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Mine Fire Diagnostics Applied to the Carbondale, PA, Mine Fire Site

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	hp	horsepower
cm^3	cubic centimeter	in	inch
ft	foot	pct	percent
ft^2	square foot	ppm	part per million

MINE FIRE DIAGNOSTICS APPLIED TO THE CARBONDALE, PA, MINE FIRE SITE

By Ann G. Kim,[1] Thomas R. Justin,[2] and John F. Miller[3]

ABSTRACT

The U.S. Bureau of Mines applied its mine fire diagnostic method to an abandoned anthracite mine fire site in Carbondale, Lackawanna County, PA. The technique to locate fires in abandoned coal mines and coal refuse piles includes the determination of hydrocarbon concentrations in mine gases, the imposition of an underground gas flow direction, and use of a surface mapping method, to define heated and cold zones in underground coal strata. The heated zones at Carbondale were characterized by elevated methane concentrations. The results of 25 communication tests were analyzed to define 2 large (approximately 100 by 250 ft) and 5 small, isolated heated zones. An approximate correlation existed between the location of the heated zones and areas of anomalous snow melt. The correlation between the results of the diagnostic test and subsurface temperatures was not significant.

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INTRODUCTION

Abandoned coal mine and coal refuse fires are a common problem in the coal regions of the United States. Areas where smoke and steam are emitted do not necessarily occur directly above their subsurface origins. Determining the location and extent of these fires can be very difficult. Aerial infrared methods are limited to determining temperature variations within a few inches of the surface, and their interpretation can be complicated by heat-absorbing features on the surface. Temperatures measured at the bottom of boreholes are essentially point-source measurements, and are only accurate for a relatively small volume of the mine atmosphere.

To overcome the problems inherent in locating fires in abandoned mines and waste banks, the U.S. Bureau of Mines is developing a diagnostic methodology that compares borehole measurements of temperature, pressure, combustion products, and desorbed hydrocarbon gases under natural or baseline conditions with values obtained when a suction fan is used to impose an underground pressure gradient (*1*).[4] It is assumed that mine gases tend to flow radially from the surrounding underground areas toward the point at which the suction is applied. Variations in a combustion signature at different points underground are related to the assumed movement of combustion products and heat from the source toward the suction point. Data collected during the mine fire diagnostic study at an abandoned mine site at Renton, PA, have shown that measurable changes in underground pressure occurred at distances up to 700 ft from the point of suction, and that the average distance affected was 250 ft (*3-4*).

An illustration of the diagnostic technique is shown in figure 1. In this figure, heated mine gases are being pulled

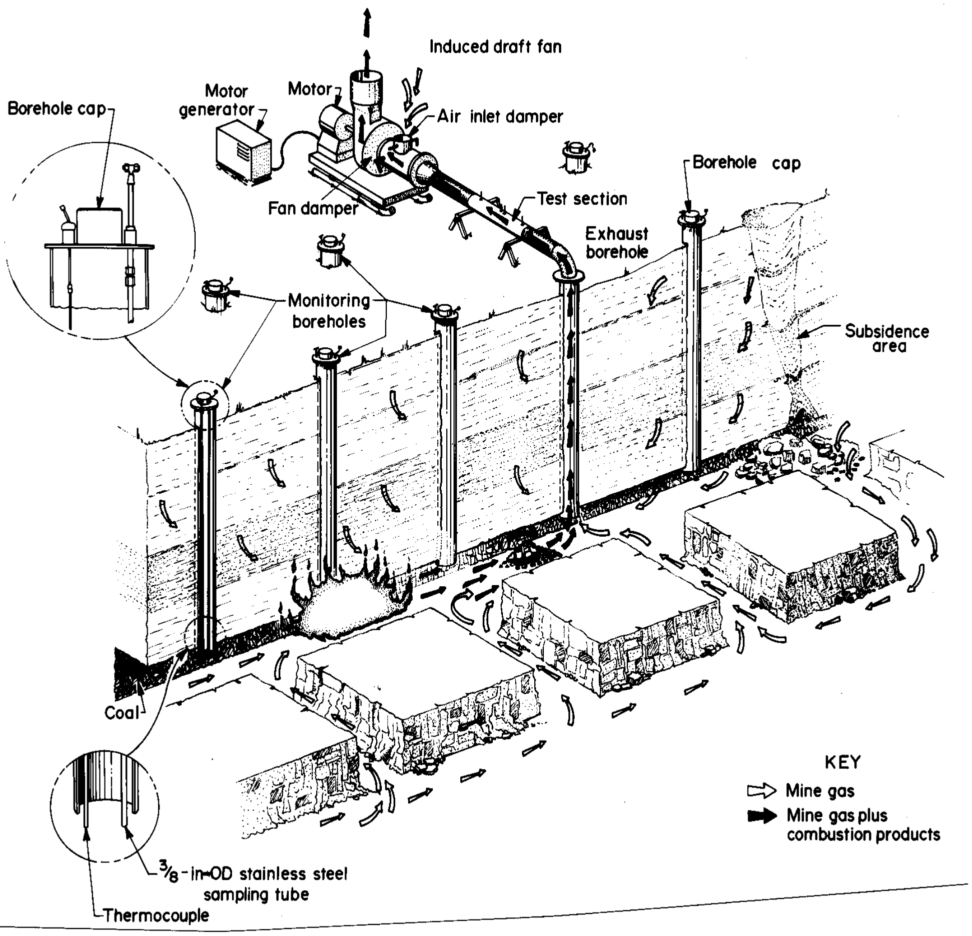

Figure 1.—Mine fire diagnostic technique applied to abandoned mine fire site (artist's depiction).

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

through the area beneath a borehole that lies between the suction borehole and the fire zone. A combustion signature can be measured at this borehole and the suction borehole. The fire zone lies at or beyond the boreholes showing combustion signature. The existence of unobstructed mine entries is not considered crucial, since the exhaust fan need cause only slight movement of underground gases in order to be effective. Collapsed mines and coal refuse piles can also be investigated with the mine fire diagnostic technique.

Evidence of fire is based on measurements of the changing mine atmosphere as determined from downborehole temperature and gas samples taken with and without suction. A particularly sensitive indicator of the presence or absence of fire is the change in concentration of low-molecular-weight hydrocarbons that are desorbed from heated coal. Increases or decreases in the concentration of hydrocarbons with assumed flow directions are related to the presence of hot and cold areas of the mine. Using a borehole grid pattern and moving the point of suction produces overlapping data "windows," which can be combined to produce a map of probable subsurface combustion zones.

In February 1987, the Bureau, at the request of the Office of Surface Mining Reclamation and Enforcement (OSMRE), used the mine fire diagnostic technique at an old mine fire site in Carbondale, PA (*6*). The 2-month field investigation, data analyses, and the results of the Bureau's mine fire diagnostic technique are described in this report. This work was done in support of the Bureau's goal to minimize the impact of mining operations on the environment.

ACKNOWLEDGMENTS

The authors acknowledge the following people who contributed to the successful completion of this project: Tim Walker and Donald McCann, Jr., mechanical technicians, of Boeing Services International, Inc., who assisted with the field work, often under adverse weather conditions; Christina Manns and Andrew Miller, physical science aides, and Joseph Slivon, Jr., engineering technician, of the Bureau, who were responsible for most of the data entry and/or equipment maintenance; and John J. Delaney, John Sharkowicz, and Al Steber, engineering technicians, of the Wilkes-Barre, PA, office of OSMRE, who contributed significantly to the timely completion of the field work. The contributions of David Philbin, mining engineer, Pat Acker, civil engineer, and John Holbrook, chief, Anthracite Reclamation Program, OSMRE, who supported the development of the mine fire diagnostic technology, and Robert F. Chaiken, supervisory research chemist, of the Bureau, who guided the development of the Bureau's mine fire diagnostic methodology, are also gratefully acknowledged.

SITE DESCRIPTION

The Carbondale mine fire site lies within Pennsylvania's Northern Anthracite Field. The site is located adjacent to an apartment complex in Carbondale, Lackawanna County, PA. The complex consists of 11 three-story apartment buildings built on an area that had been stripped and backfilled in a previous fire control project. A 1946 city dump fire had spread to underground coal mine workings (*2*). Attempts were made to extinguish the fire in 1950 by flushing and in 1974 by excavation. The excavation project had been considered successful until recently. Although there is currently some evidence of subsidence, the area had not in the past been characterized by widespread venting, subsidence, or noxious odors, which often occur at the site of an underground fire. Evidence of the suspected fire was observed during winter months when unusual snow melt areas were noticed (fig. 2).

