MINE FIRE DIAGNOSTICS TO LOCATE AND MONITOR ABANDONED MINE FIRES[1]

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Abstract.--Locating a fire in an abandoned underground coal mine or waste bank is difficult using currently available methods. The Bureau of Mines is developing a mine fire diagnostic methodology to locate and monitor such fires. The method is based upon two assumptions: (1) that measurable changes in the emission of low molecular weight hydrocarbons from coal occur as a direct result of changes in temperature, and (2) that controlling the direction of the underground gas flow between borehole sampling points provides the means for locating the source of these hydrocarbons. This mine fire diagnostic method has been applied at three field sites. It was used to define combustion zones at an abandoned underground bituminous mine at Renton, PA. At this 60-acre site, which showed several areas of venting, the technique was used to delineate three noncontiguous combustion areas totaling approximately 10 acres. It was also used to follow the progress of the extinguishment effort. At Carbondale, PA, the method was used to locate heated areas in an abandoned anthracite mine. In this test, changes in the concentration of methane during communication testing were used as the combustion indicator. The mine fire diagnostic method is currently being used to define the combustion area at an abandoned bituminous mine in Large, PA.

INTRODUCTION

Fires in abandoned coal mines and waste banks are a relatively common occurrence. Surveys taken at least 10 years ago listed 292 waste bank fires and 261 underground fires in the United States (Johnson and Miller 1978, McNay 1971). In a study of problems associated with anthracite fires (Chaiken et al. 1983), it was noted that fire control efforts are expensive and that the success rate for fire control projects is low. In many cases, high cost and low efficiency are related to the inability to accurately determine the location and extent of fire in an abandoned mine.

The methods currently used to locate and assess underground mine fires have significant shortcomings. The emission of smoke and fumes at surface fractures and vents is the usual indicator of an abandoned mine fire. These indications, however, are not necessarily located above the subsurface combustion zones. Aerial infrared photography can be used to determine temperature variations within a few inches of the surface, but is inappropriate when heated areas lie several hundred feet below the surface. Temperatures and gas samples taken at the base of boreholes are point source measurements. Their accuracy is limited to a very small volume near the sample

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point, particularly when the volume lies outside an area affected by natural underground ventilation.

In order to locate a fire, it is necessary (1) to identify a parameter characteristic of the fire, (2) to measure the parameter through appropriate sampling methods, and (3) to interpret the sampling data correctly. The mine fire diagnostic method being developed by the Bureau of Mines satisfies these criteria; it is based on hydrocarbon desorption and controlled subsurface sampling. In this method, borehole temperature and pressure, and the concentration of low-molecular-weight hydrocarbons in the mine atmosphere are measured under natural or baseline conditions. These values are compared to those obtained when a suction fan is used to cause mine gases to flow from the surrounding underground areas toward the point at which the suction is applied (fig. 1). Differences in the concentration of hydrocarbon gases at various points underground can be related to the movement of combustion products in assumed directions from the source toward the suction point. The presence of hydrocarbon gases does not necessarily indicate active combustion throughout an area, but does indicate the presence of coal that is heated above normal subsurface temperature.

concentrations as low as 1 ppm; (4) the use of an appropriate ratio can eliminate the effects of sample dilution; (5) induced pressure effects - and therefore, fires - can usually be detected several hundred feet from the suction point; (6) operation of the system is fairly simple, requiring only readily available equipment and normal technical skills; and (7) it differentiates heated and cold areas.

COAL FIRE CHARACTERIZATION

Previous work (Kim 1974, Kim 1978) by the Bureau has shown that the desorption of low-molecular-weight hydrocarbon gases from coal is strongly temperature dependent. At ambient temperatures, gas desorbed from coal is primarily methane. When coal is heated, the rate at which gas is emitted increases, and hydrocarbons other than methane are also desorbed. Changes in the concentration of desorbed methane and the C_2 to C_5 alkanes can be detected at temperatures lower than 100° C.

