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REPORT OF INVESTIGATIONS/1991

Mine Fire Diagnostics and Implementation of Water Injection With Fume Exhaustion at Renton, PA

By Louis E. Dalverny and Robert F. Chaiken

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Btu/h	British thermal unit per hour
Btu/lb	British thermal unit per pound
°C	degree Celsius
cal/g	calorie per gram
cfm	cubic foot per minute
d/w	day per week
°F	degree Fahrenheit
ft	foot
ft^2	square foot
gal	gallon
gpm	gallon per minute
gpw	gallon per week
h	hour
h/d	hour per day
hp	horsepower
in	inch
in H_2O	inch of water (pressure)
in H_2O/scfm	inch of water (pressure) per standard cubic foot per minute
kW	kilowatt
Lpm	liter per minute
m	meter
min	minute
mL	milliliter
μm	micrometer
mmho/m	millimho per meter
pct	percent
ppm	part per million
psi	pound (force) per square inch
s	second
scfm	standard cubic foot per minute
scfm/acre	standard cubic foot per minute per acre
st	short ton
V ac	volt, alternating current

MINE FIRE DIAGNOSTICS AND IMPLEMENTATION OF WATER INJECTION WITH FUME EXHAUSTION AT RENTON, PA

By Louis E. Dalverny[1] and Robert F. Chaiken[2]

ABSTRACT

U.S. Bureau of Mines research to develop diagnostic methods to locate and evaluate fires in abandoned mines and waste banks and techniques to extinguish such fires was applied to an abandoned 60-acre underground bituminous coal mine (Renton, Allegheny County, PA) to locate and extinguish three separated fire zones.

Mine fire diagnostics interpret changes from baseline values in subsurface pressures, temperatures, and mine gas composition under imposed pressure gradients induced by a borehole exhaust fan. The effective gas sampling area surrounding each borehole is greatly enlarged. Sampling iterations, using a "communicating" boreholes set, provide "fire signature" information for locating both heated and cold areas. Time-dependent monitoring differentiates heating and cooling periods resulting from combustion front movement and/or fire extinguishment activities.

A water injection with fume exhaustion extinguishment effort involved injecting water through boreholes to quench the heated zones while exhaust fans actively removed heated gases from the mine. The technique was ineffective as implemented, primarily because of inadequate spreading of water from the injection points. The Bureau's diagnostic method determined the fire locations and the effectiveness of the water injection with fume exhaustion extinguishment technique.

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INTRODUCTION

This report describes the development and use of mine fire diagnostics to determine the location(s) of heating in an abandoned underground bituminous coal mine and the efforts made to cool and permanently extinguish the combustion using a water injection with fume exhaustion technique. During the progress of this project, three thermally separate combustion zones were located in one abandoned coal mine.

The actual locations of fires in old, abandoned underground mines can be very difficult to determine. Quite often, the only information to be obtained from the inaccessible workings must be from the surface through boreholes.[3] Aerial photographic and thermal surveys, among other remote sensing methods exploiting various portions of the electromagnetic spectrum, detect activity, such as venting gases and vapors, at or near the ground surface. While the burning is assumed to propagate in the carbonaceous rubble in or near entries, the source of the heated combustion products can be quite distant, laterally as well as vertically, from the vent. Core drilling at these sites will produce reliable information about the various strata including rider coal seams and other layers of combustible materials, the consolidation of several rock types, and the general pitch of the mine as a whole. The borings data are necessary for any structural evaluation. The usefulness of the holes in delineating fire zones is very limited if pressure, temperature, and gas composition measurements are taken from the bottom volume of the borehole only under ambient pressure conditions. The resulting data could reflect a nearly static environment in the mine and yield information about only a very small area around the borehole bottom (perhaps on the order of 10 ft^2).

Mine fire diagnostics techniques being developed by the U.S. Bureau of Mines improve upon and extend conventional sensing through boreholes methodology by employing measurements under dynamic as well as static subterranean conditions. Each borehole in a pattern becomes a site for measurement of changes in pressure, temperature, and gas composition induced by underground pressure gradients created by the suction of an exhaust fan attached to one of the boreholes in the grid. Evaluations of field measurements and laboratory gas analyses permit estimations of how the combustion is proceeding over wide areas underground and can provide accurate delineation of the cold boundaries[4] of the heated area(s).

