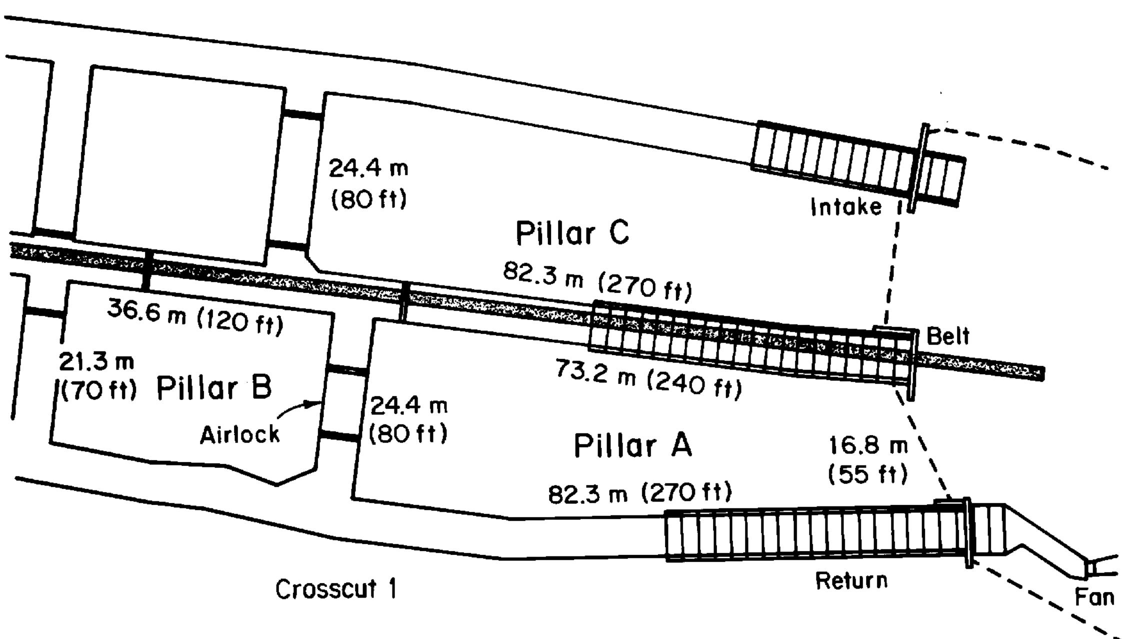
prevalent near outcrops. In this area outcrops are common because of the wide variation in surface elevation. Many of these coal outcrops have spontaneously heated, a reaction that resulted in burned coal from the exposed outcrop to some depth. The coal in these locations has been chemically changed to more closely resemble coke.

This study evaluated diverse sampling methods that were used to monitor pillars prone to spontaneous heating. These techniques were routinely employed by engineers of the Colorado Westmoreland Coal Co., which later became the Cyprus Orchard Valley Coal Co. This company is currently operating the Orchard Valley West Mine, located in the D seam in Colorado's western slope coal region just north of Paonia, CO. Orchard Valley West was developed as a replacement facility for the Orchard Valley East Mine, which was sealed in 1986 after an uncontrolled spontaneous combustion fire. Because of previous pillar spontaneous heating incidents that occurred just inby the East mine portal, three pillars in the Orchard Valley West Mine were of particular interest.

Orchard Valley West is a drift mine having coal extracted by the room-and-pillar method. Coal cleat alignment was offset from initial entry drivage by about 23°. The mine has three parallel entries driven from three separate portals. Average entry height was 2.1 m (7 ft); entry width was 5.5 m (18 ft). The entries consisted of a beltline flanked by an intake and a return entry. When this study began, a vane-axial fan was located at the return-entry portal. It exhausted approximately 80 m^3/s (170,000 ft^3/min). The belt entry was ventilated by low- velocity intake air.

The three pillars examined in this study and their associated dimensions are seen in figure 1. Two pillars, A and B, were located between the belt and the return entries and were subjected to differential pressures of 175 Pa (0.7 in H_2O) across them. Pillar C was separated by intake and belt entries and, since both entries were on intake air, had no measurable differential pressure across it.

Figure 1



Plan view of the three pillars evaluated.

SPONTANEOUS HEATING DETECTION METHODS

Previous research studies have shown ways to more closely monitor for spontaneous heating (*7-9*). Six different detection methods were used during this study. These techniques sampled from three specific pillar locations; the atmosphere surrounding the pillars, the pillar surfaces, and within the pillars. Gas detection devices measured emissions from the atmosphere surrounding the pillars as well as from within the pillars. A commercially- available infrared camera was used to survey pillar surfaces for elevated temperatures. Pressure measuring instruments were used to examine the differential pressures obtained from within the pillars. Thermocouples measured pillar internal temperatures.

GAS DETECTION DEVICES

Handheld Instruments

Throughout this evaluation the Industrial Scientific CMX-270 handheld multigas detector was used to measure day-to-day oxygen (O_2), methane, and CO emissions. Gas levels were obtained by moving the instruments along the rib surfaces of the pillars. Of specific interest was CO. When CO was detected, the location was marked with spray paint for future reference.

Gas Chromatograhy

More accurate gas sample results were obtained by gas chromatography in conjunction with handheld observations. Researchers were particularly interested in CO and O_2 levels. These were considered important indicators in the progression of spontaneous heating.

Chromatographic samples were obtained by inserting a 96%-air-evacuated, 20-ml (1.22-in^3) Vacutainer test tube into a plastic plunger. This assembly was similar to a device used to extract blood for clinical testing. Inside the plunger was a hypodermic needle. This needle punctured a rubber bladder at one end of the test tube, causing a sample of gas to enter the test tube. Pulling the test tube from the plunger resealed the rubber bladder and prevented the gas sample from escaping or being contaminated. Each test tube was returned to the laboratory where gas concentrations were determined through electron-capture analysis.

Gas chromatographic analysis was considered the most accurate method for determining the various gaseous components. However, because of the appreciable time delay that occurred between gas sample capture and analysis, initially gas chromatography was primarily used to confirm or challenge the results obtained with handheld instruments. Only after researchers were sure that the sample turnaround time was adequate to provide sufficient warning of spontaneous heating did they consider gas chromatography a viable day-to-day technique for data collection.

Minewide Monitor

A minewide CO monitoring system with attendant surface-located computer peripherals was in operation. To permit pillar emission sampling prior to the gas being diluted in the mine ventilation airstream, the sensors were located between the pillar ribs and isolation curtains that were hung from roof to floor around pillars A and B. While these instruments did detect CO emissions from the pillar, their results provided only an indication that spontaneous heating was taking place somewhere within the pillar and did little to assist in locating the spontaneous heating episode. Because of this drawback, minewide monitors were used only as backup devices.

ATMOSPHERIC STATUS EQUATIONS

Two equations were used to monitor the status of the atmosphere outside as well as within the pillars. The variables for these equations were obtained through chromatographic analyses of gas samples. Graham's Index (*10*) is also called the index of carbon monoxide (ICO). The ICO is a dimensionless number and is temperature dependent (its value rises with increasing temperature). It makes two assumptions: any CO detected is fire generated, and the oxygen-to-inert-gas (nitrogen [N_2] plus argon [Ar]) ratio is 0.265, indicating that the available air is from a normal atmosphere. The equation is:

$$ICO = (CO \times 100)/(\{0.265 \times [N_2 + Ar]\} - O_2),$$

where CO = carbon monoxide, in pct,

and $(0.265 \times [N_2 + Ar]) - O_2$

= oxygen deficiency, in pct.

Mitchell (*11*) states that the CO-CO_2 ratio is an excellent tool for determining changing atmospheric status. While individually these gases can be affected by dilution, their dimensionless ratio is not. Mitchell also contends that flaming combustion can be expected when CO-CO_2 values approach 0.5.[5]

[5]Lecture on Mine Fires presented by D. W. Mitchell at BethEnergy Mining Company, Eighty Four, PA, 1989.

ICO and CO-O_2 values were meaningful only when they were used to develop a trend; individually these numbers were worthless. A rule of thumb states that, if three successive samples indicate a rise in either the ICO or CO-CO_2 ratio, the sampling frequency should be increased.

SURFACE TEMPERATURE DETECTION DEVICE

The surfaces of pillars A, B, and C were routinely scanned with a Hughes Probeye infrared camera to locate elevated temperatures. This device was traversed across the coal surface and displayed the temperature as one of 10 different hues of a single color. The camera was calibrated so that the brightest hue corresponded with skin temperature (about 34 °C). Since the Orchard Valley West Mine was on exhausting ventilation, scanning initially was performed primarily on the return sides of pillars A and B.

PRESSURE AND TEMPERATURE MONITORING DEVICES

To obtain information from within each pillar, several small-diameter boreholes were drilled into pillars A, B, and C. A small-diameter copper sampling line was then placed within each borehole. This line provided a means for obtaining gas samples and enabled researchers to measure the pressure differential between the far end of the borehole and the entry from which the borehole was driven. A Magnehelic-type pressure measuring instrument assessed pressures at the various boreholes.

A thermocouple was installed inside each borehole. If the area near a borehole undergoes spontaneous heating, thermal conduction should cause the temperature within the borehole to rise. Any temperature increase should be accompanied by a corresponding rise in CO at the same location.