In order to relate the concept of hydrocarbon desorption to changes in temperature, the Bureau conducted a laboratory study (Kim 1986) in which

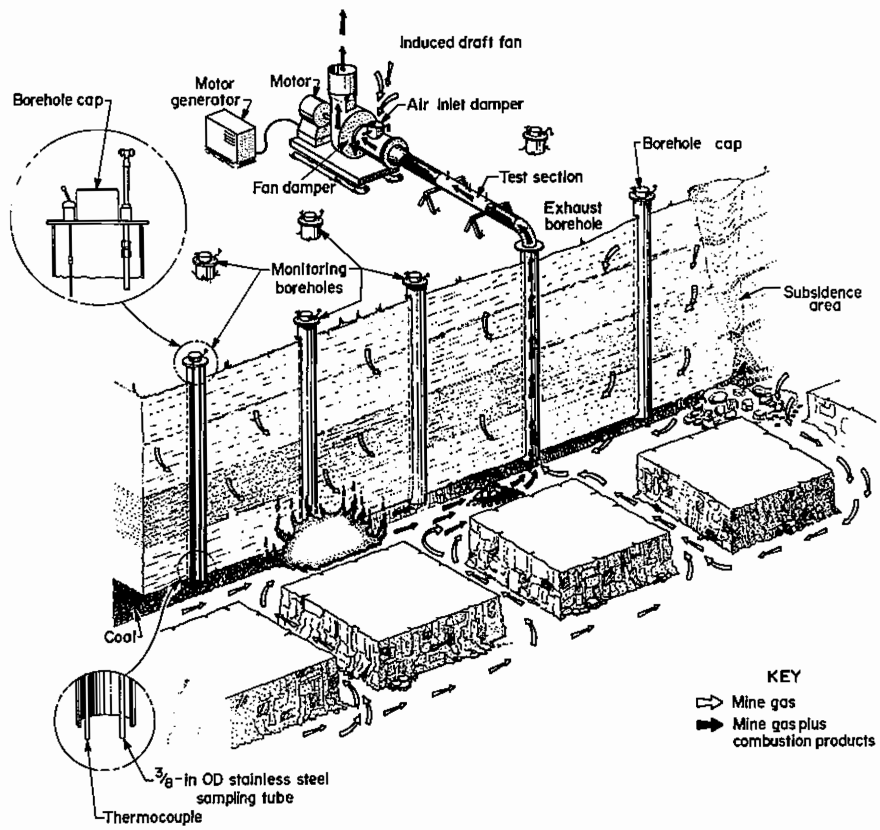

Figure 1.--Mine fire diagnostic technique. (Artist's version of an abandoned mine site application.)

The Bureau's mine fire diagnostic method has several advantages: (1) Changes in hydrocarbon emission are caused only by changes in temperature; (2) changes in hydrocarbon emission can be detected for temperatures below the ignition point of coal, thereby increasing the sensitivity of the method; (3) hydrocarbons can be detected at

samples of coal and coal waste (table 1) were heated in a tubular combustion furnace. Gas samples were taken during heating and cooling phases of the experiment, and analyzed for oxygen, nitrogen, carbon dioxide, carbon monoxide, hydrogen, and the hydrocarbons, methane, ethane, ethylene, acetylene, propane, propylene, iso- and normal butane and pentanes.

Table 1.—Sample identification and analysis.

Sample	Source	Moisture pct	Ash pct	VM[1] pct	FC[2] pct	Btu
Albright waste	WV	9.1	42.3	17.5	31.2	6719
Anthracite #1	PA	2.3	8.2	7.0	82.6	13536
Anthracite #2	PA	5.0	12.0	4.8	78.1	12184
An[3] waste #1	PA	1.5	69.6	7.1	21.7	3492
An waste #2	PA	2.0	60.3	7.0	30.8	4940
Black Creek	AL	2.2	2.0	37.2	58.6	14655
D seam	CO	7.9	5.6	36.2	50.3	12368
Freeport	PA	1.6	6.1	37.8	54.5	14196
Illinois #6	IL	12.0	27.8	29.4	30.7	8417
Pittsburgh	PA	1.4	4.8	37.3	56.4	14205
Pocahontas #4	VA	1.0	10.5	16.6	71.9	13934

[1]VM: volatile matter.
[2]FC: fixed carbon.
[3]An: anthracite.

Since the concentration of methane and the concentration of higher molecular-weight hydrocarbons both increase with temperature, a concentration ratio was defined which relates both factors in a single parameter suitable for graphical presentation. This ratio, R1, is defined as:

$$R1 = \frac{(1.01\,[THC] - [CH_4])}{([THC] + c)} \times 1000$$

where: [THC] = concentration of total hydrocarbons, ppm
$[CH_4]$ = concentration of methane, ppm
c = constant, 0.01 ppm.