[3]Maps detailing the entry locations often are not found in those mine map repositories that have been organized by various Federal and State agencies.

[4]By definition, a cold boundary is that line that separates burning zones (net exothermic reacting coals) and nonburning zones (net chemically stable coals).

This type of information is essential for fire extinguishment activities, both in terms of designing an extinguishment project and determining when a fire is completely and permanently extinguished. Knowing the cold boundaries can help eliminate the possibility of chasing a combustion front during the application of an extinguishment method such as excavation. Monitoring of boreholes during the quenching or smothering of a fire can yield information about the effectiveness of the fire-fighting activity and indicate when a fire is permanently extinguished.

In the Bureau's water injection with fume exhaustion fire extinguishment technique, water with its large heat capacity and latent heat of vaporization converts to steam by absorbing energy from the heated coal and strata. Exhausting the water vapor and other gases from the mine removes a large quantity of heat from the underground fire zones. By this technique of *convective heat transport* (i.e., energy transfer via fume exhaustion), the coal and surrounding rock strata can be cooled and the fire permanently extinguished in a time period much shorter than if the heat were removed solely by *thermal conduction* (i.e., transfer of the heat energy through the solid) through the overburden. The time constant for thermal conduction can be taken as the ratio of the square of the transport distance to the thermal diffusivity. The time constant for convective heat transport can be taken as the ratio of overburden mass to the rate of exhaust of gaseous mass. For a 100-ft overburden thickness, the time constants are, for—

- Conduction, about 14 years, and
- Convection, about 1 year (at an exhaust rate of 8,000 scfm/acre).

Water injection with fume exhaustion was the heat removal fire extinguishment technique tried at Renton, PA, along with the development of new diagnostic methodologies employed to define the heated zones and to determine the progress of the fire activity. This report is divided between the activities concerned with the diagnostic portion of the project and the activities associated with the implementation of the extinguishment effort. The account begins with a description of the site and some of its fire-related history.

The work described in this report was supported through an interagency Agreement (HQ-51-CT-6-01492) with the U.S. Office of Surface Mining and Reclamation and Enforcement (OSMRE). Rolland R. Maits was the technical project officer for the Eastern Technical Center, OSMRE. Important historical data were provided by OSMRE personnel Richard Balogh, Pittsburgh, PA, and Peter Hartmann, Johnstown, PA.

ACKNOWLEDGMENTS

Numerous persons made significant contributions to the success of the field project. From the Pittsburgh Research Center: Thomas R. Justin, electrical engineer, Joseph P. Slivon, physical science technician, and Andrew D. Miller, physical science aid, designed and installed required field apparatus; Ann G. Kim, research chemist, and Thomas R. Justin developed computer software for data analysis; Kenneth J. Ladwig, hydrologist, designed and evaluated the drainage monitoring program employed at the site; and Helen W. Lang, supervisory research chemist, guided the development of procedures for analysis of thousands of gas samples collected during the course of the study. From Boeing Services International Inc. (BSI), Pittsburgh, PA: Mark H. Wesolowski, lead chemist, led the BSI analytical group in carrying out gas and water analyses; John F. Miller, mechanical engineer, and David S. Hutcheson, engineering aid, carried out the reduction of field data as well as leading the BSI team responsible for much of the daily field activities.

SITE DESCRIPTION AND HISTORY

The area of concern at Renton, PA (Plum Borough, Allegheny County), is shown on the U.S. Geological Survey map in figure 1. Fire activity was in an abandoned mined portion of the Pittsburgh coal seam under a hill extending over more than the 60 acres that are outlined in the aerial photograph shown in figure 2. Some 20 dwellings existed on or within a few hundred feet of the hill; a 1-million-gal municipal water storage tank had been erected in the southern central part of the site on the crest of the hill. The drift mine was abandoned about 1914, but strip mining of approximately one-third of the perimeter occurred just after World War II. The outcrop is buried except for a portion visible from an elementary school parking area on the south side of the main thoroughfare (Renton Road). The only known portal is a concrete tunnel under Renton Road about 500 ft east of the southwestern corner of the site; the tunnel is plugged with soil.