PILLAR SPONTANEOUS HEATING AND CONTROL

During a routine survey with the infrared camera, elevated surface temperatures were discovered along the pillar A rib in the crosscut 1 airlock (figure 2). Further investigations found heatings within the airlock along pillars A and B. A Magnehelic-type device found that pressure fell 175 Pa (0.7 in H_2O) from the belt side to the return side of the crosscut 1 airlock. Since air was flowing through the pillar and then into the airlock, the pillar A heating could have occurred anywhere along a line roughly paralleling the coal cleat between the belt-entry pillar rib and the crosscut 1 rib. Conversely, the heating along the pillar B rib had to be near the surface because air was flowing into the pillar at that location.

A CO sensor was positioned inside the airlock on the pillar A rib and connected to the minewide monitor. A brattice curtain was hung within the airlock along the pil-lar A rib to isolate the CO sensor from the remainder of the airlock volume. This curtain was located about 1 m (3.3 ft) away from and parallel to the pillar A rib, effectively isolating the rib. CO levels in the airlock behind the curtain stabilized at about 26 ppm.

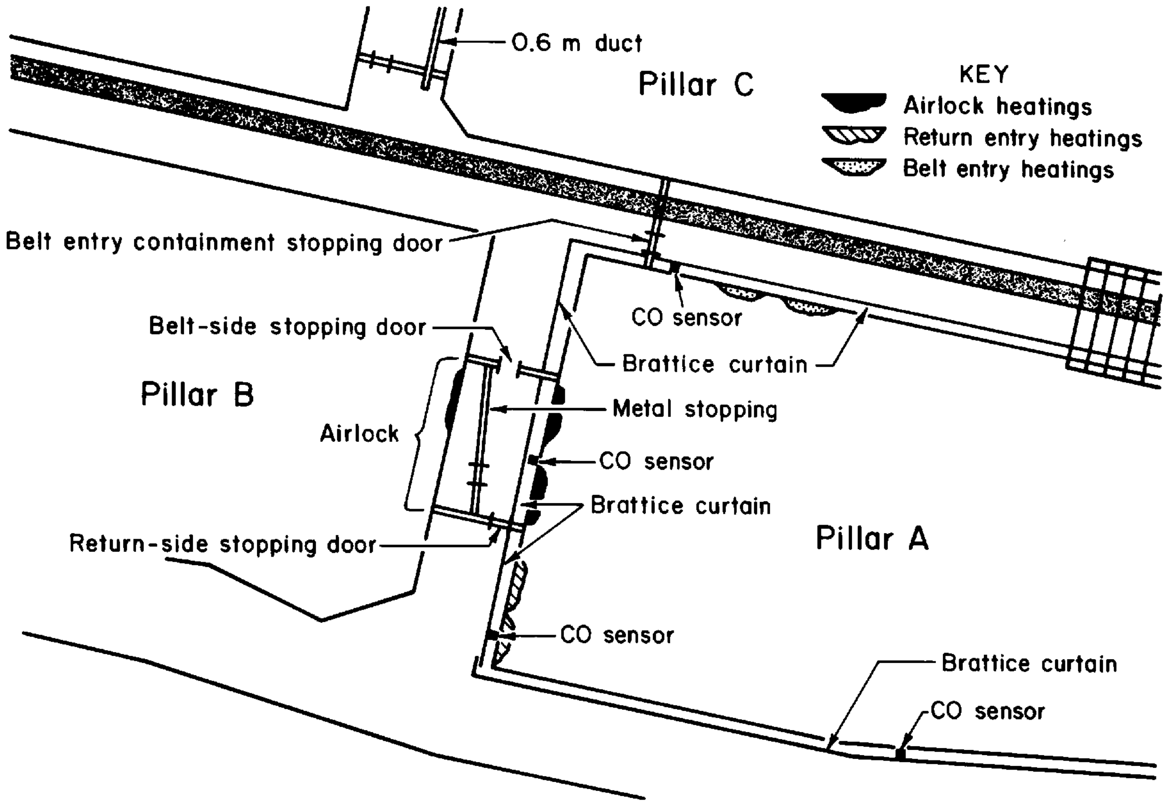
An attempt was made to reduce airflow through pillar A. The doors in the airlock belt-side stopping and the belt-entry containment stopping were opened to provide a low-resistance flow path between the belt and the airlock return-side stopping. A 0.6-m (2-ft) diameter duct was opened in crosscut 1 between the belt and the intake entries, which effectively balanced ventilation pressure between the belt and the intake entries. The belt-to-return pressure differential was now across the crosscut 1 airlock return-side stopping. These changes increased the flow path distance, raised the resistance, and reduced the potential for air flow through pillar A. CO levels within the airlock stabilized at about 10 ppm.

As previously mentioned, the infrared camera also found elevated surface temperatures inside the airlock along the pillar B rib. When the belt-side door of the crosscut 1 airlock was opened, as described above, the flow path distance through pillar B was reduced considerably. To limit air flow, and thus the likelihood of spontaneous heating, a metal stopping was built along the pillar B rib extending from the belt-side stopping to the return-side stopping. Air could then enter pillar B only upstream of the belt-side stopping. This additional flow distance reduced the potential for air to flow through the pillar, making spontaneous heating less likely.

The infrared camera was used at regular intervals to scan both the belt- and return-entry surfaces of pillar A, the crosscut 1 airlock, and the return-entry surfaces of pillar B in the vicinity of the airlock. Although no evidence of additional heating was found within the airlock or along pillar B, two hot spots were found in pillar A between the return-side stopping of the crosscut 1 airlock and the return entry. A follow-up survey with a handheld detector found CO emissions in excess of 200 ppm. It became apparent that the increased resistance through pillar A did not eliminate the potential for spontaneous heating but simply moved it.

To obtain CO emissions from heating in the new pillar A before they became diluted by the high-volume return air, a brattice curtain was hung between the return-side airlock stopping in crosscut 1 and the return entry. This curtain was parallel to and about 1 m (3.3 ft) from the pillar A rib. A CO sensor, connected to the minewide system, was then positioned

Figure 2



Detection of spontaneous heating episodes and resulting control measures implemented.

between the curtain and the pillar rib. Because of excessive condensation within the enclosed volume, this sensor malfunctioned a few days after installation. To overcome this problem, the instrument was disconnected and removed between sample periods.

The effects of changing door positions on crosscut 1 CO emissions were determined by alternately opening and closing the belt-side and return-side airlock doors. With the airlock belt-side stopping door open and the return-side stopping door closed, the handheld CO levels were 10 ppm inside the airlock and 12 ppm in the return. The belt-side stopping door was then closed and the return-side door opened. Handheld CO values rose to 17 ppm in the airlock and 30 ppm in the return. Both the airlock belt-side and return-side stopping doors were then closed to maximize resistance through the airlock. CO levels at the air-lock and in the return increased to about 30 ppm. The belt-side stopping door was then reopened and stayed in this position for the remainder of the study. CO levels then returned to their original values.

An attempt was made to isolate pillar A from the ventilation pressures thought responsible for the elevated CO within crosscut 1. A floor-to-roof brattice curtain was hung in the belt entry from the portal to the containment stopping. A second curtain was hung between the containment stopping and the airlock. A third brattice curtain was suspended from the return-side stopping of the crosscut 1 airlock to just inby the fan in the return portal. These three curtains effectively enclosed pillar A.

To monitor the status within the curtained-off volume, CO sensors were installed between the curtains and pillar A. One CO sensor was placed in the belt entry just outby the containment stopping. A second CO sensor was located within the return enclosure. Both the curtains and the CO sensors remained in place for the remainder of the study.

During a routine survey shortly after the curtains surrounding pillar A were erected, the infrared camera found two heatings between the portal and the containment stopping in the belt-entry enclosed volume. Since these heatings were on the intake side of pillar A (similar to that found in the crosscut 1 airlock at pillar B) they were expected to be just beneath the surface. After a small amount of coal rib was removed from the pillars, the heatings were found. They were extinguished by digging out the smoldering material and then flushing the areas with water.

LONG-TERM PILLAR SPONTANEOUS HEATING DETECTION

Mine officials believed the survival of this mine hinged on the ability to rapidly detect, locate, and extinguish every pillar spontaneous heating episode. Following the initial heatings in pillars A and B and the subsequent ventilation changes made to control these heatings, a long-term study of the atmospheres both outside and inside pillars A, B, and C was begun.

MONITORING OUTSIDE THE PILLARS

Gas samples were obtained at regular intervals from the curtained-off atmospheres in both the crosscut 1 airlock and the crosscut 1 return location. Results of all sampling locations are presented in four specific graphs, including: handheld results, CO and O_2 data derived through gas chromatography, the ICO, and the CO-CO_2 ratio.

Crosscut 1 Airlock

As previously described, elevated surface temperatures within the crosscut 1 airlock were initially found with the infrared camera. To obtain additional information, two gas sampling positions were established within the curtained-off volume in the airlock near the airlock return-side stopping and were labelled "high" and "low." High samples were obtained from the coal rib surface about 1.8 m (6 ft) above the floor. Low samples were obtained from the coal rib about 0.3 m (1 ft) above the floor.

Handheld CO values are shown in figure 3*A*. Even though these results remained relatively stable throughout the evaluation, the presence of CO in the atmosphere indicated that some level of oxidation was taking place within pillar A and was being vented to the atmosphere in the airlock.