The ratio R1 was defined to: (1) equal zero when and only when the concentration of total hydrocarbons was zero; (2) have a unique value when methane was the only hydrocarbon; (3) eliminate the possibility of division by zero, a constraint necessary for computer processing of data; and (4) increase as temperature increased. As defined, the ratio R1 is an increasing function of the percentage of higher hydrocarbons, has a value of zero when no hydrocarbons are detected, a value of 10 when methane is the only hydrocarbon, and a limiting value of about 1000. The only constraint on the use of R1 as an indicator of heated coal is that the concentration of methane in the gas samples be greater than 20 ppm. Below this level, the concentration of hydrocarbons in the sample could be below the current 1 ppm detection limit of standard gas chromatographic (GC) techniques; thus, changes in the hydrocarbon concentration might not be detected.

The results of the laboratory heating tests varied with the rank of coal. For bituminous samples, the concentration of hydrocarbons and the value of R1 generally increased during heating and decreased during cooling (table 2). The emission of hydrocarbons from the anthracite samples was very low, usually less than 20 ppm, and the higher hydrocarbons were not generally detected.

Table 2.--Variation in R1 with temperature.

Sample	Temperature, °C Heating 100	150	200	225	250	Cooling 225	200	150	100
Albright Waste	30	40	50	75	400	125	60	30	10
Anthracite #1	130	10	80	10	10	10	10	10	10
Anthracite #2	10	10	10	10	10	10	10	10	10
An Waste #1	145	140	125	115	115	10	10	10	10
An Waste #2	10	10	10	10	10	10	10	10	10
Black Creek	150	200	350	440	540	400	250	125	10
D Seam	710	880	890	910	825	700	625	690	675
Freeport	50	70	80	150	325	275	225	10	10
Illinois #6	675	660	625	625	625	410	375	375	10
Pittsburgh	520	540	590	550	550	200	180	150	
Pocahontas #4	100	110	125	150	300	190	160	85	10

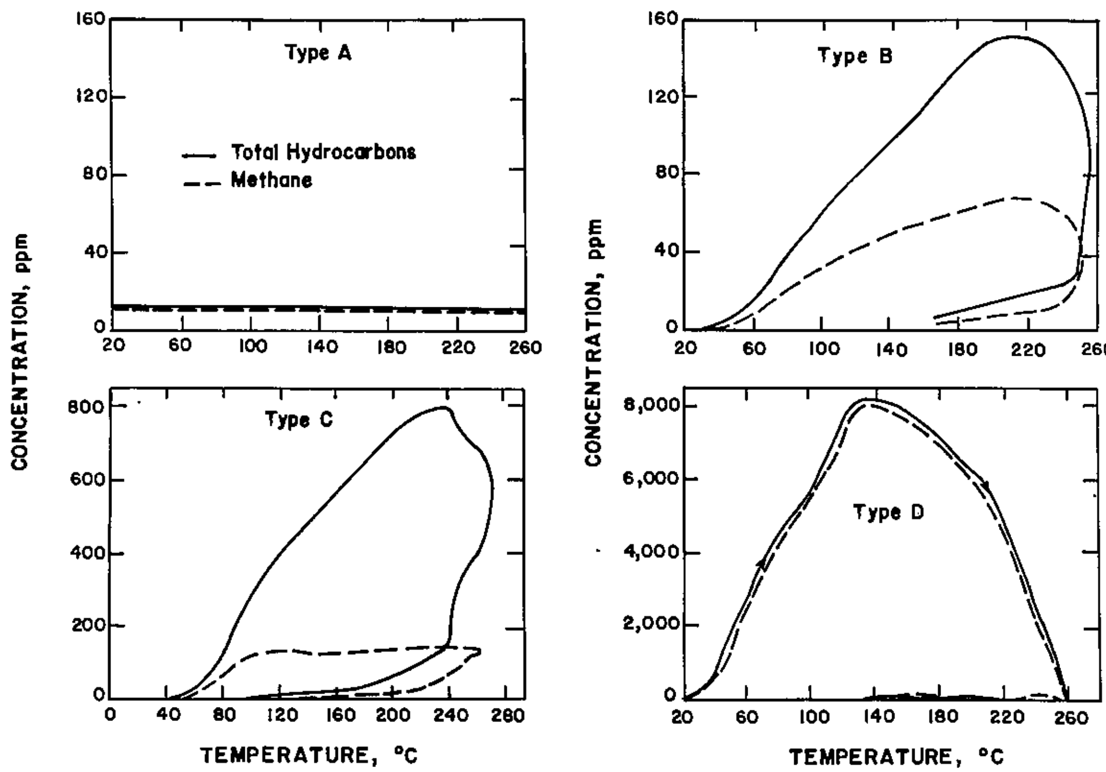

Figure 2.--Hydrocarbon emission from heated coal - types A through D.