The Carbondale mine fire site has 34 boreholes within an area of approximately 8-1/2 acres. The boreholes were installed in 1986 by OSMRE for monitoring purposes, and were subsequently used for the fire diagnostic study. Thirty-two of the boreholes were cased with 6-in-ID casings and two were cased with 4-in-ID casings.

Geological records indicate that at least six coal seams are found in the Carbondale area. The six primary seams are the Grassy, New County, Clark, and Dunmore Nos. 1, 2, and 3. These seams are relatively flat lying. The driller's logs indicate the presence of two distinct coal horizons, which may be either the Clark and Dunmore No. 1 seams, or the Top and Bottom Clark seams. Coal and/or carbonaceous shales were found within the 1,045-ft through 970-ft elevation interval at the site with the surface elevation of 1,120 to 1,080 ft. Data obtained from the driller's logs indicated that during the 1974 fire extinguishment project the top seam had been stripped and backfilled from the area that is now in front of the apartment buildings (fig. 3). Behind the apartment buildings, both

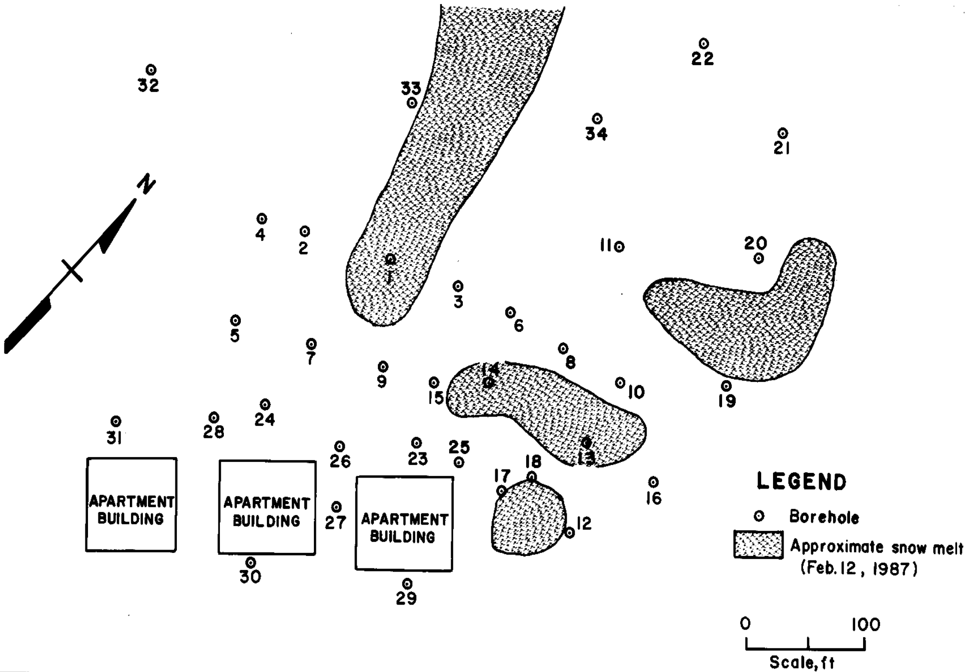

Figure 2.—Carbondale site map with snow melt areas and location of boreholes.

coal seams were present (fig. 3) at approximate elevations of 1,005 and 983 ft. The topmost coal seam was about 75 ft below the surface. Upslope from the apartment buildings, drill logs indicated the presence of coal in the 1,005- to 1,040-ft elevation interval (fig. 3), 60 to 100 ft below the surface. Driller's logs also indicated that most of the holes had been cased through the top coal seam, the most likely source of heating, and some had been cased below the lower seam. Although there was concern about the ability to obtain gas samples from the boreholes that had been cased through the coal zones, pressure and gas composition data indicated that this was not a factor in the results of the study.

MINE FIRE DIAGNOSTICS

Application of the Bureau's mine fire diagnostic method may be divided into three parts: (1) coal fire characterization, (2) coal fire detection, and (3) interpretation.

COAL FIRE CHARACTERIZATION

Determining a suitable fire signature in the mine atmosphere is an integral part of the Bureau's diagnostic method. The concentrations of combustion products such as carbon dioxide (CO_2) and carbon monoxide (CO) are frequently used as indicators of combustion. However, variations in carbon dioxide concentration may be related to chemical reactivity, the adsorption of water, the presence of bacteria, or other factors not directly dependent on temperature. In laboratory studies, the concentration of carbon dioxide did not always increase with increased temperature (fig. 4). Although the production of carbon monoxide is temperature dependent, the concentration of carbon monoxide at temperatures below 120° C is relatively low (fig. 5). Field measurements of carbon monoxide also exhibit limited change with variations in borehole temperature (fig. 6).

Previous research (*8-9*) by the Bureau has shown that the desorption of low-molecular-weight hydrocarbons from bituminous coal, methane (CH_4) to pentane (C_5H_{12}), is strongly temperature dependent, and that changes in such gas emissions are observable at temperatures as low as 100° C.

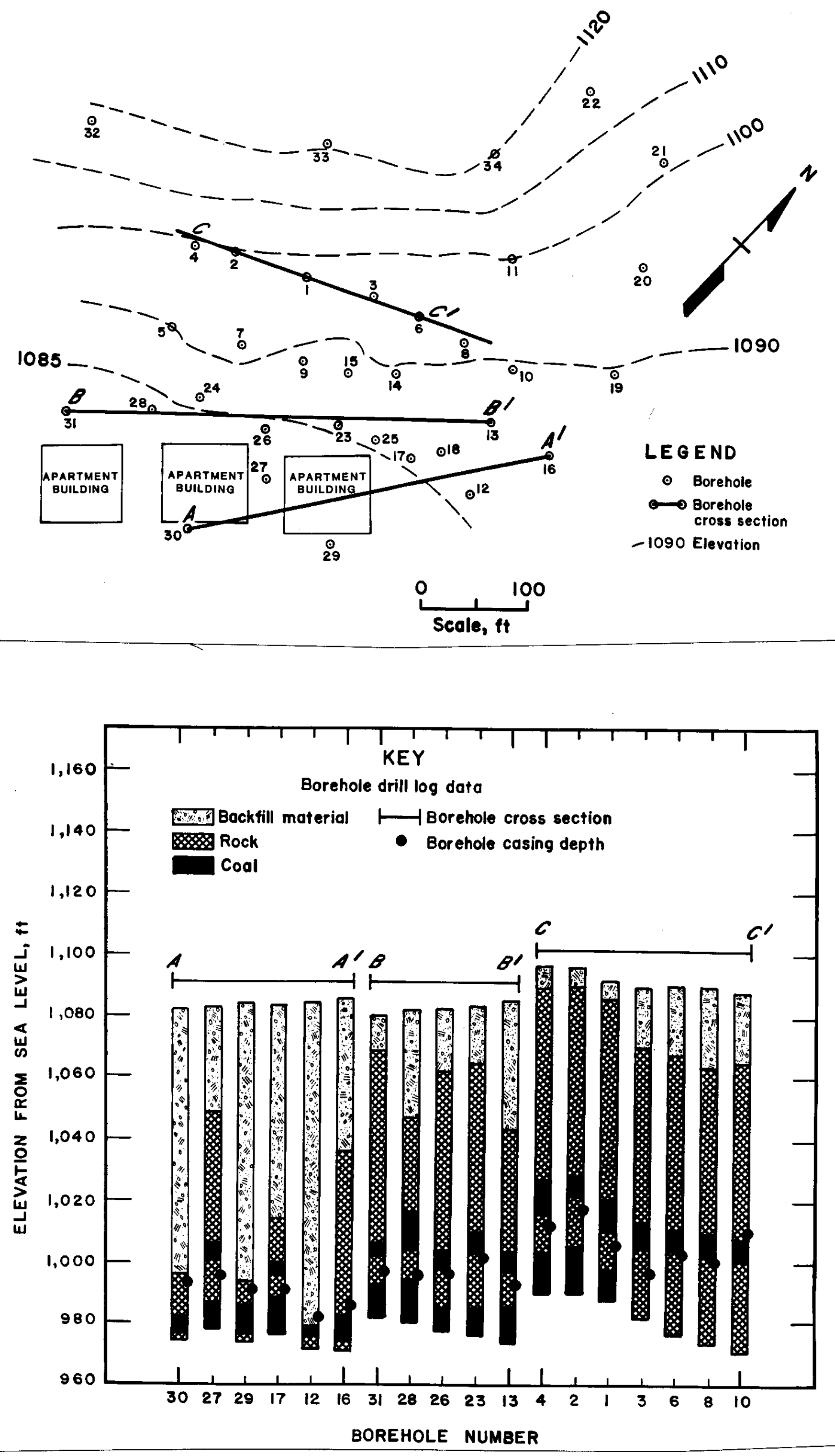

Figure 3.—Geologic cross sections based on driller's logs. Top, site map; bottom, cross sections based on drill log data. *A—A'*, Presumed area of 1974 extinguishment project, *B—B'*, 1,080 elevation behind apartment buildings, *C—C'*, boreholes upslope of apartment buildings.

