MINE FIRE DIAGNOSTICS IN ABANDONED BITUMINOUS COAL MINES[1]

by

Louis E. Dalverny, Robert F. Chaiken, and Ann G. Kim[2]

Abstract. The Bureau of Mines is developing a Mine Fire Diagnostic methodology to locate and monitor fires in abandoned coal mines and waste banks. The method assumes that: (1) measurable changes in the emission of low molecular weight hydrocarbons from coal are directly temperature dependent, and (2) analysis of controlled underground air flow between borehole sampling points can determine the source of the hydrocarbons.

A hydrocarbon ratio, R1, a signature for heated coal, is related to the relative concentrations of methane and total hydrocarbons (methane through pentane). An exhaust fan attached to a borehole creates underground pressure gradients that control the movement of gases past a network of borehole sampling points. Changes in R1 value are correlated with the assumed direction of gas flow between borehole pairs. Multiple tests with different orientations allow spatial definition of both heated and cold subsurface zones.

The Mine Fire Diagnostic methodology has been used to define non-contiguous combustion zones, locate cold boundaries in remote combustion areas, determine effects of extinguishment activities on the fire, and accomplish long-term monitoring. Results obtained at two abandoned bituminous coal mine fires are discussed. This method's advantages are: (1) hydrocarbon emission changes are caused only by temperature changes; (2) emission changes can be detected for temperatures well below the ignition point of coal; (3) hydrocarbons in gas samples can be detected at concentrations of 1 ppm; (4) use of a ratio eliminates air dilution effects; (5) induced vacuums can be detected and mine gases withdrawn several hundred feet from the suction point; and, (6) system operation is relatively simple, requiring only readily available equipment.

Introduction

Fires in abandoned coal mines and waste banks are a relatively common occurrence found in every coal producing state. Abandoned mine fires present serious health, safety, and environmental hazards caused by the emission of toxic fumes, subsidence, and the deterioration of air quality. Such fires usually depress property values for affected land and for adjacent areas. Surveys from 10 years ago (Johnson 1978, McNay 1971) listed 292 waste bank fires and 261 underground fires. Data from the 1988 National Abandoned Mine Lands Inventory indicate about 95 underground mine fires (Maynard 1989). In a study of problems associated with anthracite fires (Chaiken 1983), it was observed that successful fire control efforts are expensive and that many fires have required repeated efforts to finally control them. Although there are several fire extinguishment methods, in many cases the high cost (between $250,000 and $100 million per project) and low efficiency (less than 75 pct) are related to the inability (1) to accurately determine the location and extent of the combustion zones within an abandoned mine, and (2) to identify some point at which the fire can be reliably considered extinguished.

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The emission of smoke and fumes at surface fractures and vents is the conventional indicator of an abandoned mine fire. Because hot gases follow the path of least resistance, the surface evidence of fires may not be related by straight line paths to the source of combustion. Aerial infrared photography determines temperature variations within a few inches of the surface, but is inappropriate when heated areas lie one hundred or more feet beneath the surface. Interpretation of aerial infrared can also be complicated by the presence of heat absorbing surface features. Temperature and gas samples taken at boreholes are point source measurements; their accuracy is limited to a very small volume at the base of the borehole. Because wasted coal fires may be confined to one or more areas of smoldering combustion that may or may not be connected, and because surrounding rock and coal masses can serve as insulating media, it is possible to measure near normal underground temperatures within several feet of a combustion zone. In abandoned mines, submicron particulate detectors have given ambiguous results, probably because of the high moisture content of the mine atmosphere.

Indicators based on the evolution of products of combustion such as CO_2, CO, H_2, and oxygen deficiency have not given reliable results, probably because changes in these indicators may be produced by processes other than combustion. Also, there may be a reservoir of such gases in which changes in concentration caused by combustion are insignificant. In contrast, previous work by the Bureau (Kim 1974, Kim 1978) has shown that the desorption of low molecular weight hydrocarbon gases from coal is strongly temperature dependent. Changes in the concentration of desorbed hydrocarbons can be detected at temperatures of less than 100° C. The Bureau's Mine Fire Diagnostic method is based on the temperature dependent desorption of low molecular weight hydrocarbon gases from coal and controlled subsurface sampling and is not constrained by the other factors.