The relative emission of total hydrocarbons and methane from the 11 samples could be described by 4 emission curve types (table 3). Type A emission, which was characterized by low hydrocarbon emission and no difference between methane and total hydrocarbons, was characteristic of all anthracite samples (fig. 2). In types B and C, the total hydrocarbon emission rate was greater than that of methane. In type D emission, the concentrations of total hydrocarbons and of methane increased rapidly and at similar rates. Hydrocarbon emission decreased rapidly during cooling.

Table 3.--Summary of hydrocarbon emission characteristics.

	[THC]max ppm	R1max	Emission type	Ratio type
Albright Waste	385	425	D	II
An Waste #1	85	150	A	III
An Waste #2	20	10	A	III
Anthracite #1	10	10	A	III
Anthracite #2	10	10	A	III
Black Creek	95	526	B	I
D Seam	615	885	C	I
Freeport	8550	450	D	II
Illinois #6	250	650	C	I
Pittsburgh	400	560	B	I
Pocahontas #4	400	370	D	II

Plots of the hydrocarbon ratios versus temperature were classified in three categories. For type I ratios (fig. 3), the R1 values during heating were higher than during cooling. Maximum values occurred around 250° C and were in the 600 to 700 ratio range. Those coals with types B and C hydrocarbon emission had type I ratios (table 3). Type II ratios initially increased at a lower rate than type I ratios. They increased rapidly above 200° C, and decreased at approximately the same rate during cooling, although the values during cooling could be higher than during heating. Maximum values of R1 were in the 400 to 600 ratio range. Coals which exhibited type D emission had type II ratios. Type III ratios exhibited little variation with temperature; these were from anthracite samples which had type A emission.

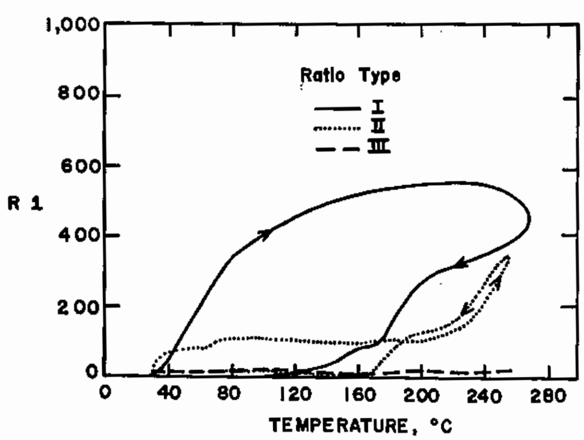

Figure 3.--Hydrocarbon ratios - types I, II, and III.

The laboratory determination of hydrocarbon emission ratios demonstrated that such ratios are strongly temperature dependent for bituminous samples. Generally, the values of the ratio R1 for bituminous coals can be interpreted on an empirical scale as:

R1	Relative Coal Temperature
0 to 50	Normal
50 to 100	Possible Heated Coal
> 100	Heated Coal

The ratio R1 was not as applicable to anthracite samples because of the lower rate of total hydrocarbon emission and the very low concentration of higher hydrocarbons.

The R1 ratio is not uniquely related to a particular coal temperature. It is, however, indicative of an average temperature condition, and over a period of time will increase with increasing temperature and decrease with decreasing temperature.

COAL FIRE DETECTION

The mine fire diagnostic method is based on the assumption that a sufficiently large negative pressure (vacuum) applied to underground regions will cause gases to flow from some distance towards the point of suction. Controlling the movement of underground gases overcomes the limitations of a point source measurement by allowing gases from a large region to be sampled at a single point; and by sampling at multiple points, it provides data for determining the presence or absence of fire along pathways between the sampling points.

