MINE FIRE DIAGNOSTICS AT THE LARGE MINE SITE[1]

A. G. Kim and L.E. Dalverny[2]

Abstract: The U.S. Bureau of Mines (USBM) has developed a Mine Fire Diagnostic Methodology to determine the location and extent of combustion zones in abandoned mines, to monitor the progress of extinguishment, and to identify the point at which a fire can be considered extinguished. In the USBM's method, a characteristic fire signature is based on the ratio of higher molecular weight hydrocarbons (C_2 to C_5) to total hydrocarbons. Initially, samples are obtained at the bottom of boreholes under baseline or static conditions. A second set of samples is obtained under communication, i.e., when a suction fan is used to influence the direction of gas movement at the base of each borehole. Temperature and pressure data are also obtained to define the degree of communication between boreholes. The value of the ratio under communication conditions is taken as a measure of subsurface fire activity related to a particular flow direction. Using a Venn diagram technique, the results are mapped as quadrants on a borehole map of the site. Repetition of the communication tests provides overlapping quadrants that define hot, cold, and indeterminate areas. In a field study at the Large site in Allegheny County, PA, Mine Fire Diagnostic Methodology indicated that a mine fire extended for approximately 152 m parallel to the buried outcrop. The combustion zone also extends into the mine, possibly more than 180 m. Additional, noncontiguous, heated areas were detected in the project area.

Introduction

Fires in abandoned mines and waste banks are a relatively common occurrence in coal-producing areas (Johnson and Miller 1979, Kim 1993, McNay 1971). Abandoned mine fires present serious health, safety, and environmental hazards due to the emission of toxic fumes, subsidence, and the deterioration in air quality. In most abandoned mine fires, the application of any control method is made more difficult by the inability to accurately locate the fire. Standard indicators such as borehole temperatures or surface venting are rarely indicative of subsurface heated or cold areas. The USBM's Mine Fire Diagnostic Methodology is based on controlled subsurface sampling for low molecular weight hydrocarbons desorbed from heated coal and can be used for remote evaluation of the combustion status of areas accessible only through boreholes. Using the results of the diagnostic method, a cold boundary can be defined. Monitoring during and after extinguishment can be used to determine if the fire is being propagated to other areas of the mine and when the area has cooled below the reignition point.

Under an agreement with the Pennsylvania Department of Environmental Resources (DER), the USBM used its Mine Fire Diagnostic Methodology to determine the location and extent of combustion zones at the Large fire site. Administrative delays, problems in obtaining drilling services, and the unsuspected extent of the fire, made it necessary to perform the diagnostic work in two phases over a 4-yr period (1986-88, 1990).

Mine Fire Diagnostic Methodology

To determine the location of a subsurface fire, it is necessary to (1) identify a parameter that is characteristic of the fire, (2) measure the parameter through appropriate sampling methods, and (3) have a logical and consistent method of interpreting the results. In the Mine Fire Diagnostic Methodology developed by the USBM (Dalverny and Chaiken 1991, Kim et al. 1992), borehole measurements of temperature, pressure,

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[2]A. G. Kim, Supervisory Physical Scientist, L. E. Dalverny, Physicist, U.S. Bureau of Mines, Pittsburgh, PA.

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combustion products, and desorbed hydrocarbon gases obtained under natural or baseline conditions are compared to those obtained when a suction fan is used to impose a pressure gradient. It is assumed that mine gases will flow radially from the surrounding underground areas toward the point at which the suction is being applied. Hydrocarbon desorption from coal is temperature dependent; by relating the movement of gases to assumed flow directions, a Venn diagram technique can be used to define heated areas.

A concentration ratio of hydrocarbon gases desorbed from heated coal is the characteristic fire signature in the USBM's diagnostic method. Research by the USBM (Kim 1991) has shown that the desorption of low-molecular-weight hydrocarbons, 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. For most coals and coal wastes, as the temperature increases, the concentration of heavier hydrocarbons in the desorbed gas also increases. A relative index, R1, was defined as

$$R1 = \frac{1.01\,[THC] - [CH_4]}{[THC] + c} \times 1{,}000,$$

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

Based on laboratory tests of bituminous coals, R1 can be empirically related to coal temperature:

R1	Interpretation
0	No hydrocarbons detected
10	Only methane detected
11 to 50	Normal temperature
51 to 100	Possible heating
> 100	Heated coal.