In order to locate a fire, it is necessary that (1) a fire have a measurable characteristic, (2) the characteristic be detectable through appropriate sampling methods, and (3) the sampling data are interpreted correctly. In the method discussed here, the measurable characteristics are borehole temperature and pressure and the concentrations of low molecular weight hydrocarbons in the mine atmosphere. Their initial values are determined under natural or baseline conditions. Then, these values are compared to those obtained when a suction fan is used to impose a pressure gradient that causes mine gases to flow radially from the surrounding underground areas toward the point at which the suction is applied. Differences in the concentration of hydrocarbon gases (methane and the C2 to C5 alkanes) at various points underground can be related to the movement of the desorbed gases in assumed directions from the source toward the suction point.

The 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, increasing the effective sampling volume and sensitivity of the method; (3) hydrocarbons can be detected at concentrations as low as 1 ppm; (4) the use of an appropriate ratio can eliminate the effects of sample dilution; (5) induced pressure effects usually can be detected several hundred feet from the suction point; and, (6) operation of the system is fairly simple, requiring only readily available equipment and normal technical skills.

This paper includes short discussions of: the laboratory study to develop a data base relating hydrocarbon desorption from various coals to temperature under controlled conditions in the effort to establish measurable criteria for determining actual extinguishment; the resultant development of a ratio (a signature value) based on the concentrations of desorbed hydrocarbons that is characteristic of heated coal; the field method that creates and controls the dynamic sampling environment; and the interpretive method that defines heated and cold subsurface zones. Examples of the use of the Mine Fire Diagnostics method are also given. (Extensive descriptions are found in Dalverny 1990, Kim 1989, and Kim 1989)

Coal Fire Characterization by Hydrocarbon Signatures

The internal structure of coal is like a sponge with many small interconnected pores (micropores) with an average diameter of 5 to 20 angstroms (Kim 1978). Coal also has a system of cracks or fractures (macropores) which intersect the micropore system. Both the fracture density and the width of the fractures can vary (Kissell 1975). Hydrocarbon gases formed during coalification are adsorbed on both the micropore and macropore surfaces. These gases are a mixture of methane, ethane, propane, iso- and normal butanes and pentanes (Kim 1973, 1973, 1988). The adsorbed gas in coal may also contain small amounts of carbon dioxide and hydrogen, products of coalification; oxygen and nitrogen, occluded during deposition or introduced by percolating ground water; and helium, a product of radioactive decay. Normally, coalbed gas is more than 90 % hydrocarbons. Elevated concentrations of carbon dioxide are frequently associated with areas of tectonic activity. Carbon monoxide and sulfur compounds are not normally found in gas removed from coalbeds. All of the low molecular weight hydrocarbons associated with coal would be in the gaseous state at normal ground temperatures. Under all conditions, some gas escapes from the coal and is emitted into the atmosphere.

The rate of gas emission from coal to the atmosphere is dependent upon temperature, the pressure differential between the coal and the atmosphere, the rank of the coal, the degree of fracturing, the permeability of the coal, and the permeability of adjacent strata. The desorption and emission of hydrocarbons other than methane significantly affect the overall emission rate. Changes in the concentration of desorbed methane and the C2 to C5 alkanes can be detected at temperatures below 100° C.

At normal ground temperatures, the gas drained from coalbeds is over 90 % methane, probably because more methane is formed during coalification and because it requires less energy to desorb the lighter methane molecule. At 150° C, the concentration of methane is about 35 %. In active mines, changes in the emission rate may be related to changes in surface area due to coal breakage or to changes in barometric pressure. In abandoned mines, temperature is the major factor which affects the emission of hydrocarbons from the coal and carbonaceous shale; hence, the composition of hydrocarbon gases in the mine atmosphere would relate to the temperature of the coal in the mine.

In order to quantitatively relate hydrocarbon desorption to changes in the temperature of coal, the Bureau conducted a laboratory study (Kim 1988) in which duplicate continuous heating tests were completed on samples of six bituminous coals, one bituminous waste, two anthracite coals and two anthracite wastes. Gas samples were taken during heating and cooling phases of the tests and analyzed for oxygen, nitrogen, carbon dioxide, carbon monoxide, hydrogen, and the hydrocarbons: methane, ethane, ethylene, acetylene, propane, propylene, butanes and pentanes. The concentration of total hydrocarbons for each of the bituminous samples, including the waste, was between 100 and 1000 ppm.