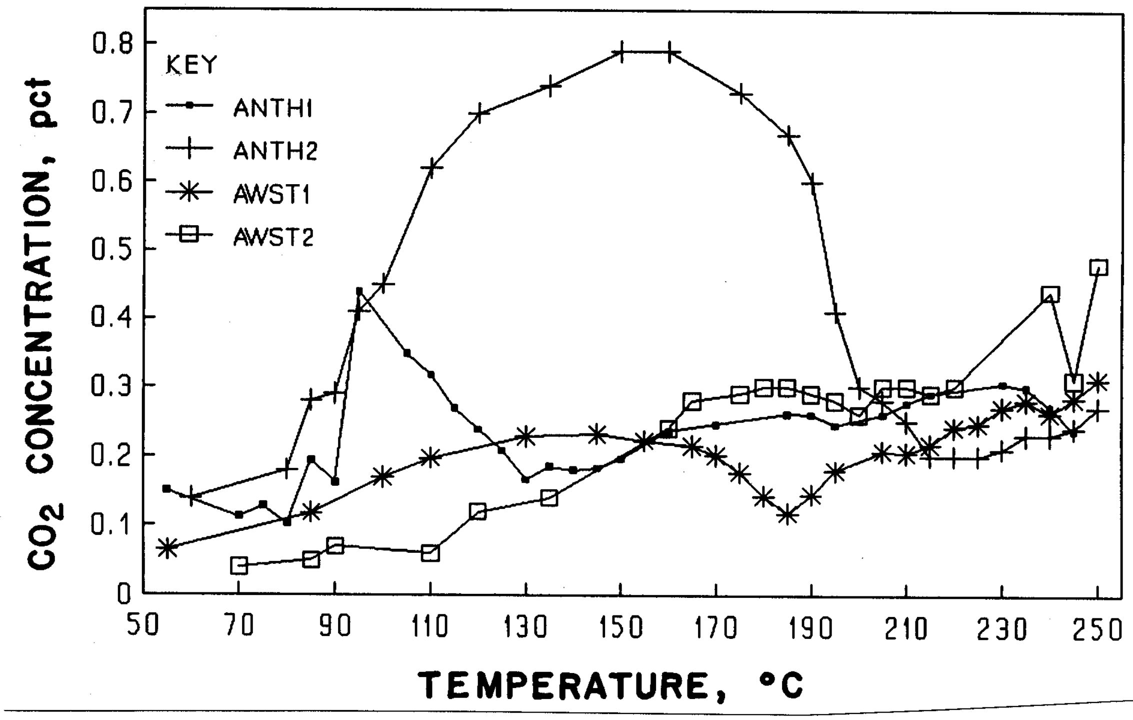

Figure 4.—Concentration of CO_2 versus temperature for anthracite (ANTH1 and ANTH2) and anthracite waste (AWST1 and AWST2) samples.

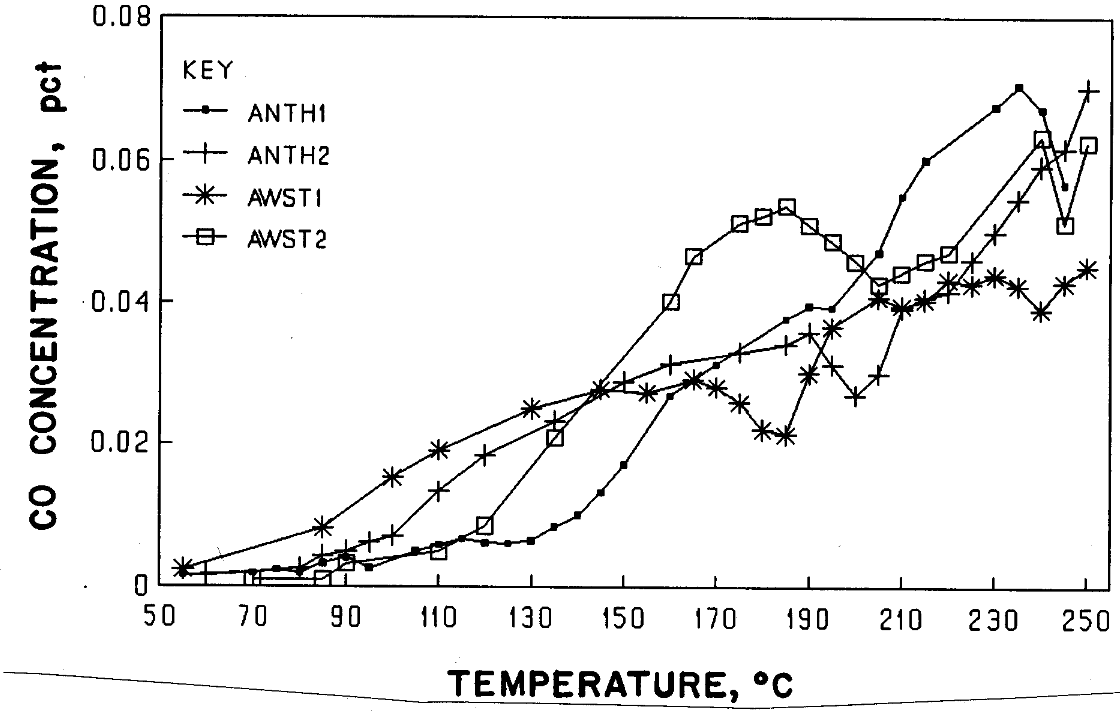

Figure 5.—Concentration of CO versus temperature for anthracite (ANTH1 and ANTH2) and anthracite waste (AWST1 and AWST2) samples.

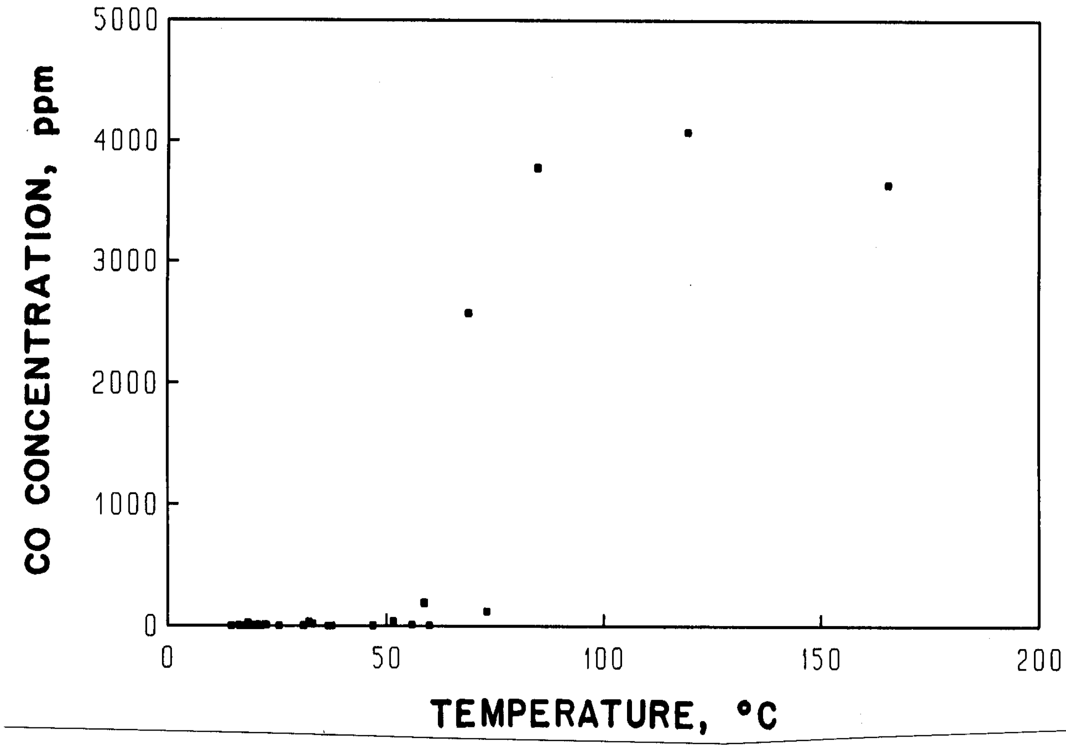

Figure 6.—Concentration of CO versus borehole temperature, Carbondale site.