Gas chromatographic analyses of airlock samples (figure 3*B*) found CO in conjunction with below-ambient oxygen concentrations (less than 20.94 pct O_2), indicating that oxygen was being consumed by the oxidation reaction. ICO and CO-CO_2 results at both the high and low sampling locations (figures 3*C* and 3*D*) remained stable with the exception of the large fluctuations in September.

Crosscut 1 Return

Two specific positions along the pillar A rib between the airlock return-side stopping and the return entry were analyzed. These positions were labelled "left" and "right."

Handheld results (figure 4*A*) showed that CO values at the right location were consistently higher. Chromatographic results (figure 4*B*) paralleled those CO values found with the handheld instruments. Depleted oxygen levels reinforced the theory that oxidation was taking place somewhere in pillar A. Conversely, both ICO and CO-CO_2 results (figures 4*C* and 4*D*) gave no indication that the oxidation reaction was accelerating in the vicinity of these locations.

MONITORING INSIDE THE PILLARS

Infrared scanning of pillar surfaces and gas sampling of the atmosphere surrounding the pillar did not provide sufficient information to permit an accurate prediction of future spontaneous heating events. Since additional heatings were likely to occur within pillar A, a decision was made to test-drill two small-diameter boreholes into the pillar, sample the atmospheres within these holes, and determine whether this information could more accurately predict future heatings.

Boreholes *1-1* and *1-2*

Two, 3.8-cm (1.5-in) outside diameter (OD) boreholes, designated boreholes *1-1* and *1-2*, were drilled into pillar A from the belt entry toward the return at roughly right angles to the coal cleat (figure 5). Each borehole was approximately 3.7 m (12 ft) deep. A 9.5-mm (0.375-in) OD copper tube was extended to the back of each borehole. The outby end of the borehole was then sealed with a urethane foam plug.

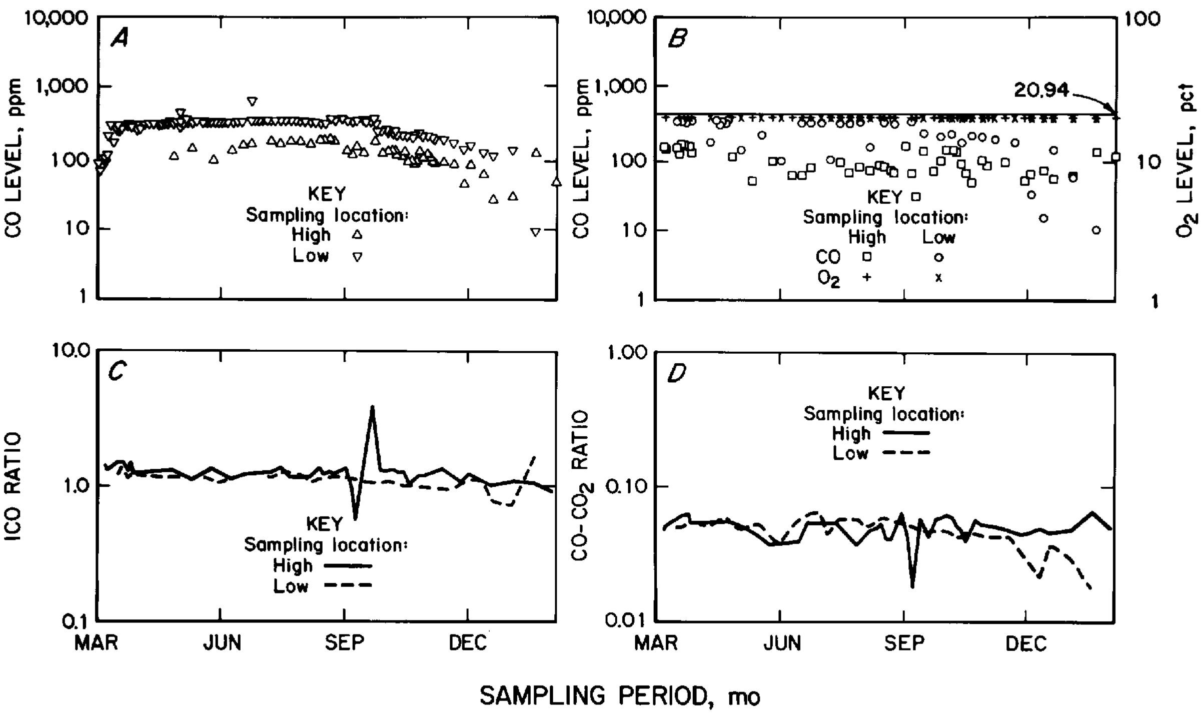
Air samples were taken from the two boreholes. Initial gas chromatographic results showed borehole *1-1* with 7 ppm CO and 20.4 pct O_2 while borehole *1-2* had 23 ppm CO and 20.3 pct O_2. This preliminary data indicated one of two things: (1) the atmosphere in this pillar was stable (oxidation was being controlled), or (2) the sample location was upstream of any spontaneous heating activity. Clearly, these introductory results did not provide the additional information expected.

Long-term handheld samples from each 3.7-m (12-ft) borehole are seen in figure 6*A*. Values at borehole *1-2* remained stable while those at borehole *1-1* showed three specific rises, one near the end of May, a second in October, and a third in December. The reason for these fluctuations was unknown.

Gas chromatographic analyses (figure 6*B*) show that O_2 concentrations remained at ambient levels while CO values rose slightly until about the midpoint of the evaluation, then gradually decreased.

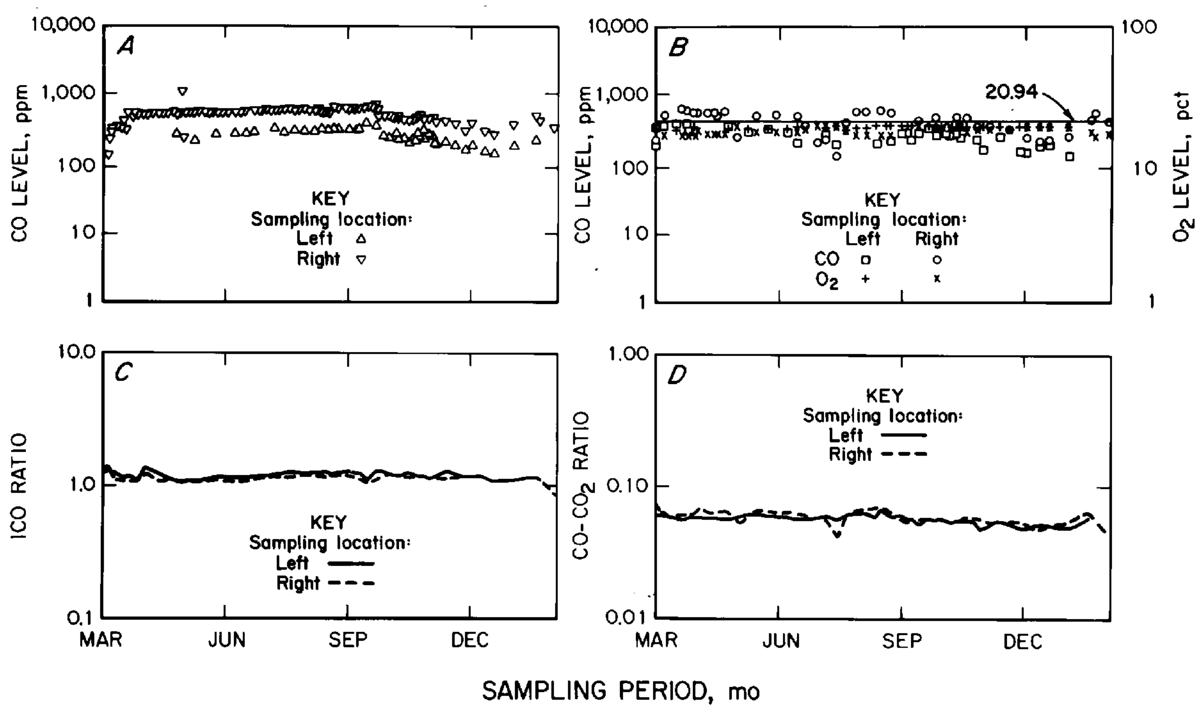
The ICO and CO-CO_2 ratios at both boreholes (fig-ures 6*C* and 6*D*) fluctuated wildly. Had the ICO been the only sampling method used to monitor for spontaneous heating, the fluctuations would probably have kept officials on constant alert throughout the study. The CO-CO_2 ratio was less than the atmospheric samples taken at the airlock or return locations and was indicative of a stable atmosphere.