The results obtained from the continuous heating tests were dependent to some degree upon the rank of the coal. For bituminous samples, the concentration of methane and the concentration of higher molecular weight hydrocarbons both increased during heating and decreased during cooling. Using these data, a concentration ratio was defined which relates both factors in a single parameter suitable for graphical presentation. By definition, this ratio is:

$$R1 = \frac{1.01[THC] - [CH4]}{[THC] + c} \times 1000$$

where [THC] = concentration of total hydrocarbons, ppm
[CH4] = concentration of methane, ppm.
c = constant, 0.01 ppm

The ratio R1 was designed so that it would (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 mandatory consideration in 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. At this time, the only constraint on the use of R1 as an indicator of heated coal is a practical one; namely, that the concentration of methane in the gas samples be greater than 20 ppm. Below this level, the concentration of other C2 to C5 hydrocarbons present could be below the current 1 ppm detection limit of standard GC analytical techniques, and thus, changes in the hydrocarbon concentrations with temperature might not be detected.

Through the laboratory studies, characteristic values of R1 could be defined for the bituminous coal samples. (Unfortunately, it was found that the anthracite coal samples had a completely different behavior; namely, that few C_2 to C_5 hydrocarbons were liberated at elevated temperatures. This could be due to the very tight micropore structure of anthracite coal relative to bituminous coal.) Generally, the values of the ratio R1 for the bituminous coal can be interpreted on an empirical scale as:

R1	Relative Coal Temperature
0 to 50	Normal (<30° C)
50 to 100	Possible Heated Coal (30° to 100° C)
> 100	Heated Coal (>100° C)

It should be emphasized that the absolute value of the R1 ratio is not necessarily uniquely defined by the coal temperature. R1 values during heating are not equal to the R1 values at the same temperature during cooling. The value is influenced by the rank and internal structure of the coal, and by the amount of gas adsorbed on the coal surface. It is however, indicative of an average temperature condition (elevated values of R1 are due only to the presence of heated coal), and over a period of time will increase with increasing temperature and decrease with decreasing temperature.

The use of a hydrocarbon ratio as a fire signature (for bituminous coals) has several advantages: (1) Hydrocarbon desorption occurs at relatively low temperatures; therefore, the mass of the coal from which the hydrocarbons are desorbed is much larger than that directly affected by combustion. Because the source is larger, the signature is more sensitive. (2) Because a ratio is used, and if the concentration is above the detection limit, dilution with air or combustion products is not a factor. The hydrocarbon ratio is independent of the concentration of other components, such as oxygen and carbon dioxide, and temperature dependent desorption is the major mechanism by which hydrocarbons are produced in an abandoned mine. The use of this hydrocarbon ratio produces a positive and sensitive indicator of remote subsurface combustion.

Remote Fire Detection using Communication Testing

The Mine Fire Diagnostic methodology is based on the assumption that a sufficiently large negative pressure (vacuum) applied to underground regions will cause the gases in the mine atmosphere to flow from some distance toward 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 through one borehole. Repeated sampling at all points in a borehole pattern provides data to determine the presence or absence of fire along pathways between the sampling points. Differences in borehole temperature, pressure, combustion products, and desorbed hydrocarbon gases, are assumed to be related to the radial flow of mine gases from the surrounding underground areas toward the point at which the suction is being applied (fig. 1). Figure 2 is a simplified, one-dimensional depiction of this concept with the exhaust fan attached to the left-most hole. If there is communication between the exhaust hole and the neighboring holes, a decrease in static pressure will be measured at the bottom of each

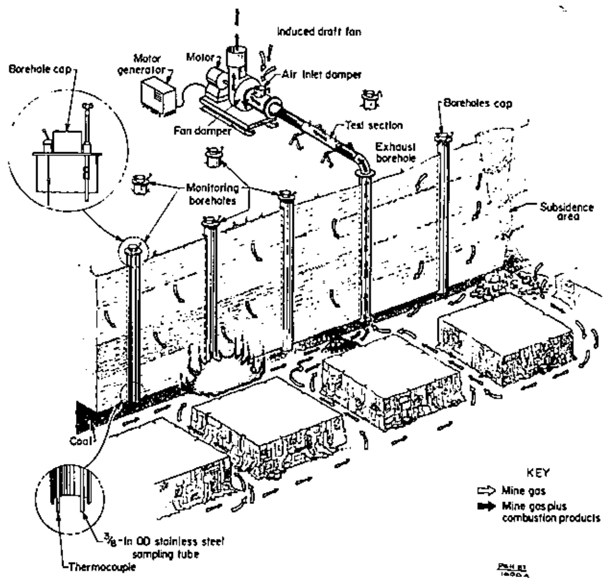

Figure 1. Artist's Representation of Mine Fire Diagnostic Technique.

casing. If a fire exists to the right of the right-most hole (Case A), fire signature gases will be detected in gas samples taken at each borehole. Similarly, a heating between the exhaust hole and its nearest neighbor (Case C), would be detected only at the exhaust hole. To verify the location of heating in an actual mine, the fan is moved to various boreholes set in a pattern and the communication test is repeated. The specific fire location is then determined by overlapping the signature data in a manner similar to triangulation.