In laboratory studies (*5, 10-11*) of gas desorption from coals and coal wastes, it was determined that as the sample temperature increased, the concentration of C_2 to C_5 hydrocarbons in the gases that desorbed from bituminous coals and bituminous wastes increased at a rate faster than that of methane, the major hydrocarbon constituent. The results of the laboratory tests with anthracite and anthracite wastes indicated that hydrocarbon emission from these samples was much lower than that from bituminous coals. At the temperatures used in the experiment (less than 250° C) higher hydrocarbons (C_2-C_5) were not always detected in the desorbed gas. However, the methane concentration had an approximate correlation with temperature (fig. 7). Similar results were found in the analysis of the gas samples from the Carbondale communication tests (fig. 8). Therefore, changes in the absolute value of the methane concentration were used in the diagnostic procedure for the Carbondale mine fire.

COAL FIRE DETECTION

The restricted sampling volume of borehole (point-source) measurements can be increased by several orders of magnitude when an exhaust fan on the surface is used to induce negative underground pressures. The pressure differential causes mine gases to flow toward the point of suction and across the borehole sampling points. An illustration of this concept is shown in figure 9. Assume that the exhaust fan is attached on the leftmost hole. If there is communication between the exhaust hole and the neighboring holes, a decrease in static pressure would be measured at the bottom of each borehole casing. If a fire exists to the right of the rightmost hole (Case A), a combustion signature would be detected in gas samples taken at each borehole. Similarly, combustion signatures would be detected at the exhaust borehole and one borehole in Case B, and only at the exhaust hole in Case C. To verify the location of heating, the fan is moved to another borehole and the communication test is repeated. The successful determination of combustion zones depends upon the ability to force and detect the movement of the gases from these zones. Previous tests have shown that radially induced pressure effects are detectable for a distance of several hundred feet from a suction point. The lateral gas sampling area from a single borehole in the underground mine is thus extended from several square feet to several

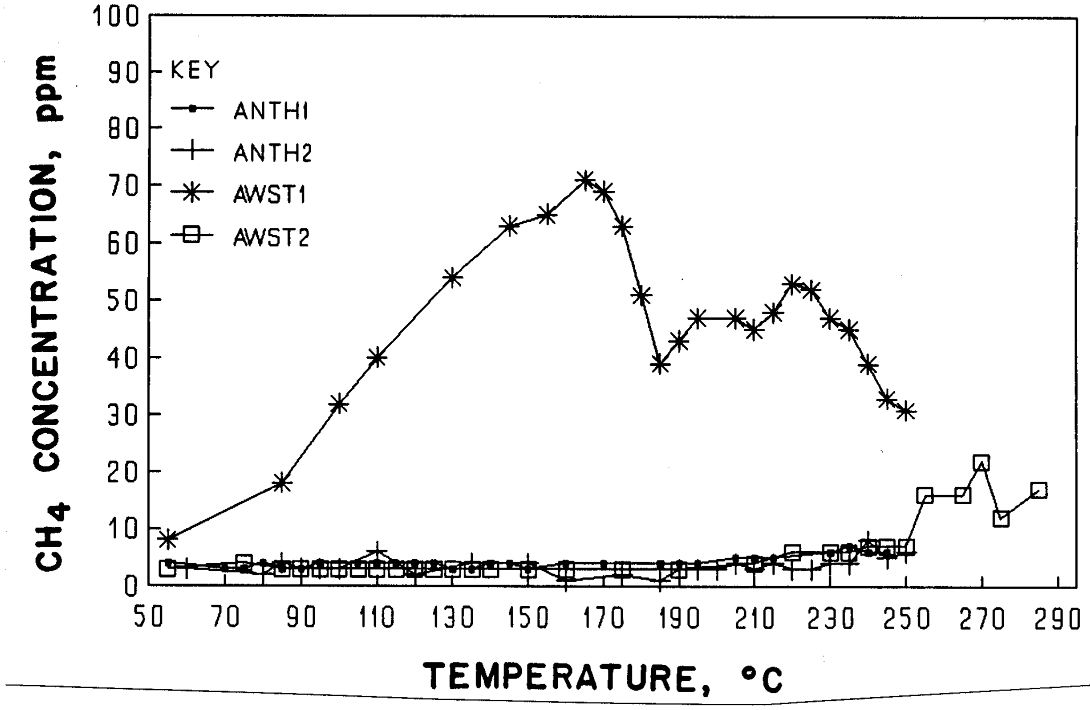

Figure 7.—Concentration of methane versus temperature for anthracite (ANTH1 and ANTH2) and anthracite waste (AWST1 and AWST2) samples.

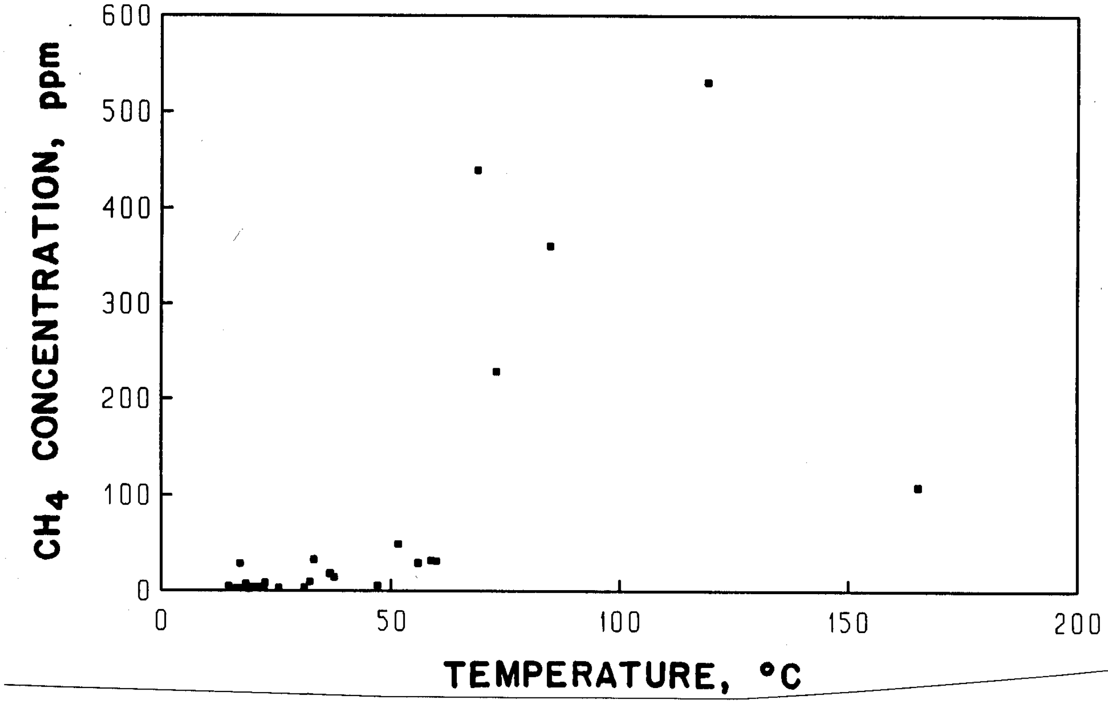

Figure 8.—Methane concentration versus borehole temperature, Carbondale site.