The method is illustrated in figure 4. If a fire exists throughout a region (Case A), the flow of gases from right to left will cause combustion products to appear at each borehole. If a borehole lies outside the fire zone, combustion products will not appear at that hole (Cases B and C). To verify the location of heating, the applied suction is moved to other boreholes and the tests are repeated. The successful determination of combustion zones depends upon the ability to force and detect the movement of gases from these zones. Radially induced pressure effects are detectable as far as several hundred feet from a point of suction. The surrounding boreholes are capped during suction to control dilution by air. If the region is highly fractured or faulted, air will be drawn in from the surface. In most cases, however, the use of concentration ratios, which are independent of dilution, will still be reliable indicators of the presence or absence of fire, except when the incoming air reduces the hydrocarbon concentration below the detection limit.

To locate underground heated zones, a series of boreholes are drilled and cased to depths consistent with coal-bearing strata. The first series of holes is used to define general heated zones. The results from the first round of testing is then used to determine the placement of additional boreholes. A second round of tests is performed to verify the location of heated zones

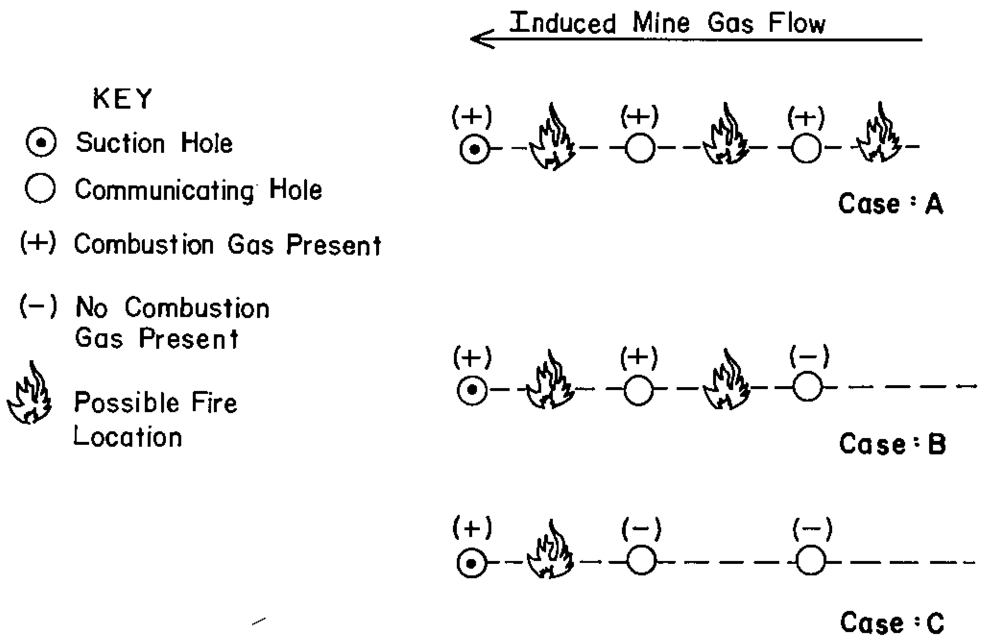

Figure 4.--Mine fire diagnostic technique .

and to establish the presence of a cold boundary. Although a variety of borehole casing dimensions have been used, it was found that an 8-in I.D. casing is preferred. With smaller diameter casing, most of the suction fan's output capacity is used to move the mine air from the bottom to the top of the borehole.

A set of communication studies is used to produce baseline data and communication data; both data subsets include static pressure, temperature, and gas concentrations at each borehole. Static pressure readings at surrounding boreholes are used to determine the pressure effect caused by suction. These data are used to draw a pressure contour which defines the area of good communication, that is, the area for which the data are considered valid. A flow probe in the intake piping of the fan is used to calculate the total flow through the fan.

Differences between baseline and communication measurements are calculated for the area for which the data is considered valid. The changes at each borehole can be classified as: (1) an increase in R1 (heating), (2) a decrease in R1 (cooling), or (3) no change during suction tests. To delineate the heated and cold zones it is assumed that increased hydrocarbons originated in a heated area beyond the borehole which lies on a straight line between the borehole and the suction point. Similarly, a decrease in hydrocarbons indicates a non-combustion or cold zone. Both heated and cold quadrant zones are drawn on a site map, within the pressure contour (fig. 5). By overlaying the possible combustion and non-combustion regions for each test, a composite map is drawn.
Liberal estimates of possible fire zones are mapped for each test; overlapping the results of all tests effectively bounds the possible fire zones through successive approximation. This technique defines probable combustion zones and also defines zones that show no signs of combustion, an important point in defining a fire area.