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.

In the first step of the testing procedure, a series of boreholes is drilled and cased to depths consistent with coal bearing strata. Borehole locations are based on surface evidence of the fire, mine maps if available, and efforts to achieve a regular pattern on approximately 100 ft. centers. Although various sizes of boreholes have been used, 8-in. I.D. casing is preferred. With smaller diameter casings, frictional resistance to air flow can cause most of the fan's capacity to be used to move air from the bottom to the top of the casing. With larger diameter pipe, the lower resistance to air flow allows the fan-induced vacuum to affect a larger underground area. Also, there is more room in the larger pipe for lowering monitoring equipment such as water sample bottles, cameras, pressure transducers, sampling lines and thermocouples.

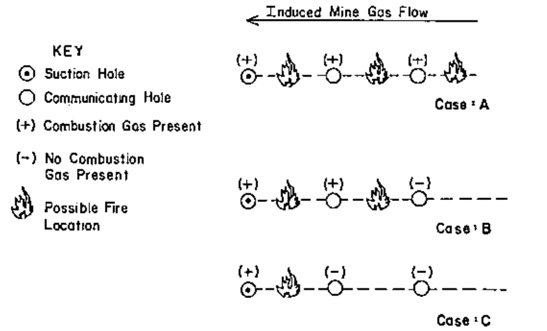

Figure 2. Schematic of Mine Fire Diagnostics

Tests in the first series of holes are used to define heated areas in general. The results from the first round of testing are then used to determine the placement of additional boreholes. A second round of tests is performed to verify the location of heated zones and to establish the presence of a cold boundary. The number of tests in each round is determined by the number of boreholes used as fan attachment points. Depending on the site conditions, some holes may not be used as suction points, and some may be used more than once.

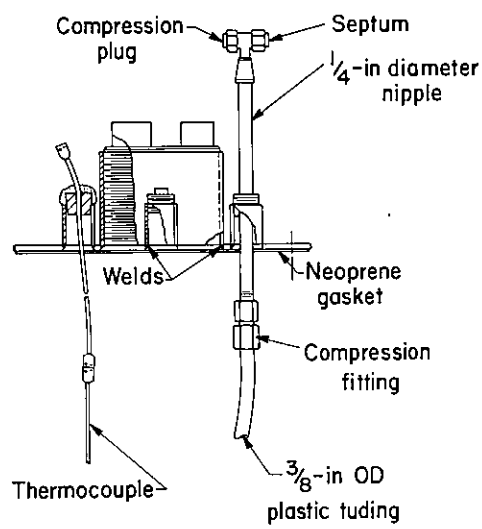

Figure 3. Instrumented Borehole Cap.

The borehole instrumentation cap (fig. 3) holds temperature and pressure probes and a gas sampling tube at or near the bottom of the borehole. To measure the borehole pressure and to obtain gas samples, a 3/8-in. O.D. plastic sampling tube is connected to a tee and septum arrangement at the borehole cap. This tube extends approximately 6 to 12-in. below the bottom of the casing. One side of the tee is capped with a compression plug which is removed for attachment to the gas sampling pump; the other end contains a septum to allow for needle connection to a pressure gauge. Pressure measurements are made with a Magnehelic[3] pressure gauge. Gauge measurements are accurate to +/- 0.005-in. w.c. One port of the pressure gauge is attached to the sampling tube, via a length of 1/4-in. tubing and a hollow needle arrangement, at the borehole cap's septum port. The septum allows measurement of the pressure in the sample tube without disturbing or contaminating the gas within the tube. The other gauge port is left open to the atmosphere. Changes in pressure during communication tests establish whether the suction fan is affecting the area around the borehole. Normally, pressure changes in the range of 0.005 to several inches w.c. are measured. A diaphragm pump (MSA model S) capable of 0-10 l/min. at 20 to 40-in. w.c. is used to sample the mine gases. An inlet line with a Y-connector and needle arrangement is attached to the sampling port on the tee in the borehole cap. Once the sample line has been purged, an evacuated tube (Vacutainer) is used to collect the gas sample on the outlet side of the pump. It should be noted that the commercially available Vacutainers are not completely evacuated, and must be completely evacuated prior to their use for collecting field gas samples. The use of this type of evacuated tube to store gas samples is preferred over other methods because of the ease in sampling, storage, and transport. The use of the diaphragm pump and the small evacuated glass tubes for gas sample collection has proven to be an easy and efficient method of obtaining uncontaminated gas samples from subsurface areas.