Figure 3



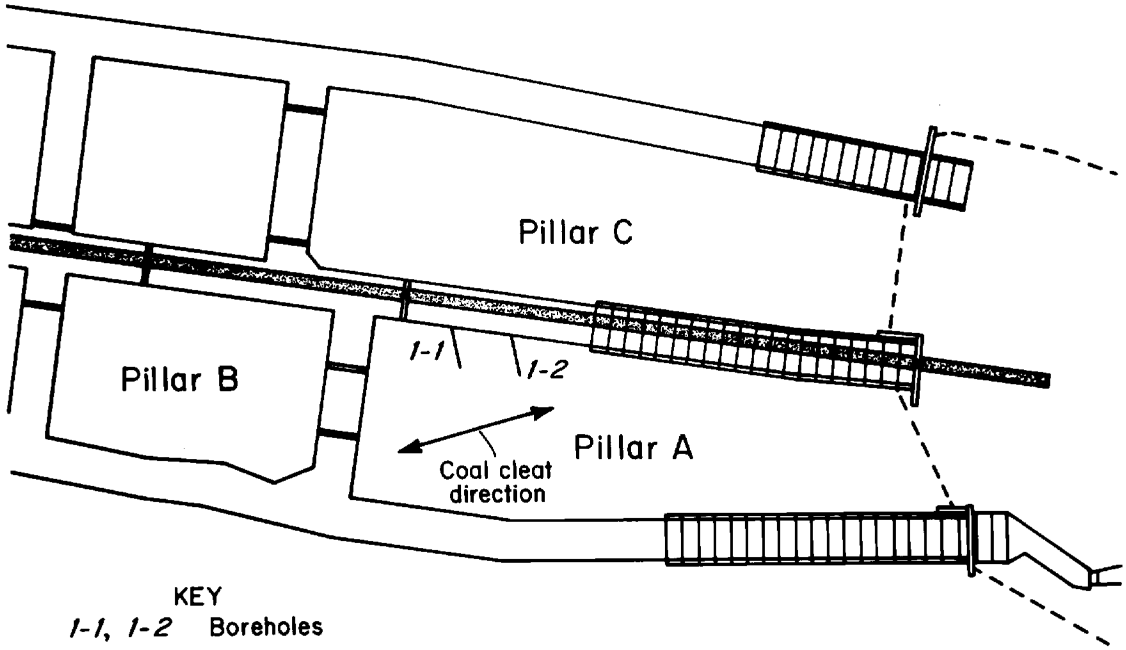
Crosscut 1 airlock. A, Handheld results; B, gas chromatography data; C, ICO; and D, CO-CO₂ ratio.

Figure 4



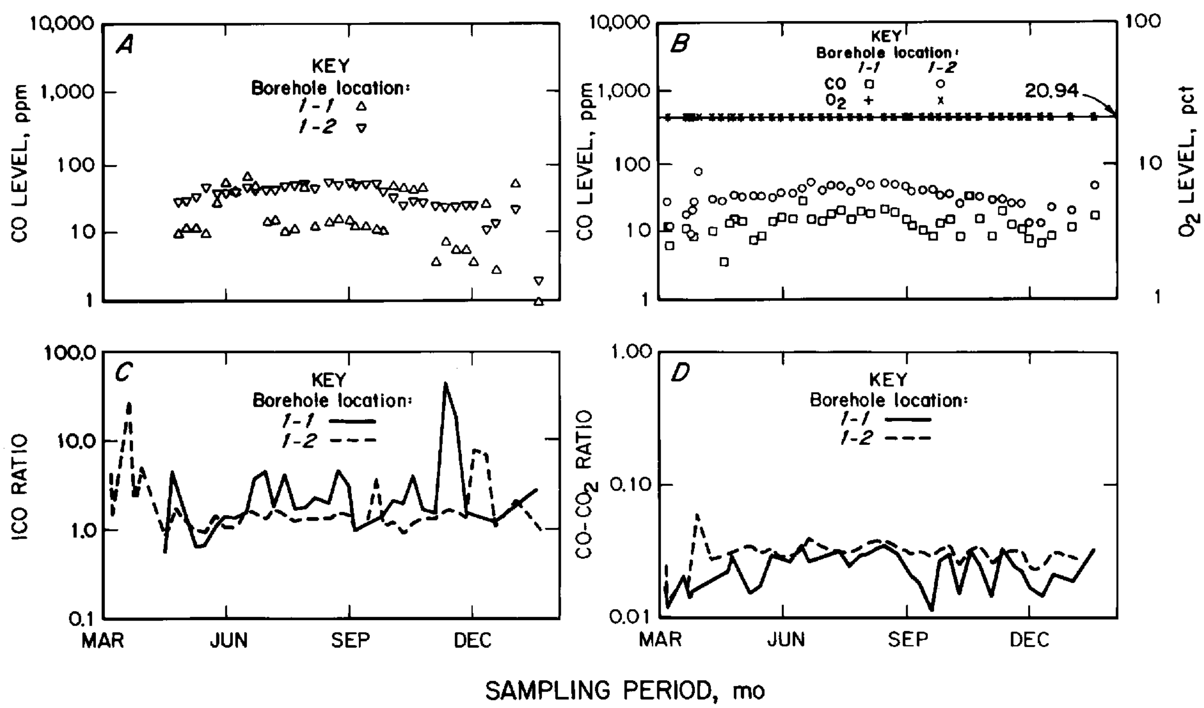
Crosscut 1 return. A, Handheld results; B, gas chromatography data; C, ICO; and D, CO-CO₂ ratio.

Figure 5



Locations of prototype 3.7-m boreholes.

Figure 6



3.7-m boreholes. A, Handheld results; B, gas chromatography data; C, ICO; and D, CO-CO_2 ratio.

Boreholes *2-1* through *2-7*

A more comprehensive pillar sampling strategy was developed. Seven 3.8-cm (1.5-in) OD boreholes were drilled into pillars A, B, and C (figure 7). Boreholes *2-1*, *2-5*, *2-6*, and *2-7* were drilled into pillar A; borehole *2-2* was drilled into pillar B; and boreholes *2-3* and *2-4* were drilled into pillar C. As with boreholes *1-1* and *1-2*, these seven were aligned at right angles to the coal cleat. All holes were drilled horizontally except borehole *2-5*, which was angled downward, projecting into the coal seam immediately beneath the D seam.

A 0.95-cm (0.375-in) OD gas-sampling line was extended to the back of each borehole. Gas samples obtained from the back or far end of each hole were called "inby" samples. A second 0.95-cm (0.375-in) OD line stopped just inside the borehole opening. Results from these locations were referred to as "outby." The end of each hole was then sealed with a urethane foam plug.

Borehole *2-1* was 21.3 m (70 ft) deep. The inby end of this hole was in close proximity to the belt entry. Handheld results (figure 8*A*) showed that CO levels at the inby sampling location resembled those values at borehole *1-2* while the outby sampling location was consistently higher, by about a factor of 20.

Results obtained through gas chromatography (figure 8*B*) resembled handheld samples. Again, a measurable difference existed in CO levels between inby and outby sampling positions. Values of O_2 at the inby position were slightly depleted, while those at the outby position were well below ambient. These results supported the premise that ambient air was flowing parallel to the coal cleat and O_2 was being consumed as it flowed through the pillar.

ICO and CO-CO_2 trends paralleled each other throughout this study (figures 8*C* and 8*D*). The increase near the end of the study was probably due to efforts performed in response to a spontaneous combustion episode that occurred in pillar A at borehole *2-6*.

Borehole *2-2*, 19.5 m (64 ft) deep, was the only hole drilled in pillar B. This borehole was created to determine if air was flowing through the pillar. Handheld results at both inby and outby sampling positions (figure 9*A*) showed appreciable fluctuation throughout the study. These data provided little information relative to the identification or location of spontaneous heating in pillar B.

Throughout the study, gas chromatographic CO values from borehole *2-2* averaged about 1,000 ppm at inby and outby locations (figure 9*B*). While O_2 levels at both locations were initially depressed, they appeared to rise slowly throughout the study. These results tend to show that oxidation was taking place.

The ICO ratio appeared stable (figure 9*C*). The CO-CO_2 ratio (figure 9*D*) slowly increased throughout the study, signifying that some level of spontaneous heating was taking place. Comparing the CO-CO_2 ratio, the ICO, the raw CO and O_2 data, and the pressure differential across pillar B tended to reinforce the belief that the heating would not accelerate.

Borehole *2-3*, drilled into pillar C, was 13.7 m (45 ft) deep. Pillar C was located between the intake and belt entries and had no measurable pressure differential across it. This resulted in no airflow through the pillar. It was therefore presumed that gas sampling results from within pillar C would model normal coal oxidation rates within all pillars. Measurable CO values were predicted however, because no air was flowing through pillar C, O_2 was expected to be depleted.

Handheld results (figure 10*A*) showed that CO levels remained elevated and stable throughout the evaluation, with both inby and outby locations having similar results. Gas chromatographic data (figure 10*B*) found that inby and outby CO values paralleled the handheld results. Levels of O_2 remained below ambient; there was no explanation for the fluctuations.

ICO and CO-CO_2 results (figures 10*C* and 10*D*) remained stable and below values found at the other test hole locations. These results were believed to be a signature of normal oxidation within coal pillars having no differential pressure, and thus no appreciable airflow, through them.