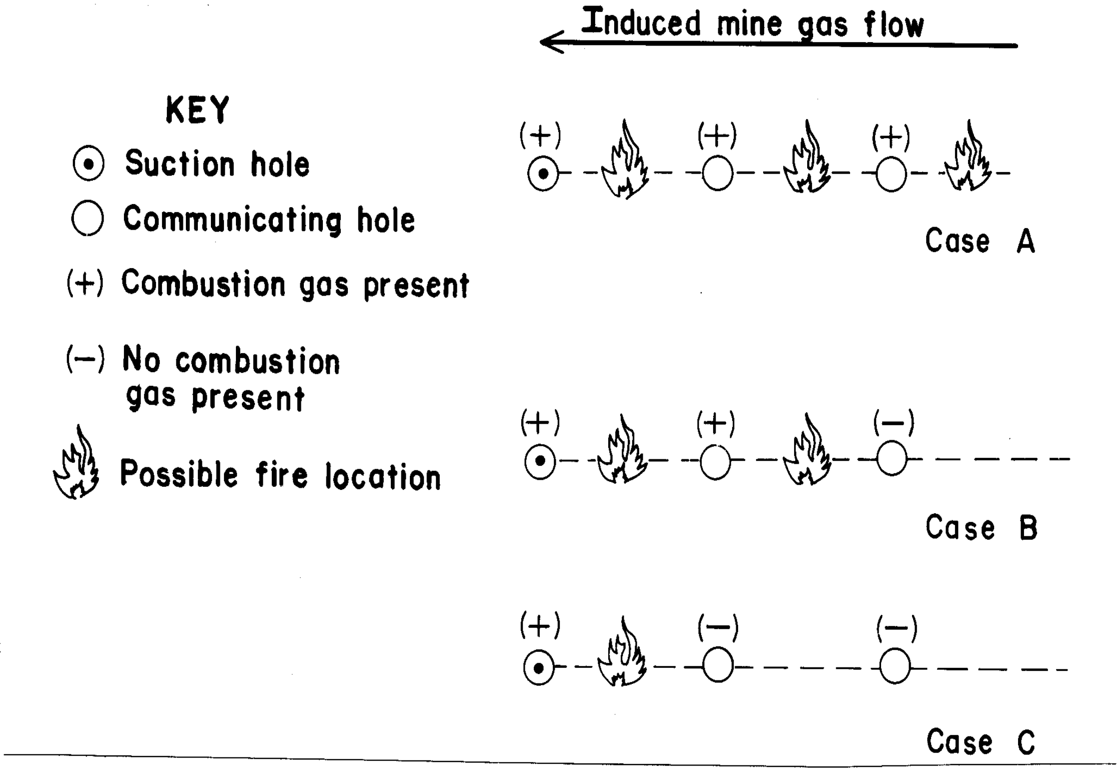

Figure 9.—Mine fire diagnostic technique.

acres. The surrounding boreholes are capped during suction to limit dilution by atmospheric gases.

At Carbondale, a primary concern was whether the borehole casing diameter and depth would allow enough underground gas flow throughout the fire zones to obtain meaningful pressure and gas measurements. Pressure drop due to flow of gas through the borehole casing during suction is a major design consideration in sizing the exhaust fan, casing diameter, and other hardware. A variety of borehole casing dimensions have been used in monitoring abandoned mine fires. To maintain proper airflows during communication tests, 8-in-ID casing was found to be adequate for pipe lengths of 100 ft or less. This diameter casing also allows adequate space for lowering borehole monitoring equipment such as water sample bottles, cameras, pressure transducers, and thermocouples. Boreholes for the Bureau's diagnostics are normally drilled to a predetermined depth beyond coal-bearing strata of interest and are cased with 8-in-diameter pipe to the top of the first evident coal seam. Although attempts are made to drill into voided areas, boreholes that are drilled into nonvoid regions are generally still within the airflow path, as determined from suction test pressure measurements, and are therefore considered valid monitoring points.

At Carbondale, the boreholes were drilled and cased before the Bureau's diagnostic techniques had been considered. In most of the boreholes, the 6-in-ID steel casing extended through one or both coal seams. A pipe flow velocity and pressure test was conducted using a 40-hp exhaust fan connected to a 90-ft length of 6-in-ID casing. The pressure at the end of the casing was measured with a Magnehelic[5] pressure gauge (rates at 0- to 40-in vacuum water column (w.c.)). The results of this test indicated that a 20-in vacuum pressure drop could be expected for every 100-ft length of 6-in casing. Use of two fans configured in series increased the potential vacuum to 80 in to overcome the borehole sizing constraints.

A special borehole instrumentation cap was designed to facilitate both borehole monitoring and easy attachment of a suction fan. The borehole instrumentation cap (fig. 10)

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

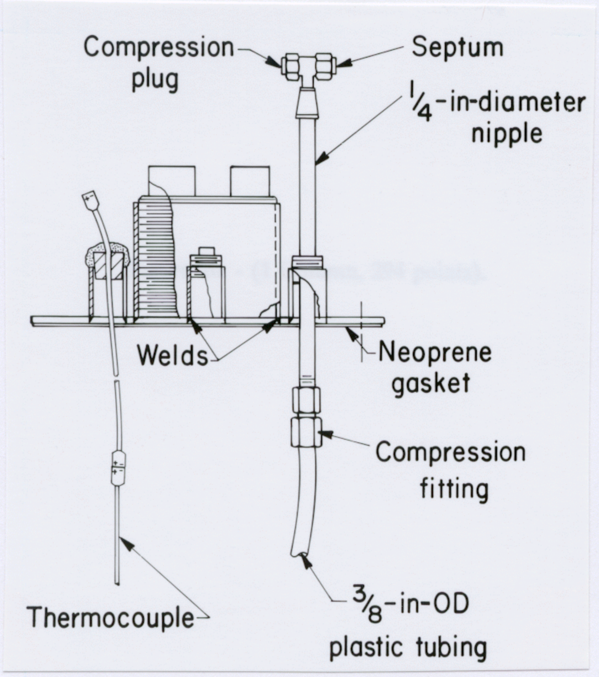

Figure 10.—Borehole instrumentation cap for mine fire diagnostics.

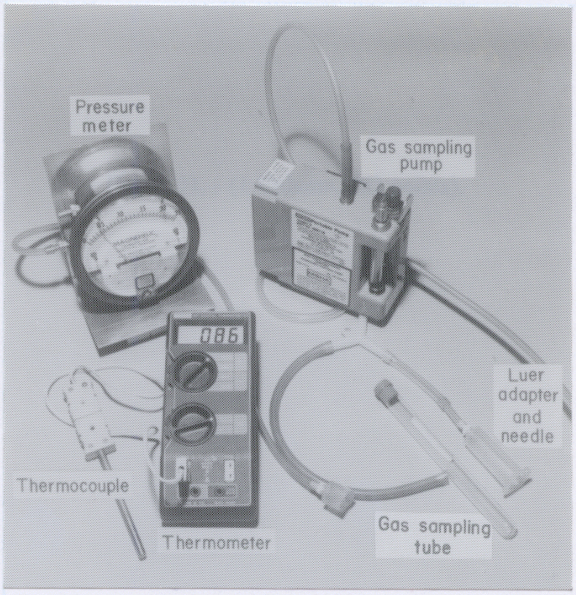

Figure 11.—Equipment used to measure borehole temperature and pressure and to obtain gas samples.

allows the placement of temperature and pressure and gas sampling lines at or near the bottom of each borehole.

To measure the borehole pressure and to obtain gas samples, a hollow 3/8-in-OD plastic sampling line (stainless steel for extremely hot holes) is permanently connected to the instrumentation cap and is suspended to the bottom of the borehole casing. A portable diaphragm pump (fig. 11) is used to sample the mine gases via the down-borehole sample line. Completely evacuated 20-cm^3 test tubes with resealable septa are used to collect gas samples. As mentioned above, pressure measurements also utilize the gas sample tubing. A special borehole-cap tee and septum arrangement facilitates both pressure and sample measurements from the same port (fig. 10). Also suspended along the full length of the casing is a thermocouple probe to monitor the temperature near the sample point.