The use of hydrocarbon emission as a diagnostic indicator has several advantages: (1) Changes in the rate of hydrocarbon emission are caused by changes in temperature, (2) changes in hydrocarbon emission can be detected for temperatures far below the "ignition" temperature for coal, thus increasing the sensitivity of the method, (3) hydrocarbons can be routinely detected by gas chromatographic analysis at concentrations as low as 1 ppm, and (4) the use of a ratio of gas concentrations can minimize the effect of dilution. R1 can also be used for time-dependent monitoring of relative changes in temperature, such as during remote extinguishment, after extinguishment to obtain early warning of reignition, and after surface sealing.

To determine changes in the combustion signature, access to the coal horizon and a method for remotely obtaining uncontaminated samples are required. In the Mine Fire Diagnostic Methodology, boreholes are drilled to the base of the coal bearing strata and cased to within 1 m of the coal mine roof. A thermocouple and sampling line extend to near the bottom of the borehole from a borehole instrumentation cap. A diaphragm pump and evacuated sample tube are used to sample the mine gases.

Two types of data are obtained during a fire project. Baseline measurements (temperature, pressure, and gas composition) are made under natural conditions. Communications measurements are made while suction is being applied to the underground environment. Differences in pressure, between baseline and communication values, indicate the extent to which the suction fan affects the mine at any sampling point. Positive or negative changes in the gas composition, as indicated by R1 values, are related to heated or cold areas.

The data analysis involves several steps. A change in the pressure at the bottom of the boreholes of at least 5 Pa (.02 in-H_2O) indicates communication between the boreholes and the suction hole, and defines the area for which the data are valid. A 90° shaded quadrant having a radius of 15 m is drawn on a scaled site map at each borehole. The quadrant apex is centered at the borehole, and the quadrant appears to be pointing towards the suction borehole. The quadrant shading based on the R1 value represents areas that are cold, warm, or hot. Areas for which there are no data are also defined. A composite of all test results is constructed. Combining the results of all tests effectively bounds the possible fire zones through successive approximation. The method defines probable combustion zones and also indicates the location of the cold boundary, an important consideration in implementing an extinguishment plan.

Site Description

The Large mine fire site is located in Allegheny County, PA. The fire is in the Pittsburgh coal seam, which at this location outcrops at the base of a hill. Approximate depth of overburden ranges from 6 to 55 m. The surface area affected by the mine fire is approximately 1 hectare (fig. 1). The slope averages 20°. Five gas pipelines and three sets of high voltage power lines cross the property.

The fire is located in what is believed to have been the Walden Pool #2 Mine. Active underground mining probably ceased in the 1920's. Between 1953 and 1964, the Pittsburgh and Redstone coal seams were partially strip mined. The property was restored to the then-current standard of the law, and the mine operator was released of liability for the mine site.

The fire apparently started at an unknown date on the stripped area and was first reported in December 1976. At that time, the fire could be seen burning along the highwall and in an entry. Apparently, some of the burning material was removed and the entry was sealed. This assumption is based on the fact that the entry is no longer visible and a small pile of burning material was located near the old mine as recently as 1986.

The elevation of the Pittsburgh Coalbed at the Large site is approximately 253 m above mean sea level. The Redstone Coalbed occurs approximately 20 m above the Pittsburgh Coalbed. Shales, sandstone, and limestone occur between the Redstone and Pittsburgh Coalbeds.

Over a 10-yr period, seven 6.35-cm (2.5-in) and sixty-four 20-cm (8-in) boreholes (BH) and four 5-cm (2-in) coreholes were drilled at the Large site. Fifty of the 20 cm holes, seven of the 6.35 cm holes, and two coreholes were used as monitoring points for the mine fire diagnostic tests. The other boreholes were not used for diagnostic testing because they terminated in solid coal and had been backfilled, because they contained more than 0.6 m of standing water, or because they had sustained well bore damage during drilling. Seven of the boreholes were terminated below the Redstone Coal instead of the Pittsburgh Coalbeds. These were retained as temperature-monitoring points but were not used for diagnostic testing.