Information about ignition and spread of the fire was gathered from reports generated by Pennsylvania Department of Environmental Resources and OSMRE personnel and from discussions with residents. On-site, visual inspections verified the locations of venting gases and water vapor at the eastern-northeastern and southern sections of the site. Higher-than-normal ground temperatures (e.g., 35° C versus 19° C) were measured at several locations including some on the west side of the hill in the vicinity of a natural gas pipeline. The earliest indication of heating was observed in 1959 at a hole in the outcrop area on the eastern side of the hill (ignition area 1 in figure 2). That heated zone spread in two directions—north and south to southwest. During late 1981, OSMRE injected a fly ash grout barrier as an emergency measure to protect three dwellings on the southeast corner of the site. The high temperatures (wall and floor were warm to the touch) and carbon monoxide (CO) concentrations (60 to 95 ppm) in the affected building decreased to ambient levels following that project. However, that combustion front apparently continued its westerly progress. The historical and anecdotal evidences imply that a second ignition area (see figure 2) in the southwestern corner of the hill became active sometime before 1973. This second heating spread both north and east. Surface venting from the easterly spread of combustion from the second ignition area ceased by 1981. The access road to the water tank was a convenient marker for the meeting of the two combustion fronts. In 1983, it was not known whether the heating was throughout the mine or only in the outcrop, and, if in the latter, which portions were affected.

To determine the location of the fire, the Bureau developed a diagnostic methodology based on knowledge garnered from various in situ combustion projects accomplished during the previous decade (*1*).[5] Subsequent to establishing the extent of the Renton fire, extinguishment was attempted using water injection with fume exhaustion to cool hot coal and overburden material in situ. This technique had been successfully used to quench a mine fire following a field evaluation of Burnout Control at an abandoned underground mine (*2*). In that prior case, the water injection with fume exhaustion technique was used to cool the fire zone prior to excavation, rather than to completely and permanently extinguish it. The apparent success in cooling the fire zone (from 600° to 160° C) in 45 days prompted the use of this technique at Renton for complete and permanent extinguishment of the mine fire.