Once each borehole has been instrumented and baseline measurements of temperature, pressure, and gas concentration have been obtained, mine-gas airflow patterns are altered by applying suction at one surface borehole per test. These tests, which are referred to as "communication tests," consist of (1) the use of an exhaust fan in the mine borehole system, to cause mine gases to flow toward the point of suction, and (2) the measurement of the mine pressure, temperature, and gas composition at all surrounding boreholes. Since the interpretation of the communication test data depends upon induced and measurable changes in pressure and gas composition, baseline measurements are obtained before the communication tests begin.

INTERPRETATION

Data acquired during baseline and communication tests are stored and presented in the same manner. A complete data entry includes borehole number; data type (i.e., baseline or communication); date; time; temperature; pressure; and the concentration of hydrogen, carbon dioxide, oxygen, nitrogen, argon, carbon monoxide, methane, ethane, ethylene, propane, propylene, butane, and pentane. Table 1 summarizes the results of the communication test performed while applying suction at borehole 3.

The diagnostic procedure used to locate underground fire zones is based upon two primary assumptions: (1) changes in the concentration of hydrocarbon gases are principally due to the presence or absence of heated coal, and (2) the suction fan influences the underground flow of gases to a measurable degree. It is further assumed that each communication test provides information within a defined area adjacent to each communicating borehole, so that each test with a different exhaust borehole will cause mine gas to flow across the communicating boreholes at different angles. As the number of tests increases, additional and overlapping information is acquired concerning the presence or absence of heated coal around the communicating boreholes. The diagnostic method's accuracy is directly related to the number of communication tests performed.

The information collected from each communication test is graphically represented on a surface map by a two-dimensional area surrounding each borehole. Delineation of the hot and cold zones involves several steps. First, the extent of communication during a test is determined by calculating the change in the pressure at the bottom of each borehole. A pressure change of at least 0.005-in H_2O indicates communication between any given borehole and the suction hole. Next, using this value, a boundary line delineating the area of communication is placed on the site map using a commercially available computer software program.[6] This boundary defines the "window" for which valid information was obtained during the communication test.

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[6] CONTOUR: A Basic Contouring Program, California Computer Products, Inc.

Table 1.—Results of communication test at suction borehole 3

Borehole[1]	Pressure change, in w.c.[2]	Fan effect	Methane change, ppm[2]	Estimated temperature regime
1	-0.011	Yes	-165	Cold
3	-20.240	Yes	+108	(3)
4	-.011	Yes	-9	Cold
5	-.010	Yes	-1	ND[4]
6	-.105	Yes	-171	Cold
7	-.003	Yes	-63	Cold
8	-.032	Yes	+22	Hot
9	-.051	Yes	+12	Hot
10	-.046	Yes	+11	Hot
11	-.060	Yes	+6	Hot
12	-.021	Yes	-36	Cold
13	0	No	+1	ND[5]
14	-.115	Yes	+324	Hot
15	-.005	Yes	-27	Cold
16	+.005	No	0	ND[4]
17	-.046	Yes	+19	Hot
18	-.036	Yes	-1	ND[4]
19	-.025	Yes	-1	ND[4]
20	-.016	Yes	0	ND[4]
21	-.009	Yes	-1	ND[4]
22	-.007	Yes	0	ND[4]
23	-.024	Yes	+1	ND[4]
24	0	No	0	ND[5]
25	-.075	Yes	-1	ND[4]
26	-.010	Yes	+40	Hot
27	-.018	Yes	0	ND[4]
28	-.035	Yes	0	ND[4]
29	-.022	Yes	0	ND[4]
30	+.009	No	0	ND[5]
31	+.018	No	0	ND[5]
32	+.004	No	+3	ND[5]
33	-.001	No	-13	ND[5]
34	-.030	Yes	0	ND[4]

ND Not determined.

[1] Borehole 2 not sampled.

[2] + = increase; - = decrease.

[3] Suction borehole.

[4] Methane change inadequate for a determination.

[5] Pressure change (fan effect) inadequate for a determination.

The change in the methane concentration was used as the signature for anthracite combustion at Carbondale. A change of at least ±5 ppm methane indicated an increase or decrease in combustion products. Within the communication contour, the boreholes exhibiting changes in methane concentration were then marked. This entailed drawing a 90° quadrant with a radius of 50 ft, the approximate distance between adjacent boreholes, on a scaled site map for each of the boreholes exhibiting the methane change. The quadrant apex was centered at the borehole and the quadrant was drawn pointing toward the suction borehole. With this quadrant size, an area of approximately 2,000 ft^2 is defined for each communicating borehole per test. The quadrant angle (90°) and size were chosen to define a zone that encompasses the radial flow path at the monitoring point (borehole) during the communication test.

Next, each quadrant was coded as to whether an increase or decrease in methane was measured at the borehole. Increases in methane concentration were denoted by shaded quadrants, and decreases by hatched quadrants, for each communication test. Figures 12*A* and 12*B* are examples of two communication studies that have been mapped in this manner. Figure 12*A* (suction borehole 3) shows seven shaded quadrants that represent the areas of at least 5-ppm increase in methane during the suction tests conducted at borehole 3. The six hatched quadrants in this figure denote the areas of at least a 5-ppm decrease in methane concentration during suction. Figure 12*B* represents the results of mapping methane concentration changes at each borehole during the suction test conducted at borehole 26. When figures 12*A* and 12*B* are superimposed, the resultant diagram (fig. 13) begins to outline regions of (1) heated coal, (2) nonheated coal, and (3) undetermined zones (i.e., zones for which inadequate information was available to make a determination).

In essence, the Bureau's diagnostic technique utilizes the Venn diagram (*1, 7, 12*) approach to zone (domain) classification. A Venn diagram (fig. 14) represents, in graphical form, the relationship between domains for which logical equations can be formulated that uniquely define the sets. In applying the diagnostic technique, each zone or quadrant represents one set of vector data (i.e., methane concentration change and flow direction) and the combined results are determined by utilizing a predetermined set of guidelines. When collating the quadrants from all the tests on the site map, these guidelines were followed: (1) when quadrants of the same type (i.e., hot or cold) overlap, the total area includes both quadrants; (2) when quadrants of different types overlap, the overlapping area is undefined unless additional tests support either of the defined quadrants; and (3) when the quadrants do not overlap, but the nearest quadrants are commonly defined, the region between the two is considered to be contiguous. Areas where data are lacking or insufficient are unbounded and interpreted as *unknown* relative to the presence or absence of fire.

Figure 15 is the map obtained when the results of the 25 communication tests are superimposed. Several separate areas of heated coal were located at the Carbondale site. The large heated region includes boreholes 1, 3, 9, 14, 15, 26, and 27. Noncombustion regions were detected around most of this area. However, the borehole spacing to the north did not permit the acquisition of sufficient data to determine where a cold boundary exists. This area is of concern because it is adjacent to two of the apartment buildings. The second major heated region includes boreholes 8, 10, 11, 13, and 18. Noncombustion areas were detected on all but the eastern side. The four boreholes (16, 19, 20, and 21) along this side were either outside the area of communication or did not exhibit changes greater than ±5 ppm methane during the majority of the communication tests. A heated area was detected south of borehole 17 adjacent to the eastern side of one building. Positive combustion signatures were determined at boreholes 32 and 33 when borehole 4 was the suction point. However, these boreholes lie on the periphery of the site (i.e., no boreholes exist beyond them) so the size and extent of these combustion zones are unknown. Samples from boreholes 28 and 31 also indicate combustion activity; this area has been a region of venting, primarily at the suspected rock fracture line. It should be noted that it is not unusual to have noncontiguous areas of combustion activity. It is quite likely that the combustion areas at boreholes 9 and 10 or boreholes 26 and 18 are in fact separated by areas in which there is no combustion. However, the negative signatures around boreholes 1 and 7 may be due to the entrainment of fresh air through the fracture line during communication tests.