Diagnostic Results

Baseline values for temperature, static differential pressure, and gas composition were determined on a regular basis at the Large site. The sampling point was approximately 1 m below the casing and 1.5 m above the bottom of the borehole. During the first diagnostic phase, the average baseline temperature for three boreholes was over 100° C (fig. 2); most of the holes had an average baseline temperature between 30° and 100°C. Ten of the holes had an average baseline temperature of less than 20°C. During the second diagnostic phase, the average baseline temperature at borehole 43 decreased from over 350° C to less than 100° C. Average baseline temperatures at other boreholes exhibited little variation; temperatures at the holes drilled near the perimeter of the work area were generally in the 30° to 50° C range. Temperatures measured in the Redstone Coal, 18 to 27 m above the mine, were also above normal subsurface values, in the 20° to 40° C range. The normal subsurface temperature in the mine would be expected to be in the 11° to 15° C range.

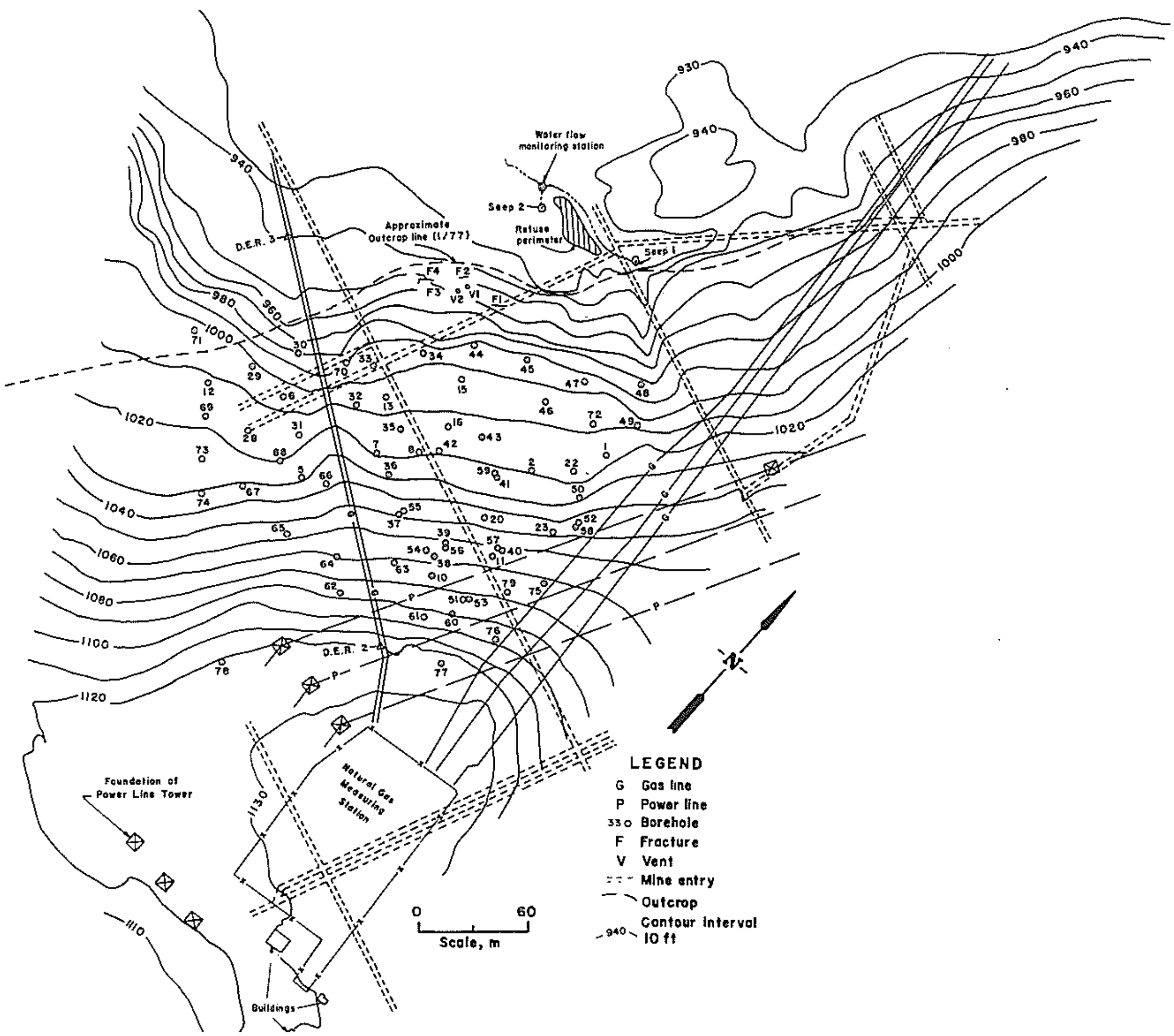

Figure 1. Plan view of the Large site with locations of boreholes, gas pipeline rights of way, power lines, and site boundaries.