CASE STUDIES

The mine fire diagnostic method has been applied at three mine sites. It was used to define combustion zones and follow the progress of extinguishment efforts at an abandoned underground bituminous mine at Renton, PA. It was used to locate both heated and cold areas in an abandoned anthracite mine in Carbondale, PA. Currently, it is being used to define the combustion area at an abandoned bituminous mine in Large, PA.

Renton Mine Fire Project

The Renton Mine Fire project was the initial phase in the development of the Bureau's Mine Fire Diagnostic Methodology. This abandoned mine fire site encompasses an approximately 60-acre region near Renton, which is characterized by several large subsidence holes and venting areas. One hundred nineteen boreholes were installed at the site. They were primarily for monitoring purposes, but some were later used as water injection or grout injection points. The mine fire diagnostic technique was used at the Renton site to delineate three separate combustion regions. Figure 6 shows the variation of R1 with time at 3 randomly selected boreholes. Boreholes 33 and 57 are heating with time, while borehole 14 is cooling with time. The ratio R1 was used to monitor a fire extinguishment technique in which water was injected into the heated areas while a suction fan was used to draw heated air from the mine (Chaiken et al. 1984). Through the applied diagnostics it was possible to determine which areas were quenched, and which heated regions were not quenched and/or were spreading.

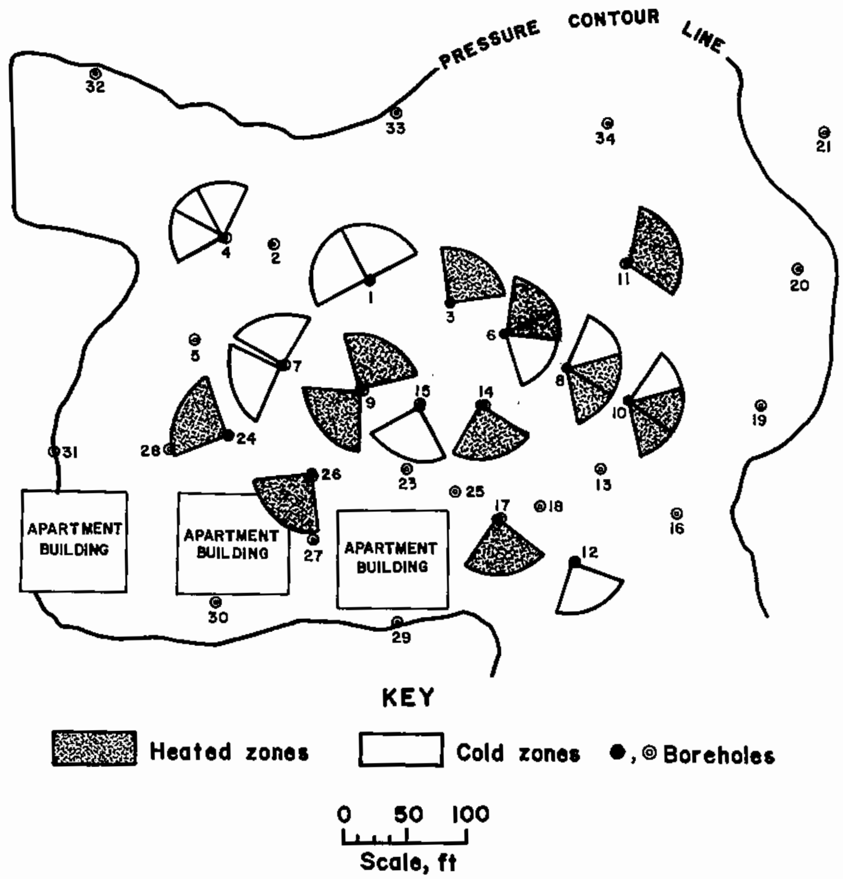

Figure 5.--Quadrant mapping of heated and cold zones after two communication tests. (Boreholes 3 and 26 are the suction points.)