The application of the mine fire diagnostic method at the Carbondale site was influenced by the size, location, and condition of the boreholes. All of the boreholes were in place before the diagnostic work began. Normally, a borehole pattern on 100-ft centers is drilled for initial testing. Based on the results, subsequent patterns are drilled to confirm the location of combustion zones and to establish a cold boundary on all sides. Since additional drilling was not an option at Carbondale, the extent of the indicated combustion zones at boreholes 17, 31, 32, and 33 could not be determined. The distance between some boreholes, e.g., between 1 through 4 and 32 through 34, contributed to uncertainty with respect to the extent of the combustion zone. Poor communication and relatively low methane levels limited the information obtained at the

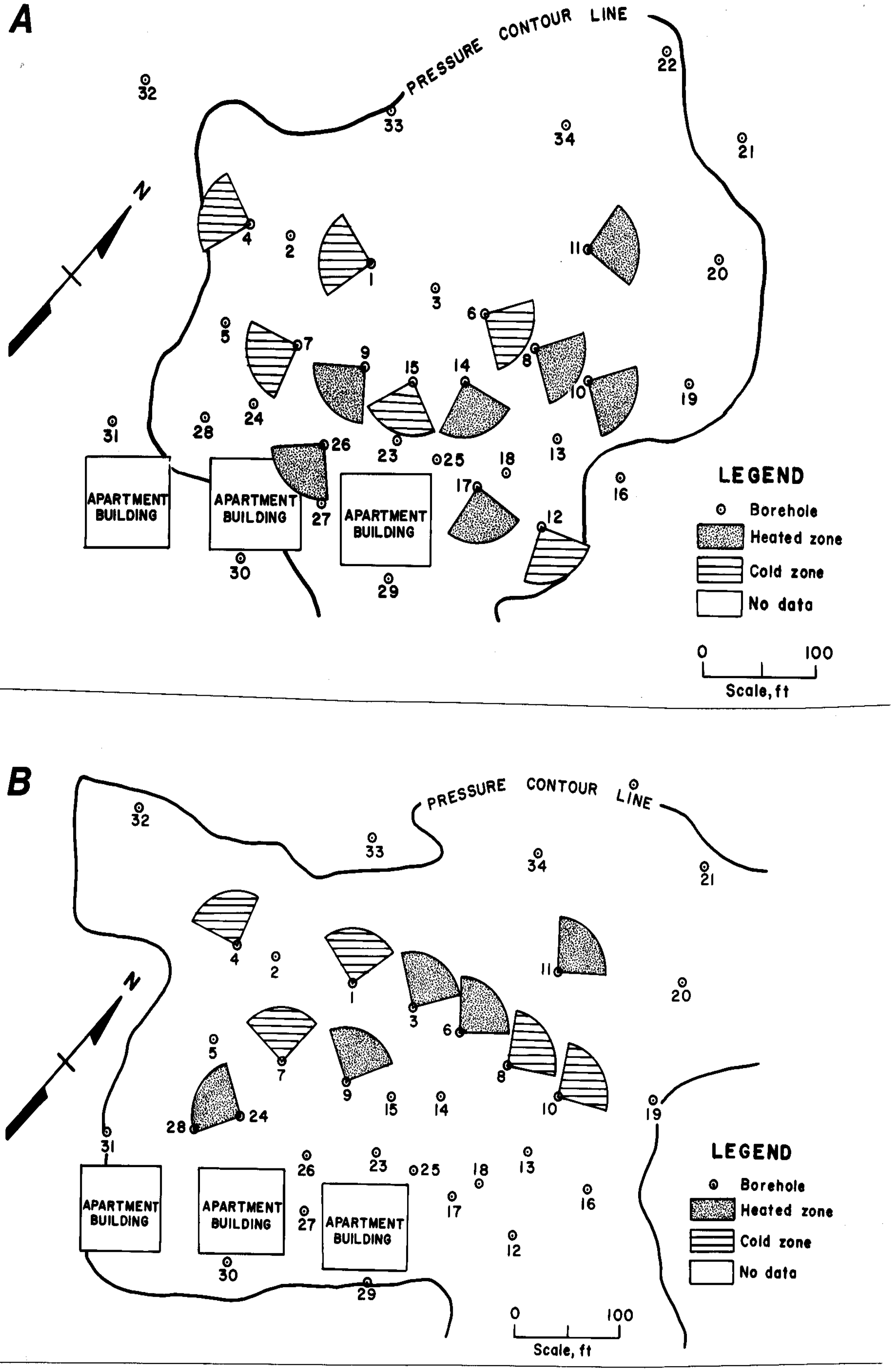

Figure 12.—Communication test results. ***A*****, Suction borehole 3,** ***B*****, suction borehole 26.**

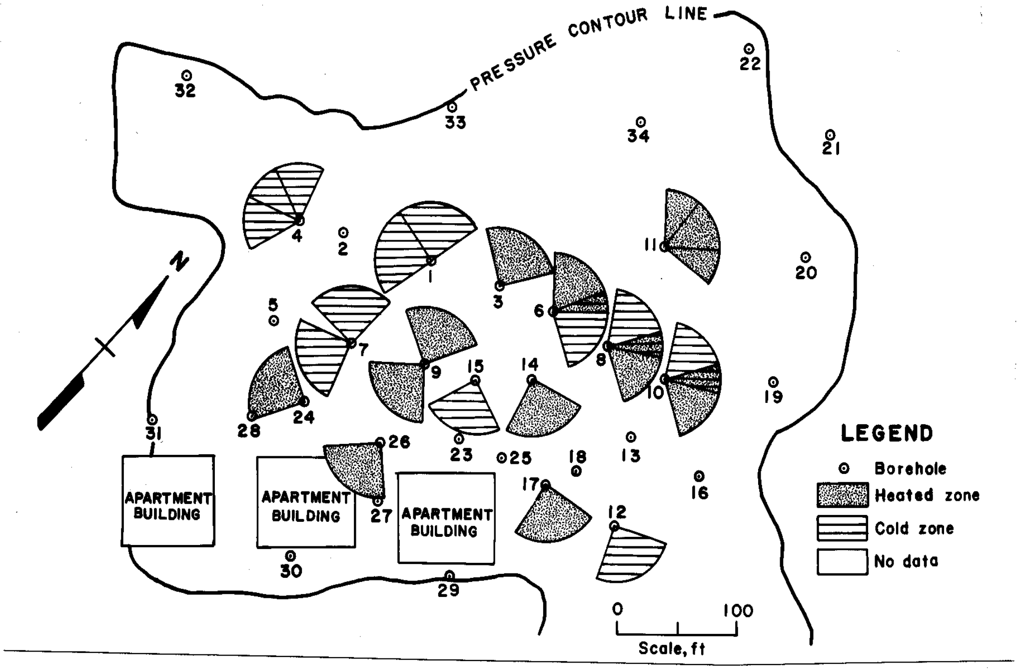

Figure 13.—Combined communication results from tests at boreholes 3 and 26.

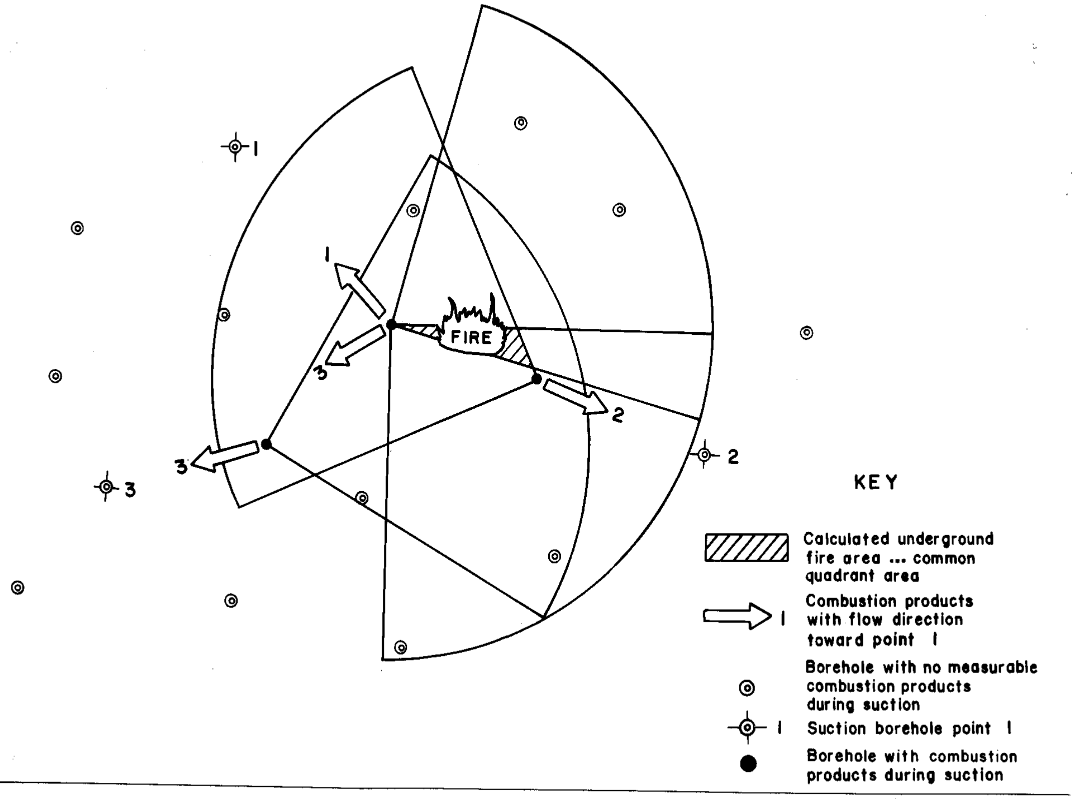

Figure 14.—Venn diagram as applied to results of communication tests.