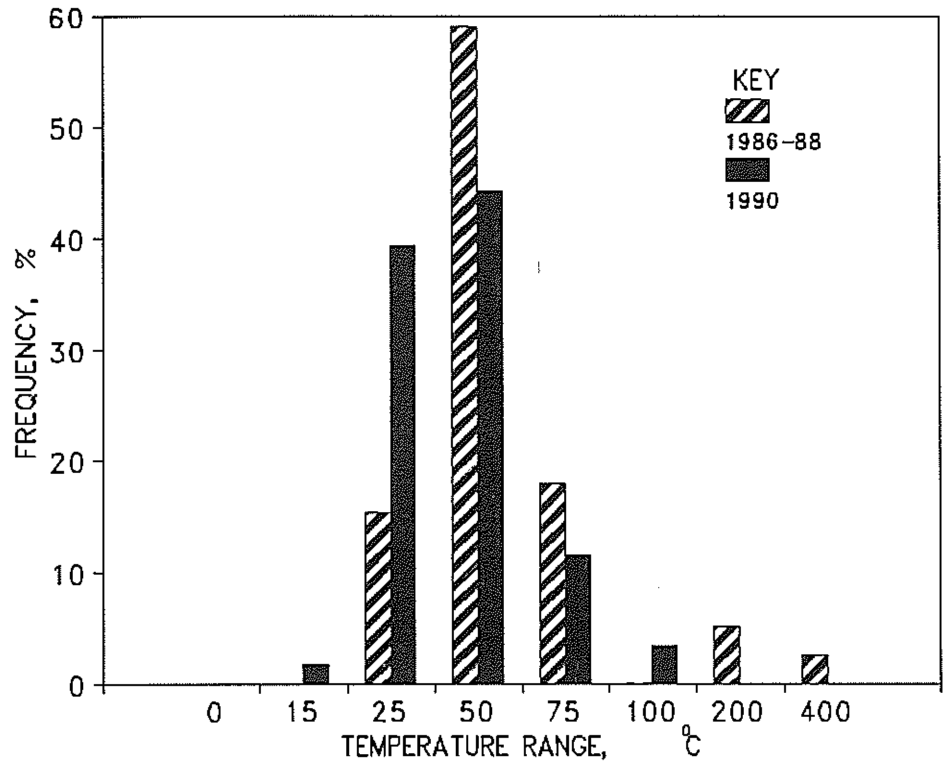

Figure 2. Relative frequency distribution of baseline temperatures at Large site for all boreholes during phase 1 (1986-88) and phase 2 (1990) of diagnostic testing.

Since the temperature at only one borehole was what would be considered a normal value, the baseline temperatures indicated that large areas of the mine were being heated by the fire.

The static differential pressure (the difference between the ambient surface barometric pressure and the measured pressure in the mine) was also determined. A differential pressure of 0 indicates that the mine is at the same pressure as the atmosphere. In the absence of a fire, the differential pressure should be uniform throughout the mine. An average baseline differential pressure greater than 0.05 cm H_2O was measured in 10 of the boreholes. Elevated pressures may be due to mass addition of combustion products to the airstream and to thermal expansion of the hot gases. Eleven of the boreholes had average differential pressures between 0 and -0.20 cm H_2O. Areas that exhibit negative differential pressures may indicate that air is being drawn into the mine. Variations in differential pressure may indicate that the mine fire is causing the formation of a convection cell within the mine.

The mean baseline hydrocarbon diagnostic ratio (R1) was greater than 100 at eight boreholes during the first diagnostic phase. During the second diagnostic phase, the average baseline R1 value was over 100 at 22 boreholes, including 4 of the holes drilled near the perimeter of the site (fig. 3). The baseline diagnostic ratio was between 50 and 100 at five boreholes and less than 50 at two boreholes. The total hydrocarbon concentration was less than 20 ppm at the remainder of the boreholes.