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

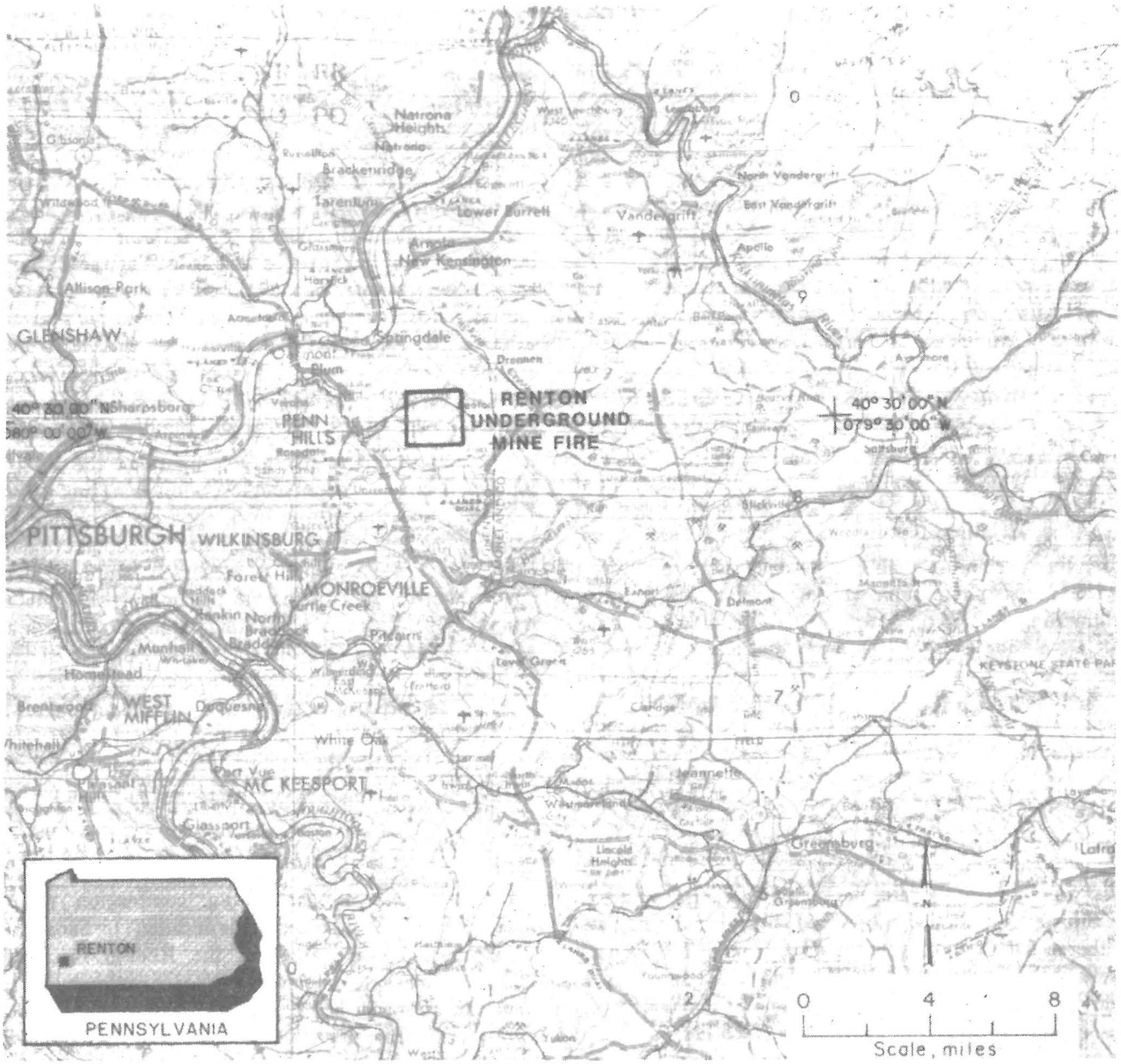

Figure 1.—Geographical location of mine fire project site.

PREPARATIONS FOR DIAGNOSTIC STUDIES: BASELINE DATA

As indicated in the introduction, the mine fire diagnostics methodology required drilling a pattern of cased boreholes to the mine level. Prior to and concurrent with the first round of borehole drilling, aerial photographs of the area were obtained. The Soil Conservation Service provided copies of photographs taken approximately every 10 years from 1938. Color pictures were obtained from the Agricultural Stabilization and Conservation Service and as part of an aerial thermal infrared study conducted by the U.S. Environmental Protection Agency (EPA) in cooperation with OSMRE (*3*). Although the aerial photographs were taken while the trees had leaves, the EPA study produced data that correlated well with ground observations of existing vents. The other pictures permitted approximate determination of the outcrop location resulting from the strip mining in the 1940's. Bureau