Data Interpretation

Before the fan is turned on, baseline data and samples are taken. When the fan is turned on, at least one hour is allowed to elapse for subsurface conditions to reach equilibrium; then, temperatures and pressures are recorded and gas samples taken at all boreholes. A communication test generally requires three to four hours to complete, depending on the number of boreholes to be sampled.

A set of communication studies produces baseline data (ambient conditions) and communication data (suction applied); both data subsets include static pressure, temperature and gas concentrations at each borehole. The static pressure differences at the bottom of the boreholes of at least 0.01 in. w.c. that occur as a result of suction indicate communication between the boreholes and the suction hole. They are used to construct a pressure contour for each communication test. This contour provides a "window" of good communication and data taken outside this region are disregarded due to probable insufficient gas movement. Temperature measurements provide minimal information with this method, but may indicate the amount of cooling or heating caused by air injection. A flow probe in the intake piping of the fan is used to calculate the total flow through the fan. Pressure and flow in the duct and the pressure changes measured at the boreholes are indicators of the extent to which the applied suction is effective.

Differences between baseline and communication measurements are calculated for the windowed area. These changes at each borehole can be classified as: (1) an increase in RI (heating), (2) a decrease in RI (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 which lies on a straight line drawn through the borehole and the suction point. Similarly, a decrease in hydrocarbons indicates a non-combustion or cold zone in the same location. Each communication test provides information for a limited area adjacent to each communicating borehole. The suction fan is assumed to cause mine gas to flow along a straight line between the borehole and the suction hole. For each communicating borehole in each test, the change due to communication (increase, decrease, or no change) is drawn on a scaled site map as a 90-degree

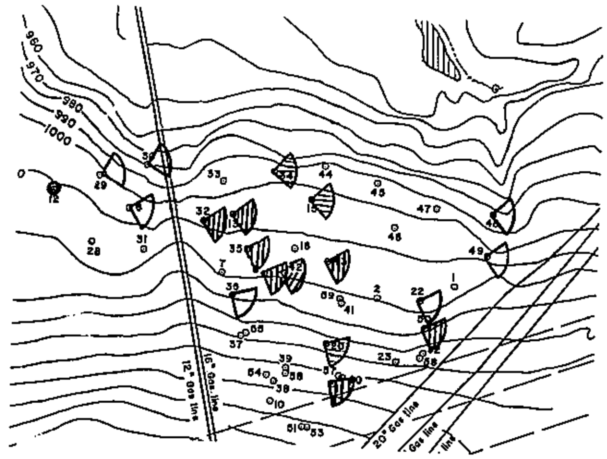

Figure 4a. Mine Fire Diagnostics Communication Test: Exhaust Borehole # 12.

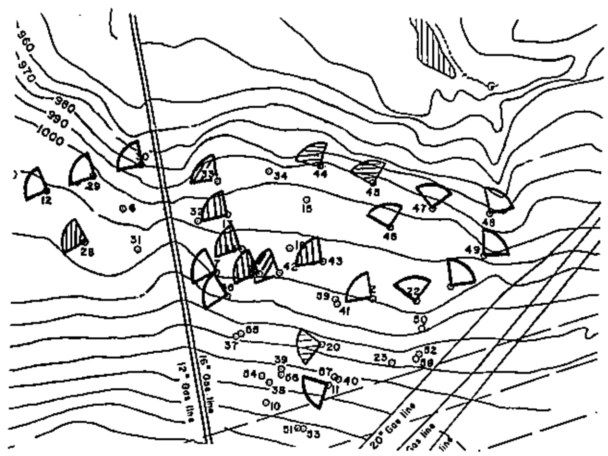

Figure 4b. Mine Fire Diagnostics Communication Test: Exhaust Borehole # 50.

quadrant having a radius of 50-ft.[4] and centered on this line (fig. 4a and 4b). The quadrant apex is centered at the borehole and the quadrant appears to be pointing toward the suction borehole. With this quadrant size, a 2000-sq.-ft. area is defined for each communicating borehole per test. By overlapping the possible combustion and noncombustion regions for all tests, a composite map is made (fig. 5). Alternatively, the quadrants can represent areas that have values of (a) CH_4 <= 20 ppm, (b) 9 <= RI < 50, (c) 50 <= RI < 100, or (d) RI > 100, as determined from analyses of the gas samples obtained during the second round of sampling while the fan is operating.