For the majority of boreholes, the mean baseline oxygen (O_2) concentration was above 12% (fig. 4), a relatively high value for an abandoned mine. The average carbon dioxide (CO_2) concentration was inversely correlated with the O_2 concentration (fig. 5) Only 10 of the boreholes had average baseline carbon monoxide (CO) concentrations greater than 0. The baseline gas composition indicated that combustion was occurring in a relatively oxygen-rich environment.

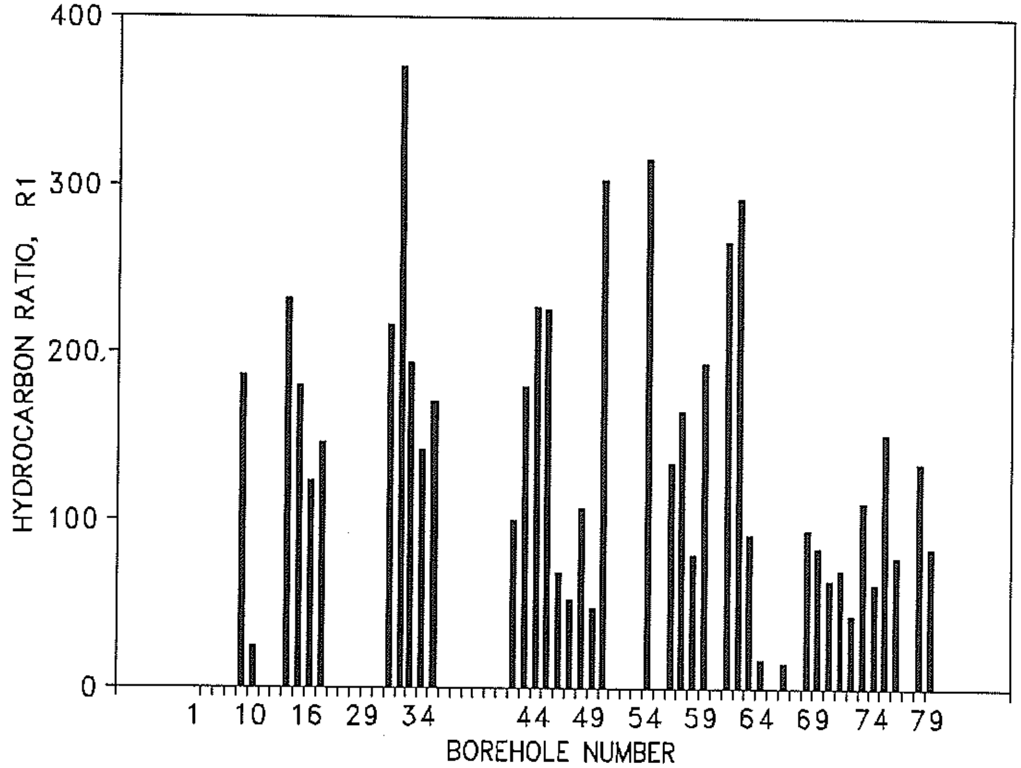

Figure 3. Baseline hydrocarbon ratio (R1) at Large site. Boreholes without values had total hydrocarbon concentration < 20ppm.