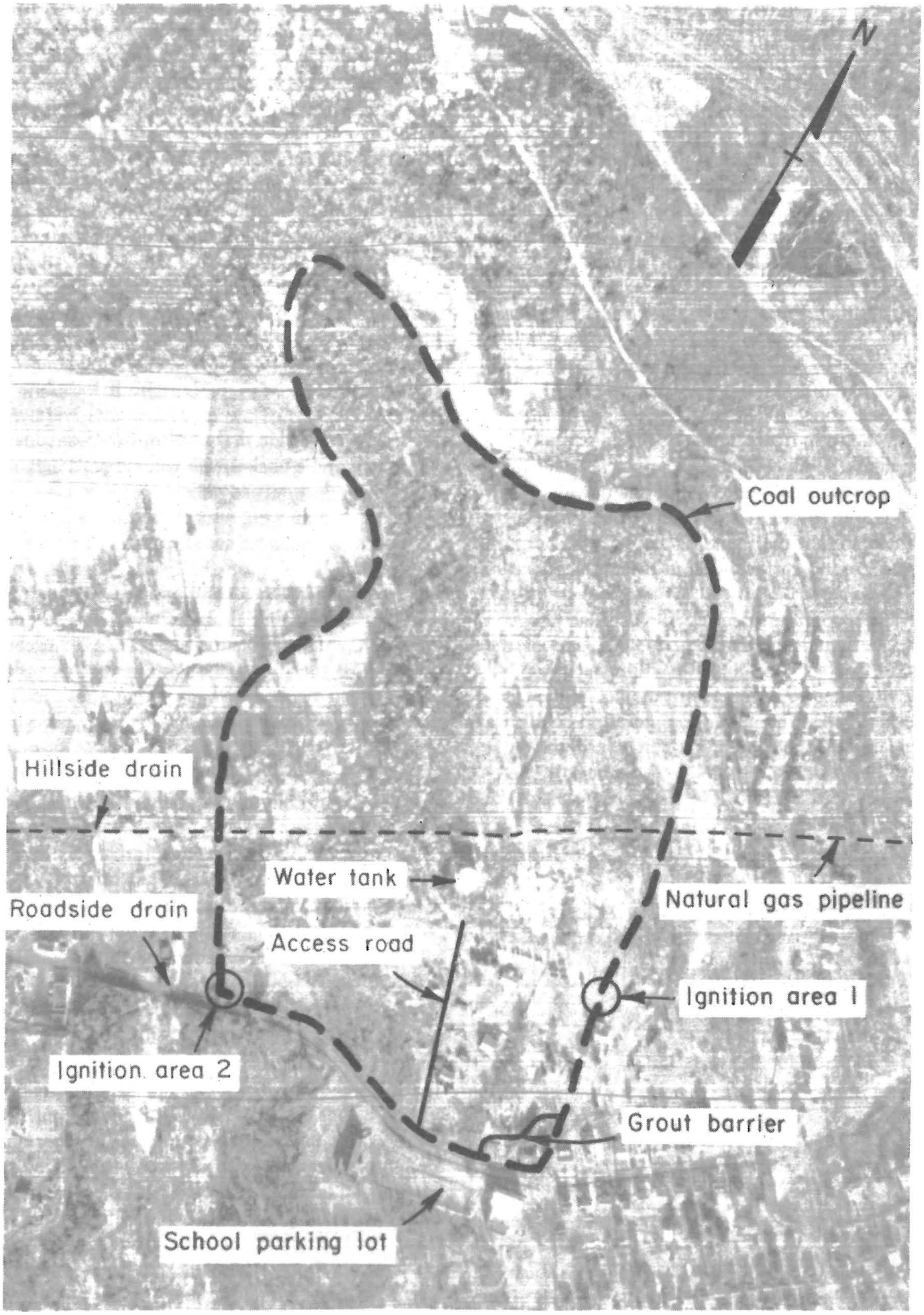

Figure 2.—Aerial view of mine fire project site.

personnel also searched for the buried outcrop on the eastern (Plum Street area) and western (Miller Farm area) sides of the hill using electromagnetic induction terrain conductivity analyses (*4*). The data for the western side indicated a density change in the vicinity of the previously estimated location of the outcrop (i.e., buried highwall). A graphical representation of measured conductivities and a cross-sectional sketch of the farm hillside are combined in figure 3. Three sets of measurements (L-1, L-2, and L-3) were made along the same heading, starting at an arbitrary point well into the spoil; the heading was estimated to be perpendicular to the buried highwall. Other than some trees that apparently did not affect the measurements, the major topographic features were shallow depressions caused by subsidence. (About 2 months later, a large subsidence hole about 6 ft in diameter and 15 ft in depth developed about 100 ft north of the measurement heading.) As shown in figure 3, the disturbed strata below the depressions produced high-conductivity readings relative to the undisturbed areas uphill and downhill from there. For all three sets of measurements, the conductivity coils were held so that the plane of the coil was perpendicular to the ground surface. The coil spacings for the L-1 and L-3 sets were 32.8 ft (10 m) and 65.6 ft (20 m), respectively; the operators walked in file; and the coil planes were perpendicular to the probable line of the highwall. The L-2 set used a 32.8-ft (10-m) spacing, but the operators walked in parallel with the coil planes parallel to the highwall. This latter configuration enabled a better delineation of the change in strata consolidation at the interface between the highwall and the backfill materials. On the eastern side, however, too many subsidence

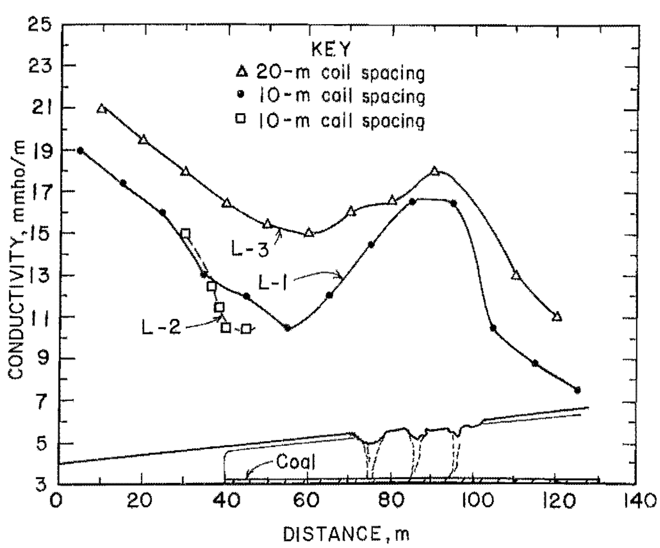

Figure 3.—Terrain conductivity survey data for Miller Farm subsite.

pits, pieces of scrap metal, and nearby houses prevented obtaining useful data.