The diagnostic method's accuracy is directly related to the number of communication tests performed. When collating the quadrants from all

[3]References to trade names are given for identification only and do not imply endorsement by the Bureau of Mines.

[4]Represents the average distance between any two adjacent boreholes.

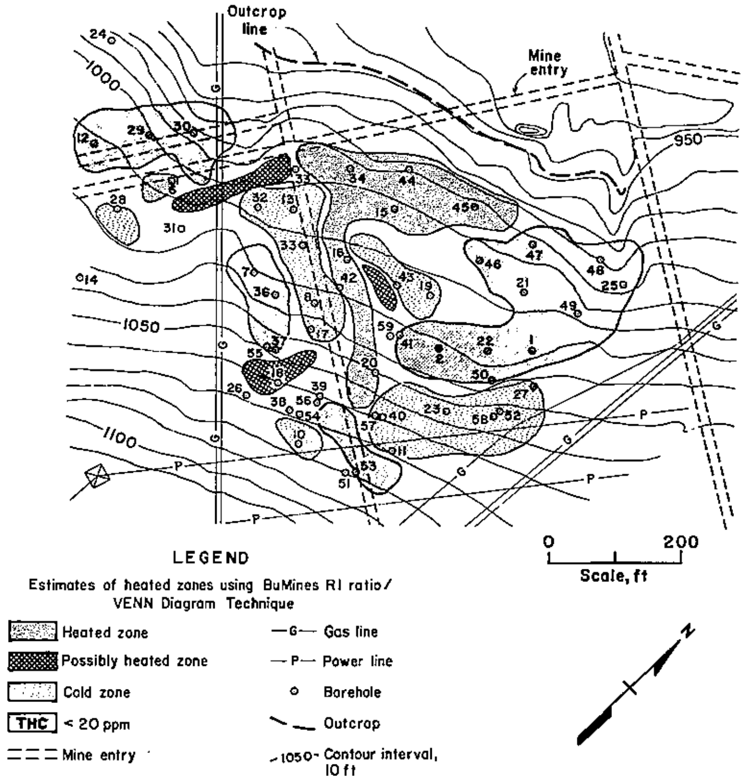

Figure 5. Mine Fire Diagnostics Communication Tests: Composite Results, Large, PA, Mine Fire Site.

the tests on the site map, these guidelines are followed:

(1) When quadrants of the same type (i.e., hot or cold or same RI interval value) overlap, the total area includes both quadrants;
(2) When quadrants of different types overlap, the overlapping area is undefined unless additional tests support either (hot/cold or RI interval value) of the defined quadrants;
(3) When the quadrants do not overlap, but the nearest quadrants are commonly defined, the region between the two is considered to be contiguous. At this point data are rechecked to make sure that no data have been overlooked, and an attempt is made to define and/or explain any area in which the method gives ambiguous results.

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, zones that show no signs of combustion (an important point in defining a fire area), and zones for which the data are inadequate to make a determination.

The diagnostic procedure used to locate underground fire zones is based upon two primary assumptions: (1) changes in the concentration of hydrocarbon gases are due only to the presence or absence of heated coal and (2) the suction fan influences the underground flow of gases to a measurable degree. Corollary assumptions are that the measured pressure gradient can characterize the communication effect at each borehole as good, poor, or none; that underground gas flows follow a straight line path toward the suction point; that the depth of the borehole casing has no effect on the measured pressures or on the gas concentration; that ambient conditions have no effect; and that changes in gas concentration are measurable. In reality, these corollary assumptions of the underground conditions do not always hold. However, if the induced suction creates a measurable pressure gradient, and if changes in gas concentration are measurable, then repetition of the communication tests should minimize the effects of non-ideal subsurface conditions.