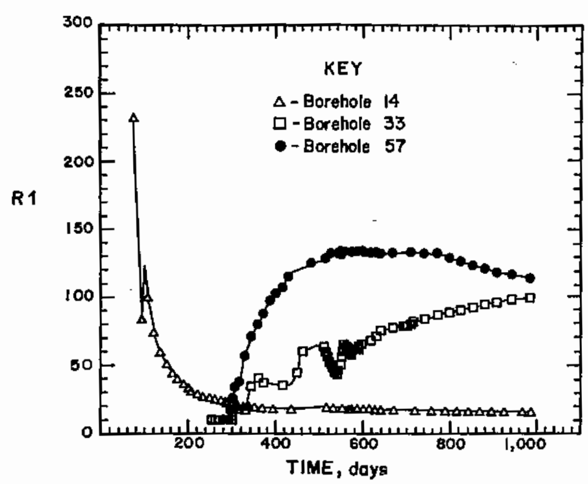

Figure 6.--R1 versus time curves for three randomly selected boreholes. (Baseline measurements taken at Renton, PA).

Carbondale Mine Fire Project

The Carbondale fire site lies within the anthracite coalfields of north-eastern Pennsylvania. It is thought that the heated zones are remnants of a 1946 city dump fire that had spread to abandoned underground coal mine workings (Chaiken et al. 1983). Attempts were made to extinguish the fire in 1950 by flushing and in 1974 by excavation. The extinguishment efforts were assumed successful until recent abnormal snow melt was observed. The Office of Surface Mining Reclamation and Enforcement (OSMRE) installed a series of 34 boreholes to monitor temperatures and CO concentrations throughout the 8-1/2-acre site. The Bureau of Mines was asked to assist in locating the heated zones.

The use of the mine fire diagnostic method at Carbondale is considered a test under nonideal conditions for the following reasons: (1) The emission rate for methane and low-molecular-weight hydrocarbons from anthracite is very low, and does not exhibit strong temperature dependence; (2) many of the boreholes were cased through the underlying coal seams; (3) the borehole diameters and depths were such that half of the suction fan's rated pressure drop would be used to overcome resistance to airflow in the pipe; and (4) a large rock fracture line crossed the region, possibly limiting the effectiveness of the communication tests. To overcome these conditions, several adaptations were made to the mine fire diagnostic method. Since the ratio R1 from laboratory tests was not expected to be a good indicator of heated coal, the change in the absolute concentration of methane was used for the index of combustion activity. Two suction fans rated at 40-in vacuum