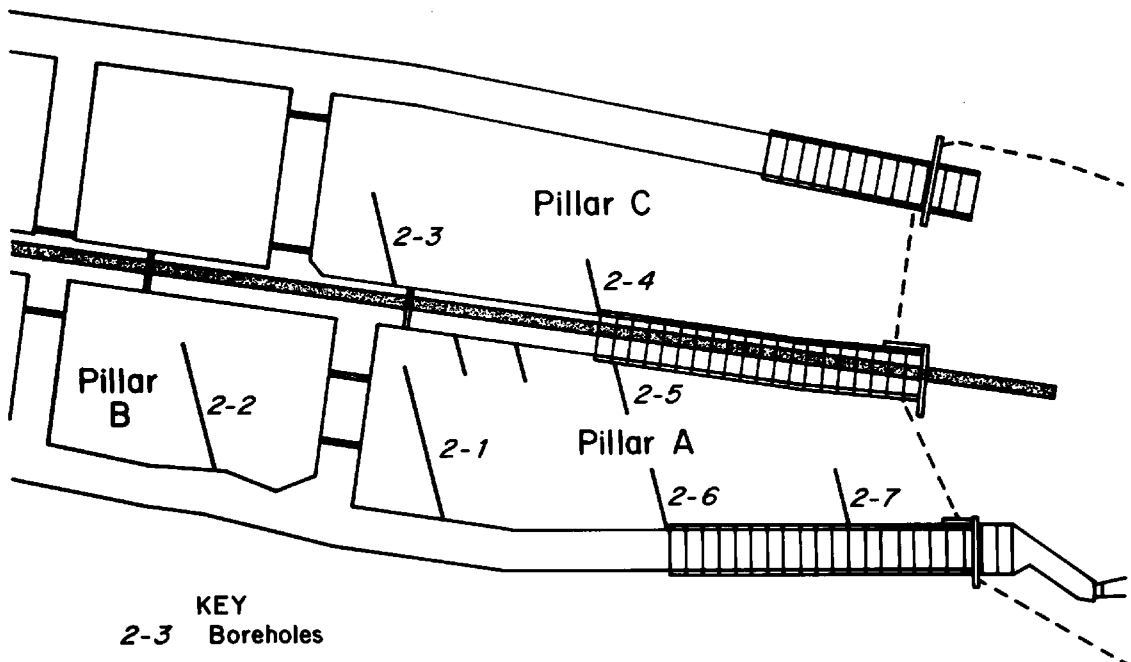
A second borehole, designated test hole *2-4*, was drilled into pillar C. This borehole was 9.1 m (30 ft) deep. Handheld CO values (figure 11*A*) and gas chromatographic results (figure 11*B*) from both the inby and outby sampling positions correlated well with each other and with those values found at test hole *2-3*. Based on comparative results between boreholes *2-3* and *2-4*, internal pillar CO values near 1,000 ppm as well as O_2 levels of about 10 pct were considered indicative of the oxidation rate in the D seam.

ICO and CO-CO_2 results from test hole *2-4* (figures 11*C* and 11*D*) were more similar to borehole *2-1* data than to borehole *2-3*. This apparent inconsistency was probably caused by the proximity of test hole *2-4* to the coal burn line.

Borehole *2-5*, 9.1 m (30 ft) deep, was angled downward into the coal seam immediately below the D seam to obtain gas samples from that seam. Figure 12*A* shows that once the concentrations stabilized, handheld results remained essentially unchanged until about a month before the end of the study. Changes in CO values were due to efforts by mine personnel to extinguish a pillar fire that was discovered in the belt entry just outby the borehole.

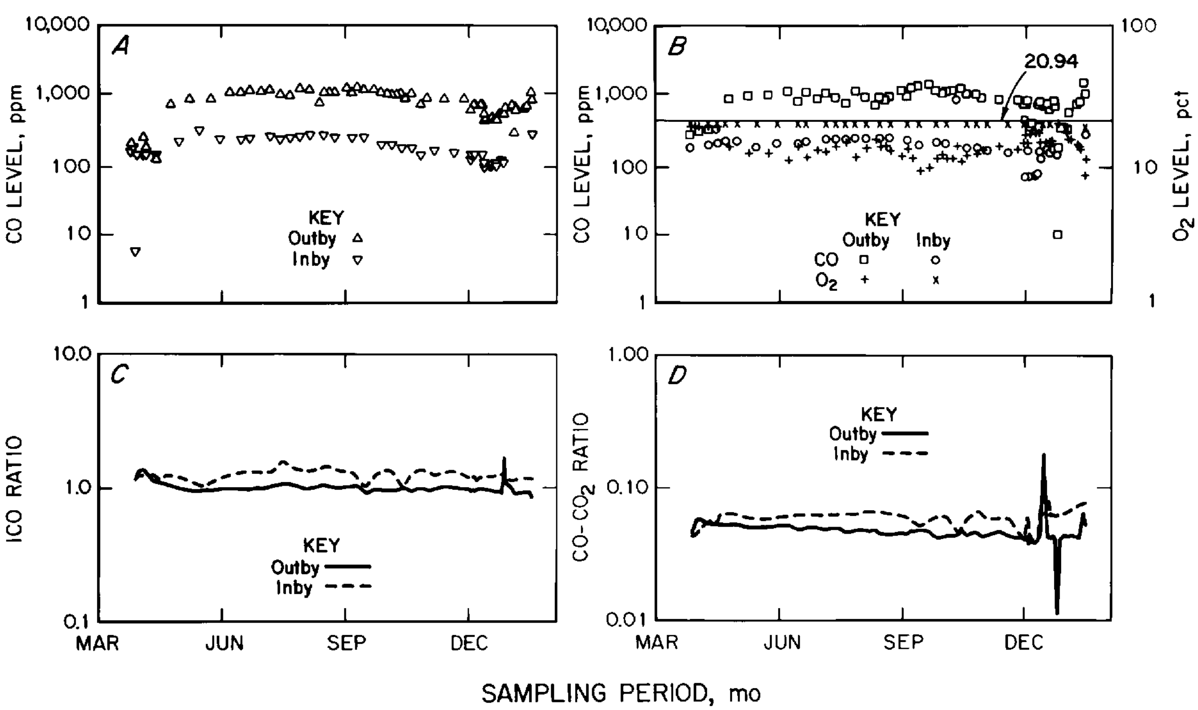
Chromatographic CO values (figure 12*B*) closely paralleled handheld concentrations. The O_2 levels at both the inby and outby positions remained close to ambient. ICO and CO-CO_2 results (figures 12*C* and 12*D*) were unchanged until the fire. The only indication of fire at borehole *2-5* was a slight increase in the ICO and a corresponding decrease in CO-CO_2. The fluctuations that followed the initial changes were believed

Figure 7



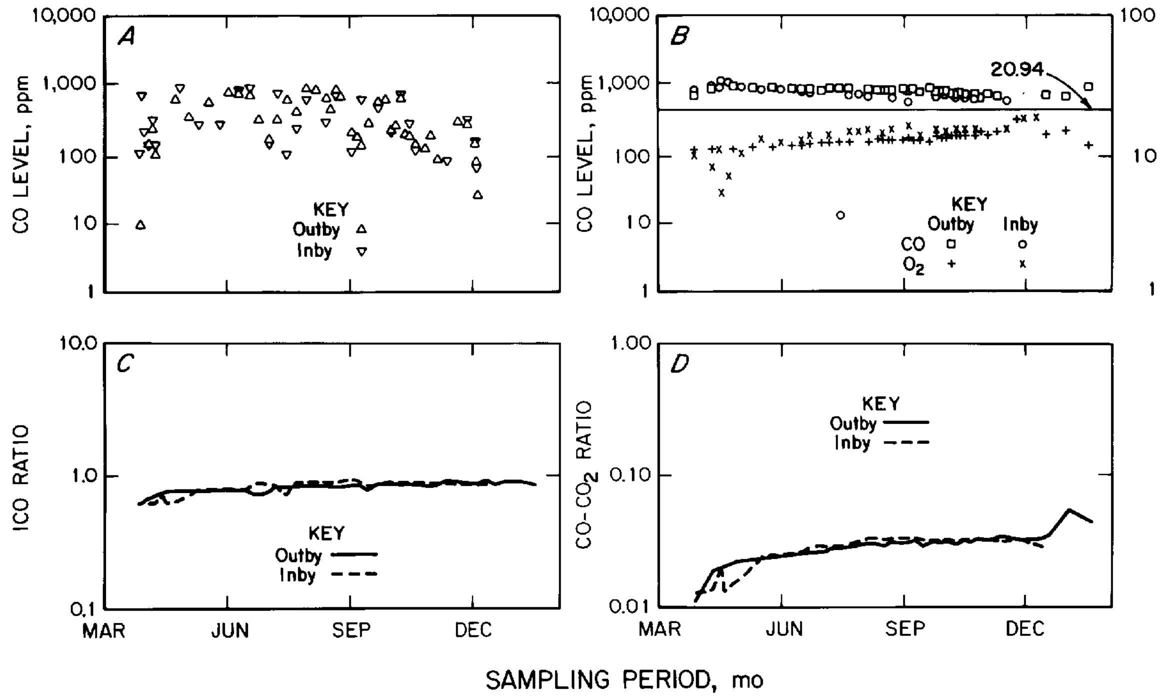
Locations of pillar boreholes.