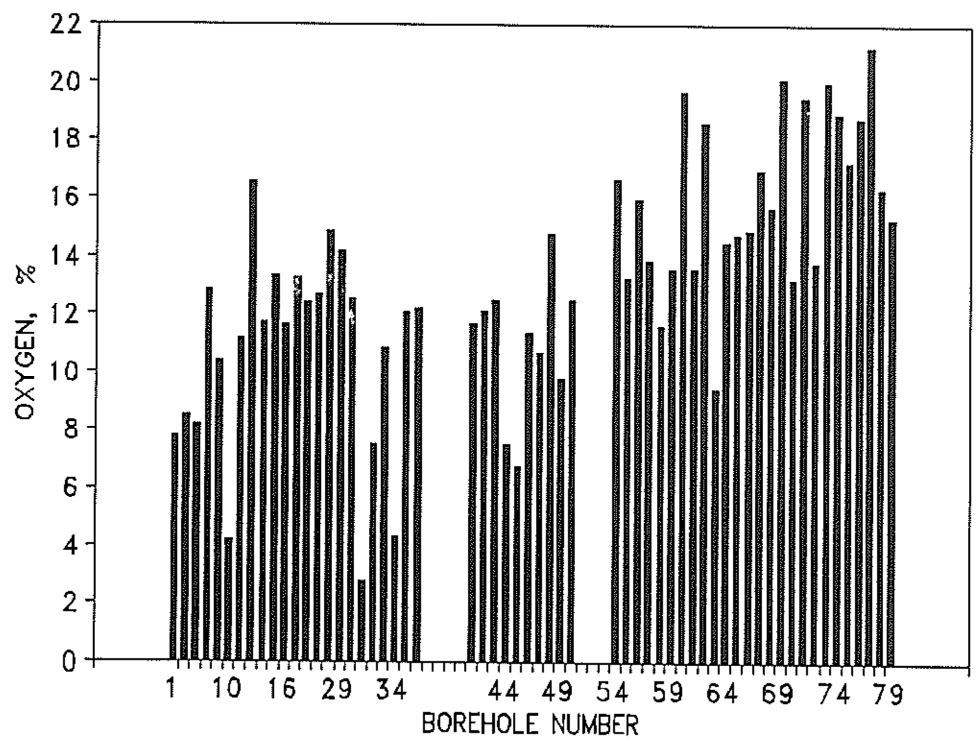

Figure 4. Mean baseline oxygen concentration (pct) at Large site for all boreholes to Pittsburgh coalbed.

Over a 4-yr period, 61 communication tests were performed at the Large site. The earliest communication tests detected a heated zone around BH 15 and 16 and BH 6 and 20. Cold areas were detected at BH 8, 10, 11, 12, and 13. At BH 1, 2, 7, and 23, the concentration of hydrocarbons was too low to determine a valid signature. From the data available at that time, it was inferred that the primary combustion zone was located near the outcrop, with possible heated areas in the interior of the mine and to the west of the northwest gas transmission lines. It was presumed that a cold boundary existed from BH 12 eastward to BH 10 and 11 and northward to BH 2.

In the next year, 25 communication tests located an extended combustion zone along the outcrop and in the interior of the mine beyond BH 20. Signature values obtained from boreholes to the west of the northwest gas transmission lines indicated an isolated heated zone around BH 6 and a cold boundary extending from BH 12 through BH 28. Although the cold boundary values were again obtained at BH 10 and 11 and at BH 52, there was an indication that the combustion zone was extending toward this area. Five communication tests in the third year confirmed the earlier tests. The only significant change was the apparent decrease in combustion activity around BH 6.

In phase 2 the results of 23 communication tests indicated a more extensive combustion zone along the outcrop. The heated area previously detected around BH 20 was determined to extend to BH 76. Heated areas were also detected beyond what had been presumed to be a cold boundary from BH 12 to BH 10.

Based on the results of all communications tests at the Large site, it was apparent that a combustion zone extended parallel to the buried outcrop for approximately 152 m (fig. 6). This zone also apparently extended 182 m into the mine, possibly along a set of main entries. There is evidence of heating to the left and right of the combustion zone that is perpendicular to the outcrop. Areas of low hydrocarbon concentrations exist to the right and left of the combustion areas. In the area around BH 47, combustion signatures were detected where the concentration of hydrocarbons in previous samples had been below the detection limit.