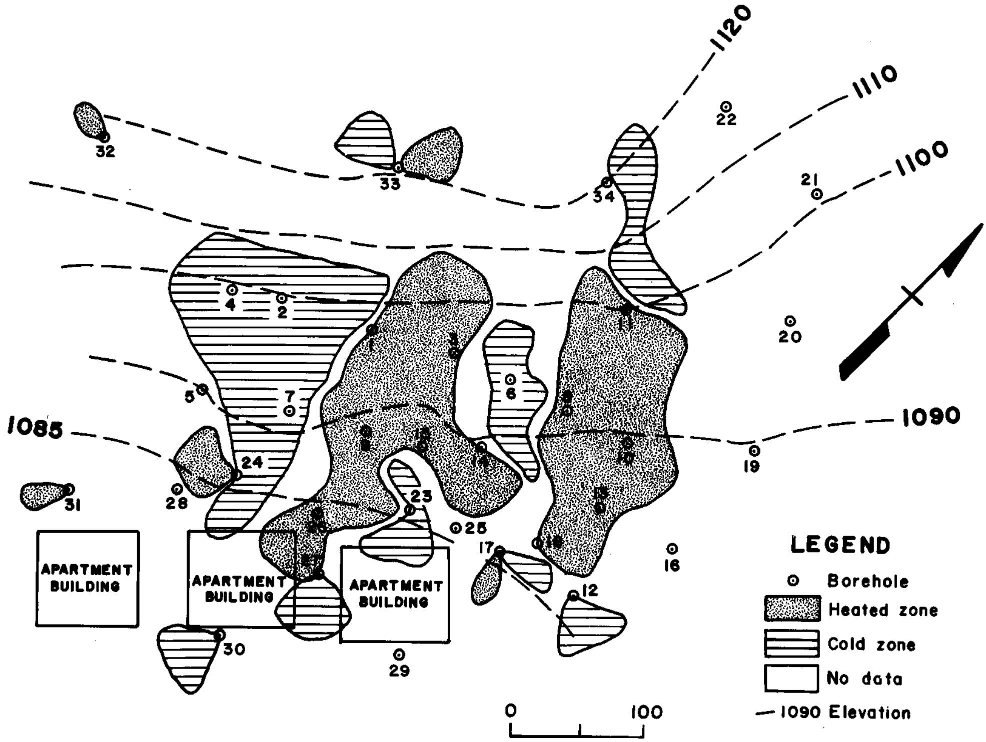

Figure 15.—Site map showing heated and cold areas inferred from Bureau's mine fire diagnostic technique.

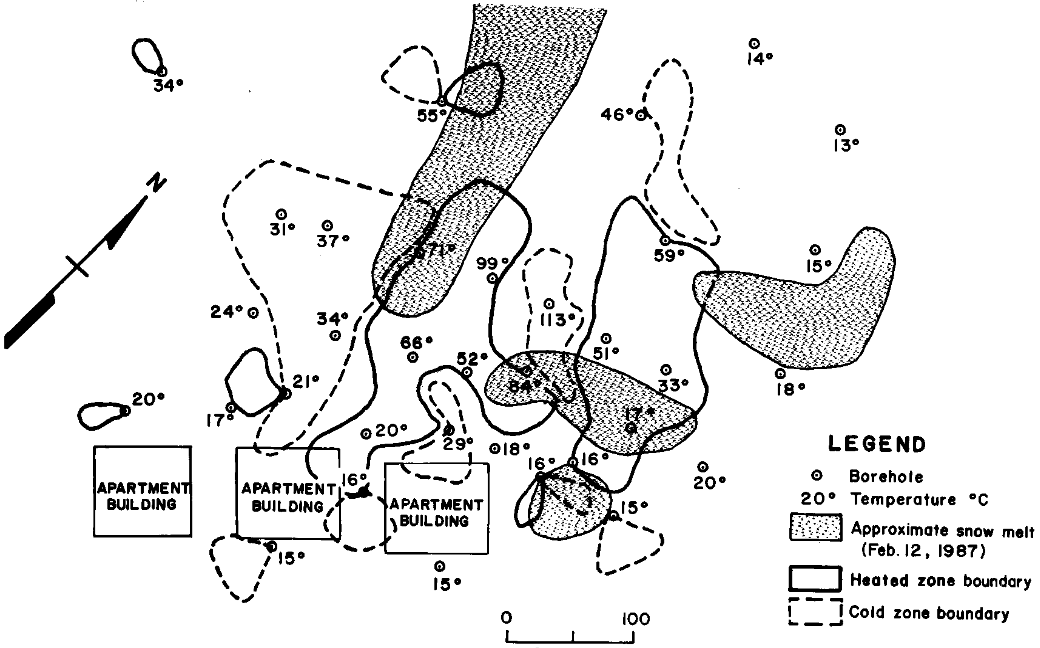

Figure 16.—Site map showing heated and cold areas, snow melt regions, and borehole temperatures.

boreholes (19 through 22) on the north-northeast perimeter of the site. The size of the boreholes and their distance from the other boreholes may have contributed to this effect.

Figure 16 is a Carbondale site map with the results of the Bureau's diagnostic technique (heated and cold zones), surface snow melt areas, and baseline borehole temperature measurements. In general, areas of snow melt can be related to heated zones. Elevated borehole temperatures (> 50° C) do not exhibit a consistent correlation with either combustion zones or areas of snow melt. Both borehole temperatures and surface temperatures are influenced by heat transfer due to the movement of hot gases. Such movement through a mine or through the overlying strata does not necessarily follow straight-line paths in either the horizontal or vertical directions.

CONCLUSIONS

The mine fire diagnostic method incorporates a sampling method that increases the detection zone of normal point-source measurements by inducing gas movement over distances greater than 200 ft. Measuring changes in a characteristic of the moving gas, i.e., hydrocarbon concentration, and plotting the results as vector quadrants rather than as points provides interpretive insight and bounds the area affected by combustion.

The mine fire diagnostic study at Carbondale indicates that most of the heated zones lie below unoccupied areas to the north of the apartment buildings. However, the outer limits of the heated coal zones could underlie surface areas adjacent to the buildings. Regular monitoring of all boreholes for subsurface temperature, pressure, and concentrations of methane, carbon monoxide, and carbon dioxide would indicate the status of the fire and give warning of any changes in combustion activity.

It should be noted that while zones of heated coal and cold coal were definitely located at the site (the bounded areas in fig. 10), there are areas where the communication data were insufficient to allow the definition of a hot or cold zone. It should also be noted that there is some degree of uncertainty in the extent of heated and cold zones. However, the results of the mine fire diagnostic technique are generally consistent with the snow melt evidence. There was no direct correlation between the borehole temperatures and the results of the mine fire diagnostic results. This may be due in part to a heat transfer problem related to the location of the casing.

Laboratory results and other field studies support the effectiveness and applicability of the Bureau's mine fire diagnostic technique in locating and monitoring abandoned mine fires. The hydrocarbon ratio used to characterize bituminous samples was not applicable to anthracite samples because of anthracite's lower rate of hydrocarbon emission and low concentration of higher hydrocarbons in the desorbed gas. However, variations in the absolute concentration of methane are considered an appropriate indication of anthracite temperature.

The Bureau's mine fire diagnostic methodology includes (1) a single parameter that is characteristic of heated coal, (2) a sampling method that qualitatively expands the sampling volume, and (3) an interpretive method that defines heated and cold areas. These factors make the Bureau's methodology a significant improvement in locating and monitoring abandoned mine fires.

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