Field Studies

Renton Mine Fire Project. Under the auspices of an interagency agreement with the OSMRE, the Bureau initially investigated the Renton, PA, abandoned mine fire site to determine the location and extent of the combustion. The site encompassed a 60 acre region, and was characterized by venting areas and several large subsidence holes in addition to a large subsidence area (Dalverny 1990). The mine was located in the Pittsburgh coal seam beneath a hill. A one-million gallon water tank was located on the top of the hill, and there were residential dwellings on and near the hill. The overburden varied between 0 and 102 ft., with the average being 42 ft. The mine had been abandoned in 1914, and no mine maps were available. The 129 boreholes (fig. 6) were installed in four rounds of drilling. They were placed primarily for purposes of locating the fire and monitoring the extinguishment, but many were later used as water injection or grout mixture injection points.

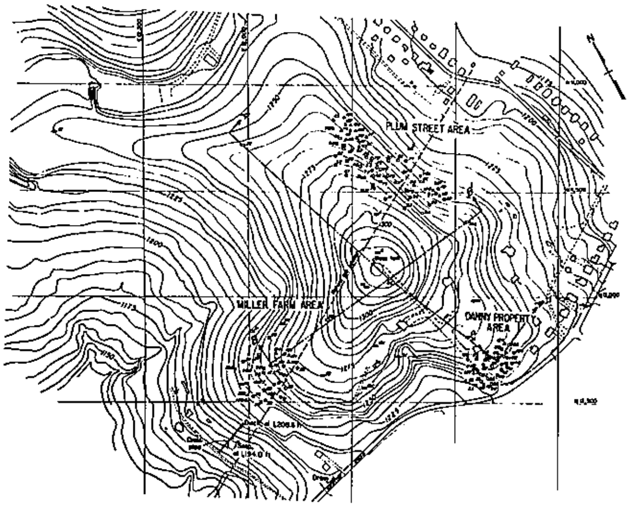

Figure 6. Renton, PA, Project Site Map with Locations of Numbered Boreholes.

At Renton, communicating boreholes, as indicated by a change in downhole pressure of at least 0.02-in. w.c., were separated by distances up to 700 ft. The typical effective distance between the suction point and the boreholes was 250 to 300 ft. The use of the Mine Fire Diagnostic method located three non-contiguous combustion zones, totaling approximately 10 acres. Analysis indicated that the area under the water tank was cold. Subsequently, the Mine Fire Diagnostic method was used to monitor the progress of the extinguishment effort that employed water injection with fume exhaustion as the extinguishment method. In this method (Chaiken 1984), water was injected into the mine to be converted to steam in the combustion areas. A suction fan would move the steam through the mine and remove the moisture and heat. Analysis of the diagnostic data from this time period showed that combustion activity decreased in one area, was unaffected in another area, and increased in the third area (fig. 7).

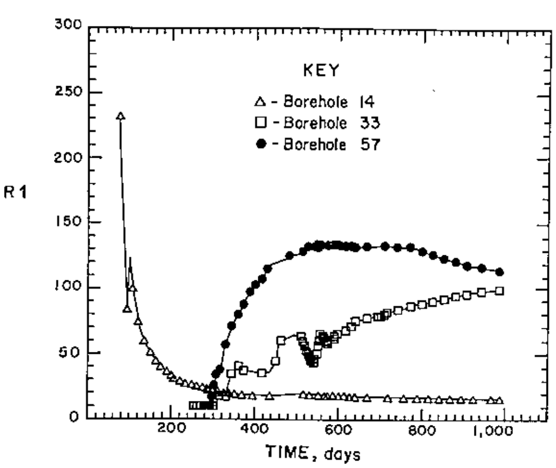

Figure 7. Variation in Baseline Values of R1 with Time at Three Boreholes, Renton, PA, Mine Fire Site.

The Mine Fire Diagnostic technique was important for the Renton project in that it was able to delineate three separate combustion regions. It was also possible to show which areas of the heated zones were being successfully quenched, and as important (or possibly more so), which heated regions were not quenched and but, rather, were spreading.

Large Mine Fire Project. At Large, Pa. a fire is located in an abandoned underground mine in the Pittsburgh coal seam with a maximum overburden of 150 ft. Entries to the mine were located at the base of a steep hill (Justin 1984). A natural gas pumping station is located on the top of the hill and high pressure gas transmission pipes and high voltage electric transmission lines cross the 15 acre site. Because of the terrain and the utilities on the surface, it was considered essential to determine the exact location of the combustion areas. Under a cooperative agreement with PA/DER, the Bureau is using the Mine Fire Diagnostic methodology to delineate heated areas and to establish the location of a cold boundary. Instrumented borehole caps were placed on seven 2-in. boreholes that had been drilled at the site during a previous project. These holes were used for baseline monitoring and as sampling points during communication testing. Seven 8-in. holes were drilled and cased for preliminary communication studies. A second set of 25 8-in. holes was drilled, based on the results of the first communication tests. Suction fan effects were measured as far as 800 ft. from the exhaust borehole.