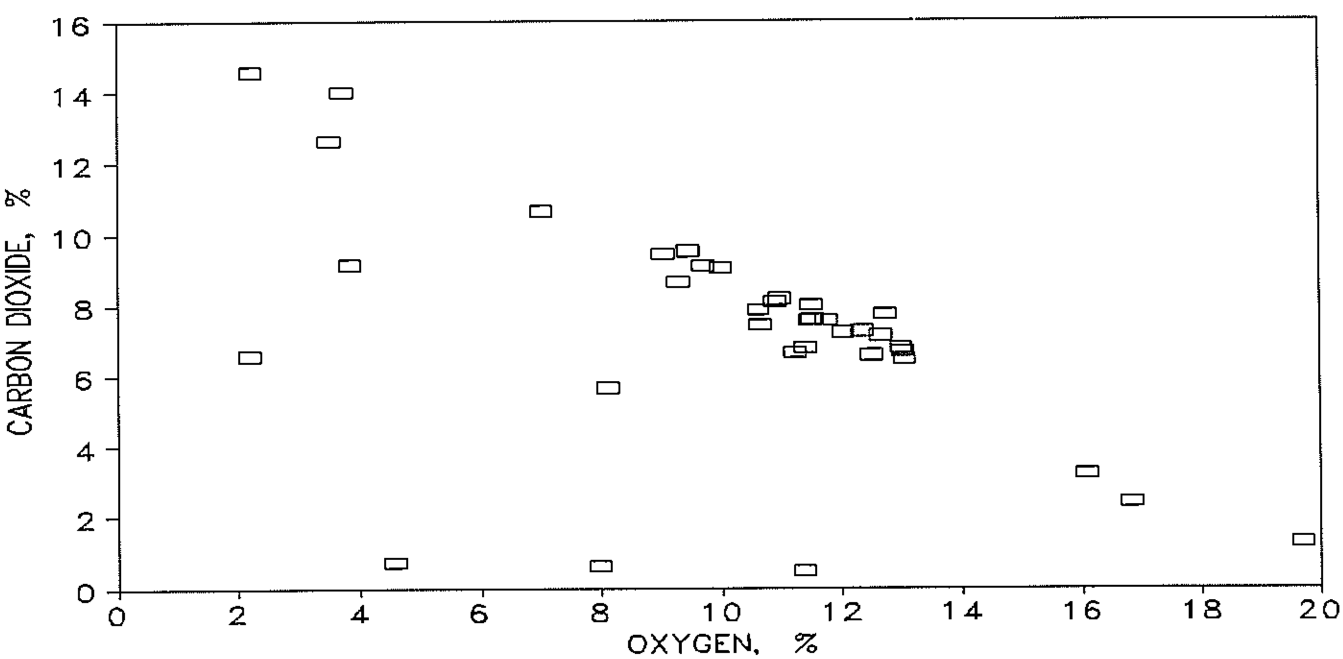

Figure 5. Variation in mean carbon dioxide concentration with mean oxygen concentration (volume pct) for baseline testing at the Large site.

The application of the USBM's Mine Fire Diagnostic Methodology at the Large mine fire indicates that the fire has propagated at least 152 m parallel to the outcrop. All surface venting occurs between the buried outcrop and the boreholes used to locate the fire. The fire also extends 180 m or more into the mine, possibly along a set of main entries. It extends beyond the area that can be sampled through the existing boreholes. Combustion in the Large Mine is occurring in a relatively oxygen-rich environment. At the majority of boreholes, the average oxygen concentration is at or above 8%. In an abandoned mine, bacterial activity and other ambient temperature processes normally reduce oxygen levels below this value. The relatively high oxygen concentration indicates that there is a source of fresh air into the mine.