Figure 8



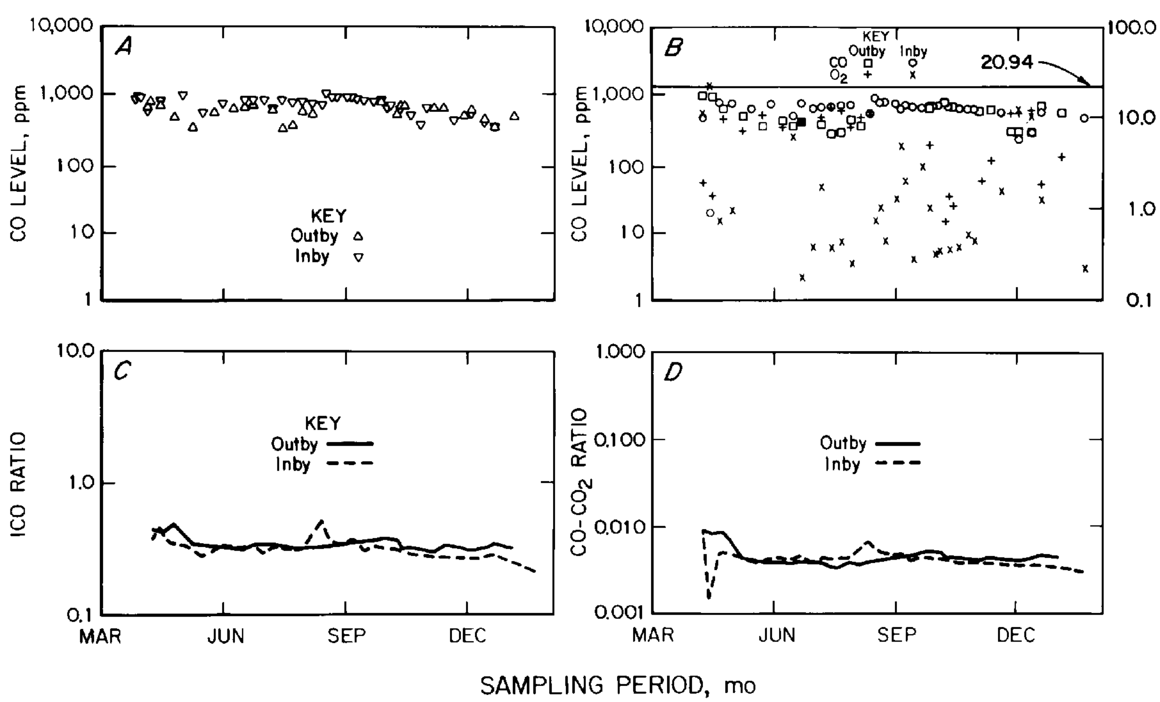
Borehole 2-1. A, Handheld results; B, gas chromatography data; C, ICO; and D, CO-CO_2 ratio.

Figure 9



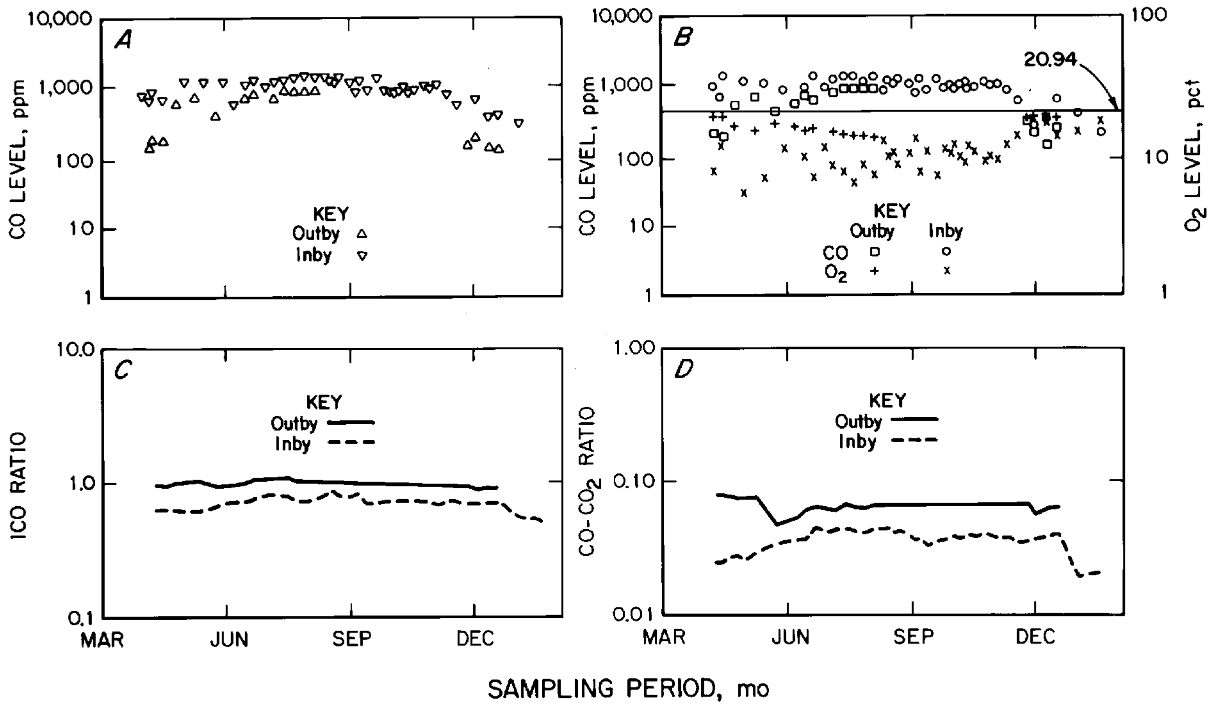
Borehole 2-2. A, Handheld results; B, gas chromatography data; C, ICO; and D, CO-CO_2 ratio.

Figure 10



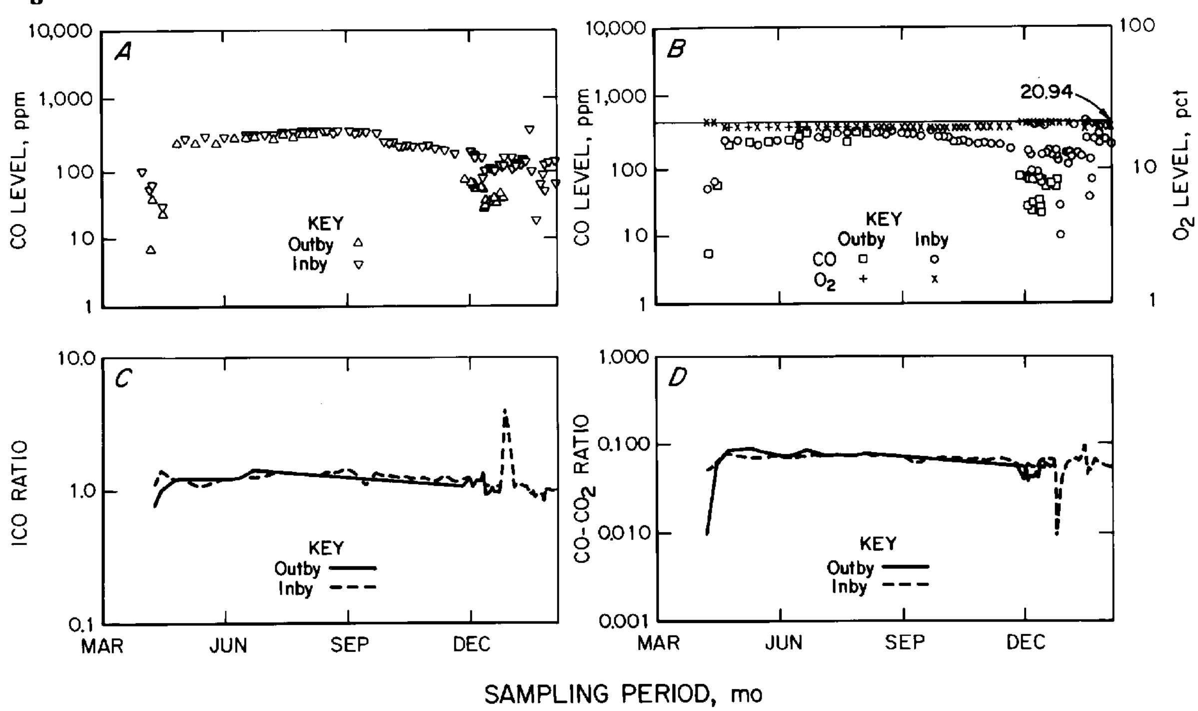
Borehole 2-3. A, Handheld results; B, gas chromatography data; C, ICO; and D, CO-CO_2 ratio.

Figure 11



Borehole 2-4. A, Handheld results; B, gas chromatography data; C, ICO; and D, $CO-CO_2$ ratio.

Figure 12



Borehole 2-5. A, Handheld results; B, gas chromatography data; C, ICO; and D, $CO-CO_2$ ratio.

to be caused by efforts to control the fire, rather than being indicative of the fire itself.

Borehole *2-6* was 9.1 m (30 ft) deep. Handheld results (figure 13*A*) from this hole fluctuated throughout the test. Chromatographic analyses (figure 13*B*) of CO slowly increased while O_2 decreased until the oxidation reaction markedly accelerated. The sampling frequency was then increased to provide additional data. The trend of subsequent samples was toward increased oxidation. ICO and $CO\text{-}CO_2$ data (figures 13*C* and 13*D*) also displayed marked increases in conjunction with other sampling results.