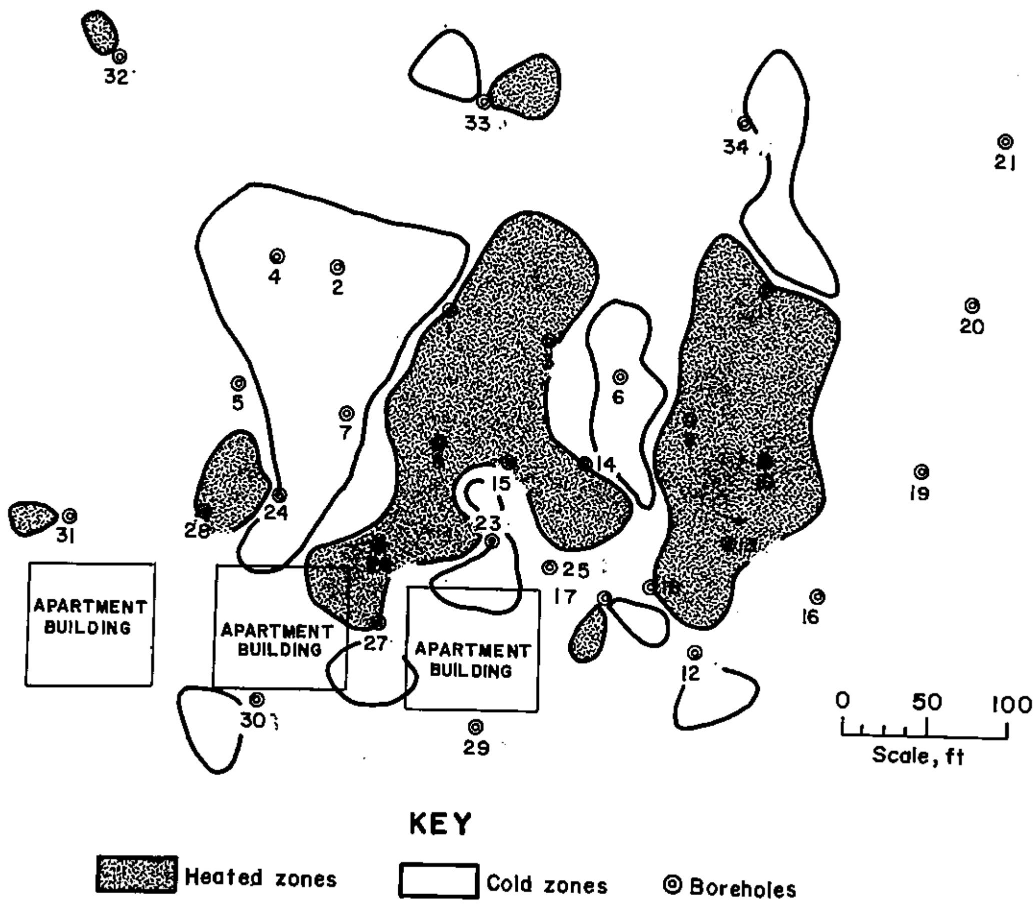

Figure 7.--Delineated heated and cold zones using the mine fire diagnostic technique. (Results of 25 communication tests at Carbondale, PA).

w.c. were connected in series in order to provide sufficient power to influence the movement of air in the mine.

The tests conducted at Carbondale located both heated and cold areas despite the nonideal conditions. The areas that show either evidence of combustion or no evidence of combustion activity, respectively, are delineated on the map of the Carbondale site (fig. 7). The seven non-contiguous heated zones that were identified included one region which had not been detected using temperature and CO concentration measurements alone.

Large Mine Fire Project

This fire is at an abandoned mine site in Large, PA. Although the project is in its early stages of development, a total of 8 mine fire diagnostic tests have been conducted at the 15-acre site. The diagnostic technique has been used to confirm the existence of fire and to obtain a preliminary estimate of the location of heated areas. These results have been used to place 25 more boreholes for additional testing to determine the location of the fire and to establish the location of a cold boundary. At Large, variations in R1 have indicated changes in subsurface conditions during long-term baseline (without suction) monitoring.

CONCLUSIONS

Laboratory results and field studies support the effectiveness and applicability of the Bureau's mine fire diagnostic technique in locating and monitoring abandoned mine fires. For the bituminous samples studied, values of the concentration ratio R1 increased with increasing temperature and decreased during cooling. Although values of R1 do not correspond to a particular temperature, elevated values of R1 are due only to the presence of heated coal. Time-dependent monitoring of changes in R1 reflect changes in the average temperature of the coal. The ratio R1 was not applicable to anthracite samples because of the lower rate of hydrocarbon emission and the very low concentration of higher hydrocarbons. However, borehole measurements of the variations in the absolute concentration of methane (often several hundred ppm in the case at Carabondale) strongly suggests that it is indicative of changes in coal temperature and therefore can be used when R1 is not appropriate.

The mine fire diagnostic method incorporates a sampling method that increases the detection zone of normal point source measurements by inducing gas movement. Measuring changes in a characteristic of the moving gas, i.e., hydrocarbon concentration, and plotting the results as vectors (magnitude and direction) rather than as points (magnitude), provides interpretive insight and bounds the area affected by combustion.

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

LITERATURE CITED

Chaiken, R. F., R. J. Brennan, B. S. Heisey, A. G. Kim, W. T. Malenka, and J. T. Schimmel. 1983. Problems in the control of anthracite mine fires: A case study of the Centralia mine fire (August 1980). BuMines RI 8799, 93 pp.

Chaiken, R. F., E. F. Divers, A. G. Kim, and K. E. Soroka. 1984. Calamity Hollow mine fire project (in five parts). 4. Quenching the fire zone. BuMines RI 8863, 18 pp.

Johnson, W., and G. C. Miller. 1978. Abandoned coal-mined lands: Nature, extent, and cost of reclamation. BuMines Spc. Publ. 679, 29 pp.

Kim, A. G. 1974. Low temperature evolution of hydrocarbon gases from coal. BuMines RI 7965, 23 pp.

Kim, A. G. 1978. Experimental studies on the origin and accumulation of coalbed gas. BuMines RI 8317, 18 pp.

Kim, A. G. 1986. Signature critieria for monitoring abandoned mine fires. In: Proc. 8th annual national absndoned mine lands conference, August 10-15, 1986, Billings, MT.

McNay, L. M. 1971. Coal refuse fires, an environmental hazard. BuMines IC 8620, 53 pp.