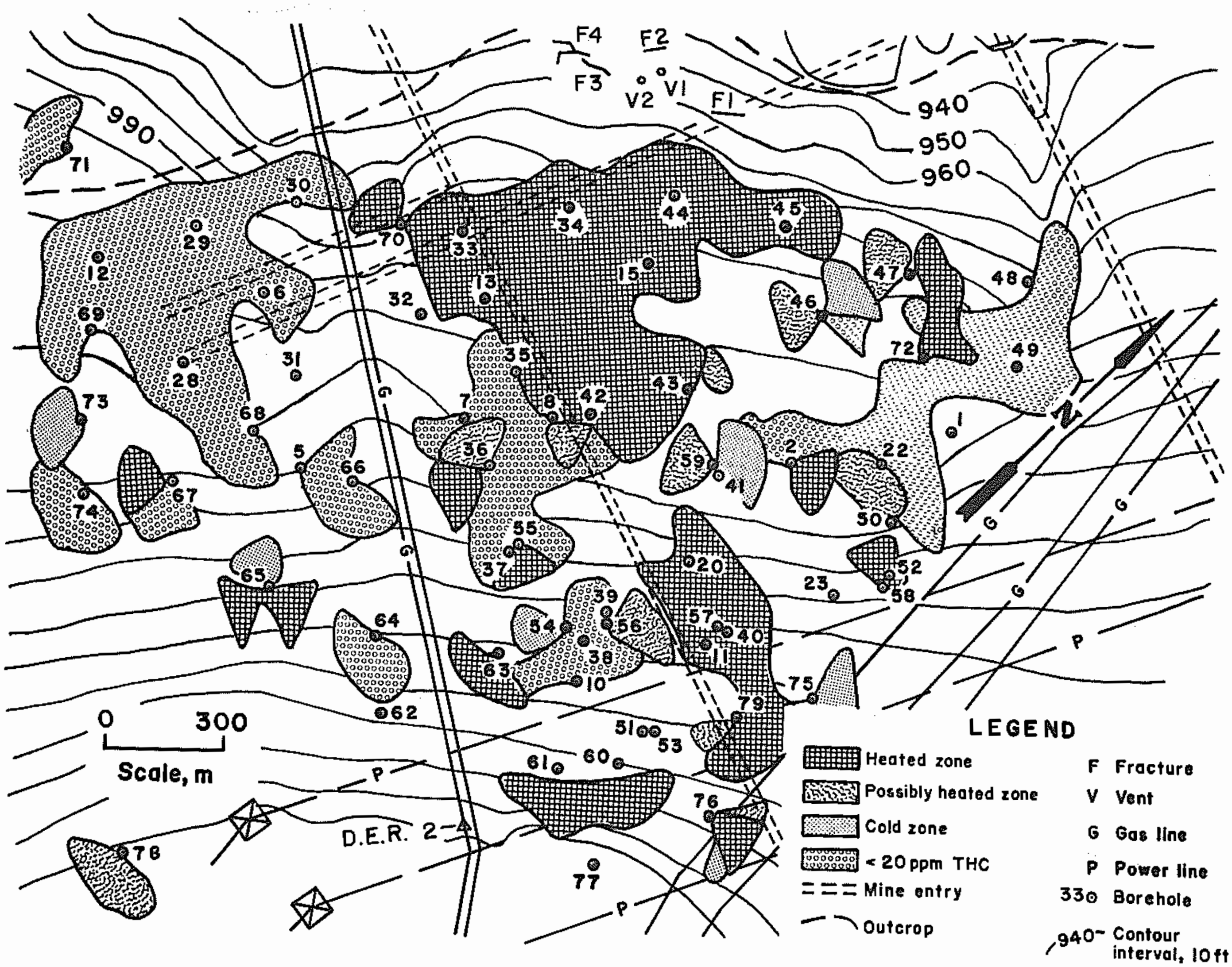

Figure 6. Map of Large Mine Fire Site showing heated and cold zones, with surface contours and approximate locations of mine entries.

Summary

The USBM has used its Mine Fire Diagnostic Methodology to determine the subsurface location of a fire in an abandoned mine. Areas of venting were confined to a relatively small area and indicated propagation along the burned outcrop. Temperature monitoring indicated that large areas of the mine were heated but did not define a combustion zone. As defined by the USBM's Mine Fire Diagnostic Methodology, the mine fire at Large extends for approximately 150 m parallel to the buried outcrop. The combustion zone also extends into the mine, by 180 m or more. This in-mine area may coincide with a set of main entries. Noncontiguous heated ares were detected in the southwest quadrant of the project area. Diagnostic testing indicates that the heated zone extends beyond the boundary of the current work area.

The apparent direction of propagation into the mine appears to coincide with the location of a set of main entries. Heated areas have been detected to the north and south of this area. By overlaying the surface map on an old mine map, it appears that the fire may be in the entries that extend beyond BH 79. This entry intersects another set of entries that extend north and south under the adjacent road. Subsurface fires generally move toward a source of air, which may be either a portal that the old maps indicated existed in the valley approximately 1 mile from the site or permeable zones in the outcrop.

A cold boundary may be presumed to exist in the area between BH 30 and 69 and in the area of BH's 48, 49, and 72. A cold boundary has not been located for the inby portion of the mine. Determining the limit of the combustion zone would require extending the borehole array and additional diagnostic testing.

The use of the USBM's Mine Fire Diagnostic Methodology at Large indicated that it is capable of defining subsurface heated and cold zones. The work at Large also indicated that the method requires an extended array of 20 cm cased boreholes. In the absence of natural features to bound the fire zone, locating a fire may require several rounds of drilling to determine the extent of combustion. The method also is labor intensive, and repeated iterations of the communication tests are time consuming. The use of more advanced instrumentation may reduce the time and labor involved in communication testing. A more efficient diagnostic system could incorporate the preliminary use of a remote noninvasive technique to indicate the extent of the combustion area, followed by the more accurate borehole diagnostic testing.

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