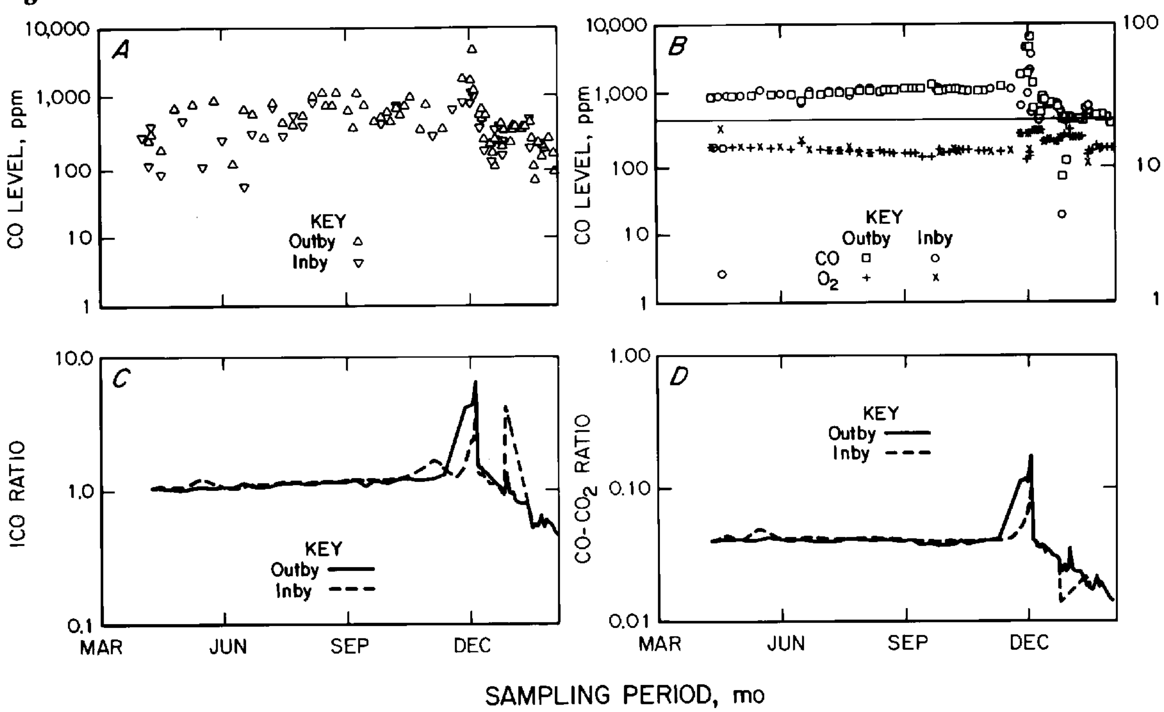
As the trend began to change, a thorough investigation of pillar A was performed with the infrared camera. An area of glowing coal was discovered behind the tunnel liner in the pillar A rib, upstream of borehole *2-6* and between the borehole and the mine portal. The burn zone extended into the pillar rib about 0.3 m (1 ft). It was extinguished by extracting the burning coal and saturating it and the remaining in situ pillar coal with water.

The following day, more smoke and glowing coal were discovered in the belt entry behind the tunnel liner, just outby the previous event. This fire was also extinguished by removing the burning material and flooding the area with water.

Borehole *2-7* was 9.1 m (30 ft) deep. Inby and outby values of handheld CO (figure 14*A*) were less than those levels found at the other holes. Chromatographic CO samples (figure 14*B*), while exhibiting a very gradual increase over time, were below the values found at all other locations. The O_2 values were unchanged but slightly below ambient throughout the study.

ICO and $CO\text{-}CO_2$ results exhibited a continual increase (figures 14*C* and 14*D*) even though they were below values found at other locations. If an increasing trend alone was regarded as a predictor of spontaneous heating, looking at this data could lead one to infer that a heating was taking place upstream of borehole *2-7* in pillar A even though no heating was ever located. These indications could have been from the pillar A belt-entry fire or from residual heating in the coked material outby the borehole.

Figure 13



Borehole 2-6. A, Handheld results; B, gas chromatography data; C, ICO; and D, $CO\text{-}CO_2$ ratio.

Temperature and Differential Pressure in Test Holes *2-1* through *2-7*

Figure 15*A* shows the borehole internal temperatures. Boreholes were divided into two groups: those having elevated-but-stable temperatures (*2-2, 2-3,* and *2-4*); and those having elevated-and-increasing temperatures (*2-1, 2-5, 2-6,* and *2-7*). Only the pillar A borehole temperatures were both elevated and increasing.

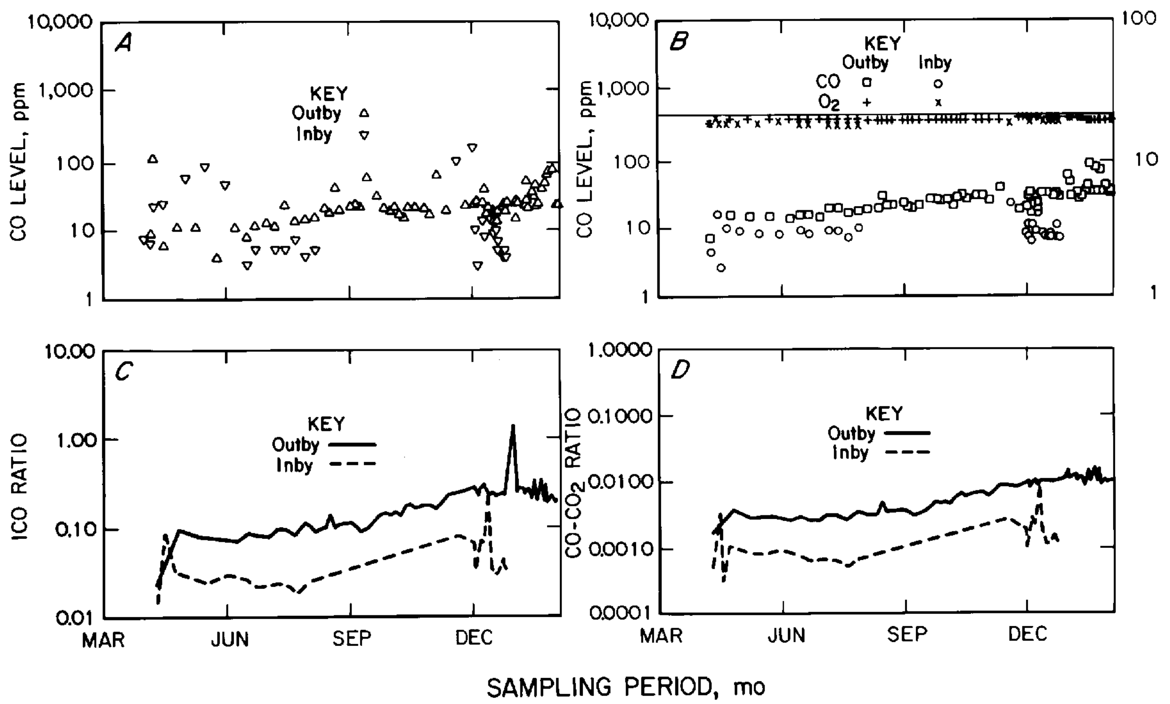
A comparison was made of those locations having elevated-but-stable temperatures with those undergoing increasing temperatures. The temperatures at boreholes *2-5* and *2-6* continually increased over time. Based solely on this information, temperature increases could lead one to conclude that the oxidation reaction was most active in the vicinity of holes *2-5* and *2-6*. The two active fires were located just outby these boreholes.

The results of the pressure measurements are shown in Figure 15*B*. Borehole *2-2,* in pillar B, exhibited only a very small pressure differential across it. Since there was a concentrated effort to balance pressures across pillar C, the pressure differentials within boreholes *2-3* and *2-4* also were minimal.

As expected, pressures differentials were highest across pillar A. Borehole *2-1* was driven so far into the pillar that its inby end was in close proximity to the belt entry. Borehole *2-5* was driven into pillar A from the belt entry, therefore the pressure differentials were negative. Pressures in hole *2-6* remained stable throughout the study. Pressure differentials were greatest at borehole *2-7,* located nearest the fan.