Surface effects and some historical information implied that the burning was occurring along the buried outcrop. Diagnostic testing, utilizing seven 2-in. boreholes and 32 8-in. boreholes on approximately 100 ft. centers, indicated an L-shaped combustion zone. Figure 5 depicts the composite map drawn from the R1 interval values. The base of the L was near the outcrop; the leg of the L extended into the abandoned mine, probably along a set of main entries. A small isolated combustion zone was located several hundred feet from the primary combustion area. There were several areas in which hydrocarbon concentrations were very low, below the 20 ppm limit considered necessary for the accurate determination of combustion signatures. These areas coincided with areas in which water was noted in some boreholes. If water vapor condensed on the surface of the coal, it could block the desorption of hydrocarbons, thus preventing the determination of a combustion signature. However, if there were sufficient water on the coal to prevent the desorption of hydrocarbons, the temperature of the coal could be assumed to be below the combustion point.

The testing at Large has indicated that long term baseline (without suction) monitoring of R1 will detect changes in subsurface conditions. Hydrocarbon ratio values determined during baseline monitoring have shown that combustion activity is affecting a small isolated area to the left of one gas line right of way. From the baseline data, changes in the hydrocarbon ratio were observable prior to changes in temperature or the concentration of other combustion products (fig. 8). Additional communication testing is planned to establish the location of the cold boundary in the interior of the mine. Eighteen more 8-in. cased boreholes have been drilled and instrumented, as have two 2.5-in. core holes placed toward the interior of the mine. The fact of water pooling in some of the boreholes adds complexity to the

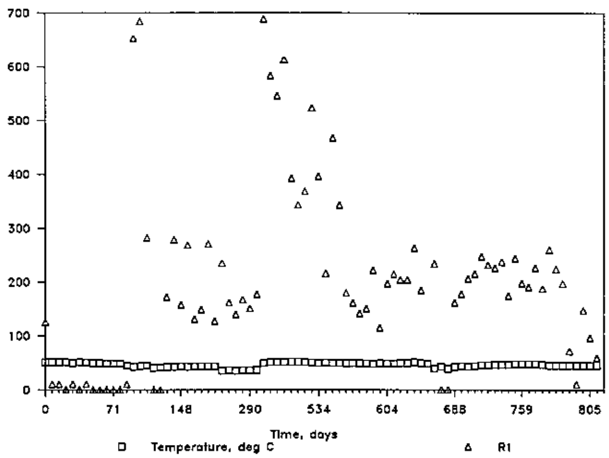

Figure 8. Baseline Values of Rl and Temperature, Borehole # 6, Large, PA, Mine Fire Site.

diagnostics analyses. Although holes bored into coal pillars can still be used during communications testing, water filled holes prevent accessing gases being drawn through the vicinity. Nonetheless, these holes can be monitored for temperature to aid in determining the quantity of heat energy stored in the strata prior to any extinguishment activities. The Large mine fire is an example of the inaccuracy of surface evidence of fire. An observed line of venting may parallel the fire zone along the outcrop, but gives no indication of the combustion areas in the interior portions of the mine. Borehole temperature data (fig. 8) when taken alone would yield misleading results with regard to the location of the combustion zones.

Summary and Conclusions

Laboratory results and field studies support the effectiveness and applicability of the Bureau's Mine Fire Diagnostic technique to the problems of locating and monitoring abandoned mine fires. For the bituminous coal samples studied, values of the concentration ratio, Rl, increased with increasing temperature and decreased during cooling. Although values of Rl do not correspond to a particular temperature, elevated values of Rl are due only to the presence of heated coal. Time dependent monitoring of changes in Rl reflect changes in the average temperature of the coal.

The Mine Fire Diagnostic method incorporates a sampling method that increases the detection zone of normal point source measurements through a gas movement scheme. Measuring one of the characteristics of this moving gas, in this case changes in hydrocarbon concentrations or in a ratio of the concentration values, and plotting the results as vectors (magnitude and direction) rather than point source (magnitude) measurements, expands and bounds the area(s) affected by combustion, as well as the area(s) not affected by combustion. These factors make the Bureau's methodology a significant improvement in locating and monitoring abandoned mine fires.

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