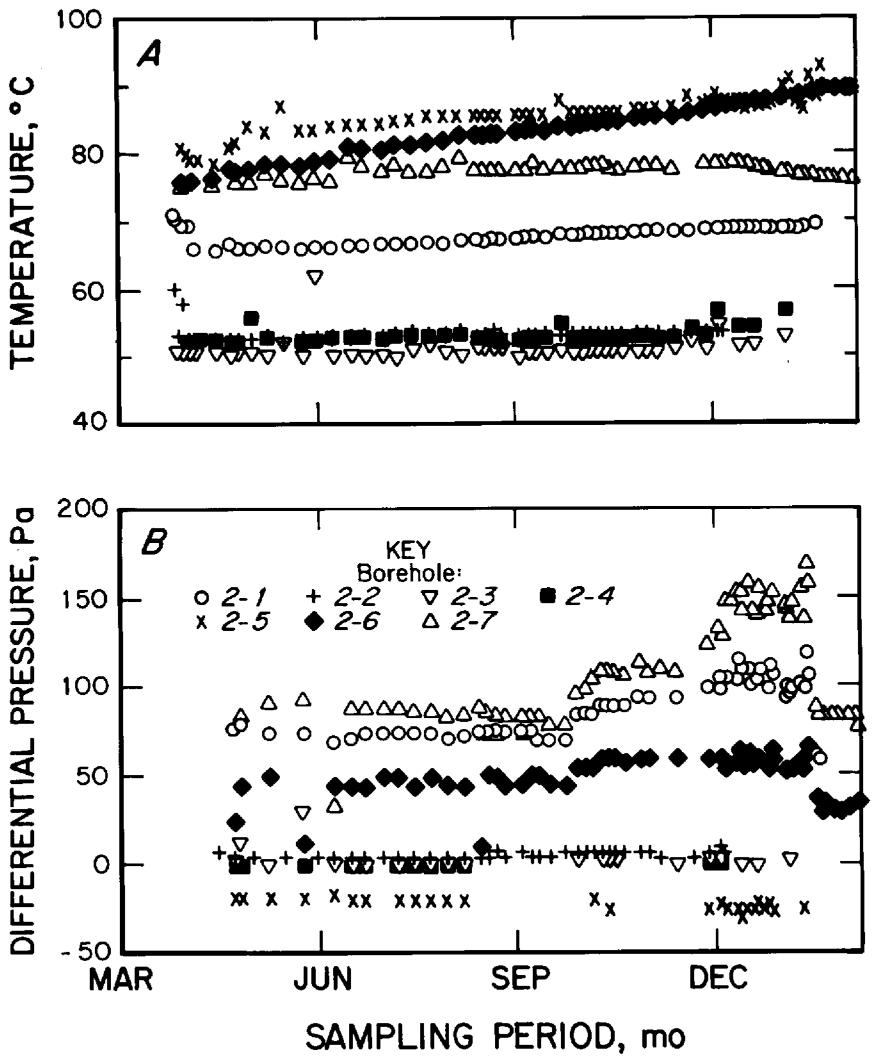
A correlation existed between borehole pressure and temperature. If a pressure differential existed within the hole, that borehole also had elevated and increasing temperatures. Temperature and pressure data reinforced the premise that some level of spontaneous heating was constantly occurring in pillar A.

Figure 14



Borehole 2-7. A, Handheld results; B, gas chromatography data; C, ICO; and D, CO-CO_2 ratio.

Figure 15



Borehole measurements. A, Temperatures; B, pressures.

PERMANENT CONTROL OF PILLAR SPONTANEOUS HEATING

Although the detection methods seemed to be capable of predicting a spontaneous heating, they did nothing to prevent future episodes. Because spontaneous heating was a constant process in pillar A, a permanent solution to the heating problem was needed. In response, two control methods were implemented.

To immediately control spontaneous heating in Pillar A, a solution of magnesium chloride and water was injected into the boreholes. This solution was designed to flow into the numerous fractures within the pillar. As the liquid evaporated, the salt that remained tended to seal many of those fractures. The resulting barrier reduced the potential for air leakage through the pillar.

The second task involved relocating the mine fan. The fan, originally located at the return-entry portal, was moved to a location approximately 150 m (500 ft) away. This location required that a 76-m (250-ft) shaft be vertically driven to intersect a return entry in the coal seam about 370 m (1,200 ft) inside the mine.

Moving the fan enabled the return entry to be converted to a second intake entry, effectively eliminating pressure differentials between the belt and the newly created intake.

Because spontaneous heating in this mine was primari-ly found in the vicinity of the burn line immediately inby the portals, relocating the fan reduced the likelihood of •••••••••• spontaneous heating not only from pillars A and B, but also for the entire mine.

CONCLUSIONS

The purpose of this study was to monitor for spontaneous heating using several different detection methods, to document the accumulated data, and to determine if the results enabled one to predict and locate any zones undergoing spontaneous heating. Six different detection methods were used including: minewide CO monitors; an infrared heat-sensing camera; handheld, real-time CO detection instruments; grab samples analyzed by gas chromatography; pillar internal temperatures; and pillar differential pressures.

Initially, monitoring methods involved evaluating only the surfaces of pillars and the gases being emitted from them. The infrared heat-sensing camera was invaluable in locating heatings that had progressed to the surface of the pillar. Because of differential pressures across the pillars, this device was most valuable in studying conditions on the return side of the pillars. Due to its limitation of surface-only analysis, the infrared camera was not considered a viable stand-alone device for spontaneous heating detection.

Two gas detection methods were used: (1) handheld instruments that were capable of providing real-time CO levels, and (2) gas data derived through chromatography that presented a historical summary of several different gases. To ensure that handheld instruments provided accurate measurements, they were calibrated at regular intervals against known CO standards. As an additional check, the handheld instruments were routinely used in parallel with samples analyzed by gas chromatography, considered the most accurate method of data acquisition. Much of the handheld data closely paralleled gas chromatographic analyses.

Chromatographic analytical efforts concentrated on measuring CO and O_2 levels since these gases were indicative of pillar oxidation. As an additional check, gas chromatographic data were incorporated into two commonly used atmospheric status equations to determine if changes in certain gas concentrations could indicate that spontaneous heating was taking place. The ICO and the CO-CO_2 ratio were referenced as appropriate for monitoring spontaneous heating-prone atmospheres. Even though the trends developed by these equations did visibly change just prior to the fire, it remained questionable whether these equations improved the ability to diagnose a heating, as compared with a direct examination of CO and O_2 levels.

To more closely pinpoint spontaneous heating locations, seven small-diameter boreholes were drilled into three different coal pillars just inby the mine portals. In hole *2-6*, following three consecutive samples with increasing CO concentrations and corresponding decreases in O_2, researchers concluded that the oxidation process was accelerating and increased sampling frequency with handheld instruments and gas chromatography. Shortly thereafter a fire was found just upstream of this borehole.

Pillar temperature data showed the influence of differential pressure on pillar temperatures. Test holes with elevated and increasing temperatures were located in the pillar between the belt and return entries, where differential pressures were greatest. These became the locations thought most likely to be undergoing accelerated oxidation. These assumptions were proven valid when the fire was discovered in the vicinity of the test holes having the highest temperatures.

Pressure measurements were based on the differences in pressure between the pillar and the entry from which the hole was driven. These results were more closely tied to ventilation parameters than to fire potential, but locations that had a greater differential pressure across them tended to exhibit the characteristics of spontaneous heating. A correlation was found between the differential pressures across the pillar and the incidence of active heatings, however this detection method alone was not considered sufficient as an early warning device.

In conclusion, the combination of several different detection methods, in conjunction with pillar boreholes, were important for detecting and locating early episodes of combustion in pillars. Handheld instruments, calibrated at regular intervals, were sufficient for day-to-day monitoring of the boreholes, especially if performed in conjunction with pillar temperature measurements. Gas chromatographic samples can initially be obtained at a reduced frequency, perhaps one sample per week, to generate a reliable baseline. If three consecutive handheld readings detect increasing CO and the corresponding temperatures are rising, handheld measurements and grab samples for gas chromatographic analyses should be performed at more frequent intervals until either CO levels return to baseline values or a heating is confirmed.

While this study was taking place, a fire was detected within a pillar. Changes in handheld gas detection data, pillar temperatures, and gas chromatographic data indicated a fire had occurred. When using a combination of these three detection methods to monitor the status of the atmospheres within these boreholes, the location of spontaneous heating was established.

To prevent future pillar heatings, two permanent controls were developed. First, a temporary control was established by injecting a magnesium chloride solution into the pillar that sealed many of the fractures. Second, the ••••••••••

mine fan was moved from the return-entry portal to a shaft some distance from the portals. This second measure eliminated differential pressures across the portal pillars, effectively eliminating spontaneous heating potential where it was most likely to occur

REFERENCES

1. Feng, K. K., R. N. Chakravorty, and T. S. Cochrane. Spontaneous Combustion - A Coal Mining Hazard. CIM Bull., v. 66, No. 738, 1973, pp. 75-84.
2. Kim, A. G. Laboratory Studies on Spontaneous Heating of Coal: A Summary of Information in the Literature. USBM IC 8756, 1977, 13 pp.
3. Kuchta, J. M., V. R. Rowe, and D. S. Burgess. Spontaneous Combustion Susceptibility of U.S. Coals. USBM RI 8474, 1980, 37 pp.
4. Singh, R. N. A Practical System of Classifying Coal Seams Liable To Spontaneous Combustion. J. Coal Qual., v. 5, No. 3, 1986, pp. 108-113.
5. Smith, A. C., and C. P. Lazzara. Spontaneous Combustion Studies of U.S. Coals. USBM RI 9079, 1987, 29 pp.
6. U.S. Bureau of Mines. A Dictionary of Mining, Mineral, and Related Terms. Spec. Publ., 1968, 1,269 pp.
7. Mitchell, D. W. Spontaneous Combustion. Sec. in Mine Fires. Maclean Hunter Publ. Co., 1990, pp. 27-38.
8. Chamberlain, E. A. C., and D. A. Hall. The Practical Early Detection of Spontaneous Combustion. Colliery Guardian, v. 221, No. 5, 1973, pp. 190-194.
9. Koenning, T. H. Spontaneous Combustion in Coal Mines. Paper in Proceedings of the Fourth U.S. Mine Ventilation Symposium. Berkeley, CA, June 5-7, 1989; SME, 1989, pp. 75-81.
10. Graham, J. I. The Normal Production of Carbon Monoxide in Coal Mines. Trans. Inst. Min. Eng., v. LX, 1920-1921, pp. 222-234.
11. Mitchell, D. W. Recommended Detection. Sec. in Mine Fires. Maclean Hunter Publ. Co., 1990, pp. 29-30.

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