Mine drainage water monitoring was initiated to establish baseline data for determining any changes that might occur during the extinguishment phase when more water would be piped into the mine. The on-site inspections revealed that mine water drainage was apparent only on the western-southwestern portion of the site where general seepage across a hillside pasture had occurred for many years. A pipe in the hillside directed as much water as possible away from the farm buildings. This drain became one of two water-monitoring locations. The second location was in an Allegheny County roadside catch basin connected to a storm sewer (see figure 2). Apparently, mine water found its way into a tributary pipe connecting with the sewer in the catch basin. Both locations provided water samples, but flow measurements were obtainable only from the hillside drain where flow was measured using a watch and a bucket with volume markings. The pipe in the catch basin was so poorly positioned that, even with the use of a pipe weir, useful measured flow data could not be obtained. Occasionally, water temperatures were measured. Results of the water monitoring will be discussed later in the section entitled "Water Injection."

Following the initial inspections and acquisition of general site information, the first 25 of 129 boreholes were drilled. The specific locations were set by considering:

1. Possible mine entry directions and locations surmised from the subsidence pattern at the northern end of the site;
2. The possibility that a main entry would parallel the main ridge of the hill;
3. General knowledge about turn-of-the-century mine engineering;
4. The locations of existing surface vents;
5. A desire to obtain sufficient data to construct stratigraphic cross sections in two directions (from combined core and rotary borings data); and
6. An attempt to have the initial borehole pattern reasonably spread over the whole site.

All boreholes, whether in apparent entries or pillars, would be considered usable for diagnostic purposes; there was no prior information concerning the permeability of the subterranean network relative to the suction exerted by the fan. All initial boreholes were drilled to 5 ft below the main coal seam and cased to within 5 ft of the top of the coal. The bottoms of the casings were intended to be just above any carbonaceous material (including rider seams) where heating could occur. Twelve of the twenty-five initial holes were cored to obtain stratigraphic data and then cased with 2-in pipe; an example of core data for one of the longest holes is presented in figure 4. The other holes were rotary drilled with water (for dust suppression) and cased with 8-in pipe. The maximum depth to the bottom of the coal was 102 ft; average depth of the 25 initial holes was about 52 ft (42 ft average depth for all 129 boreholes). The surface elevation and location of each hole was determined by both ground and aerial topographic surveys (*5*).

Instrumentation borehole caps, illustrated in figure 5, were designed and fabricated for both 2-in and 8-in casings. On the 8-in caps (figs. *5A*-*5B*), extra ports were provided for future needs such as inserting instrumentation for measurements at multiple depths. The caps were installed as shown in figure *5C*. The bottom end of the temperature probe assembly was a 5-ft-long stainless steel sheathed, Chromel-Alumel[6] type-K thermocouple. The thermocouple's length was chosen to place the plastic (signal) connectors and the plastic-coated extension wire above the casing bottom where temperatures could exceed 212° F (100° C) and melt the plastic. Temperature measurements were made using a battery-powered, handheld electronic thermometer; readings were recorded in both Fahrenheit and Celsius units. A 3/8-in-OD polyethylene tube, no shorter than the casing length, was used to take pressure measurements and withdraw gas samples from the mine itself. The tee fitting at the top of the pressure-sample-tube (fig. *5A*) was fitted with a septum on one side (pressure) and a compression plug on the other (gas sample). A hollow needle screwed into a Luer adapter (as in figure *5D*) was connected with flexible plastic tubing to a Magnehelic pressure meter. For a pressure reading, the septum was punctured with the needle so that there would be minimal effect on the internal pressure and minimal time spent making the measurement.[7] Battery-powered gas sampling pumps were sufficient to produce a sample stream (5 to 10 Lpm) from which a sample was extracted using a reevacuated 20-mL Vacutainer glass sampling tube inserted into a Luer adapter and needle assembly.[8] Tube

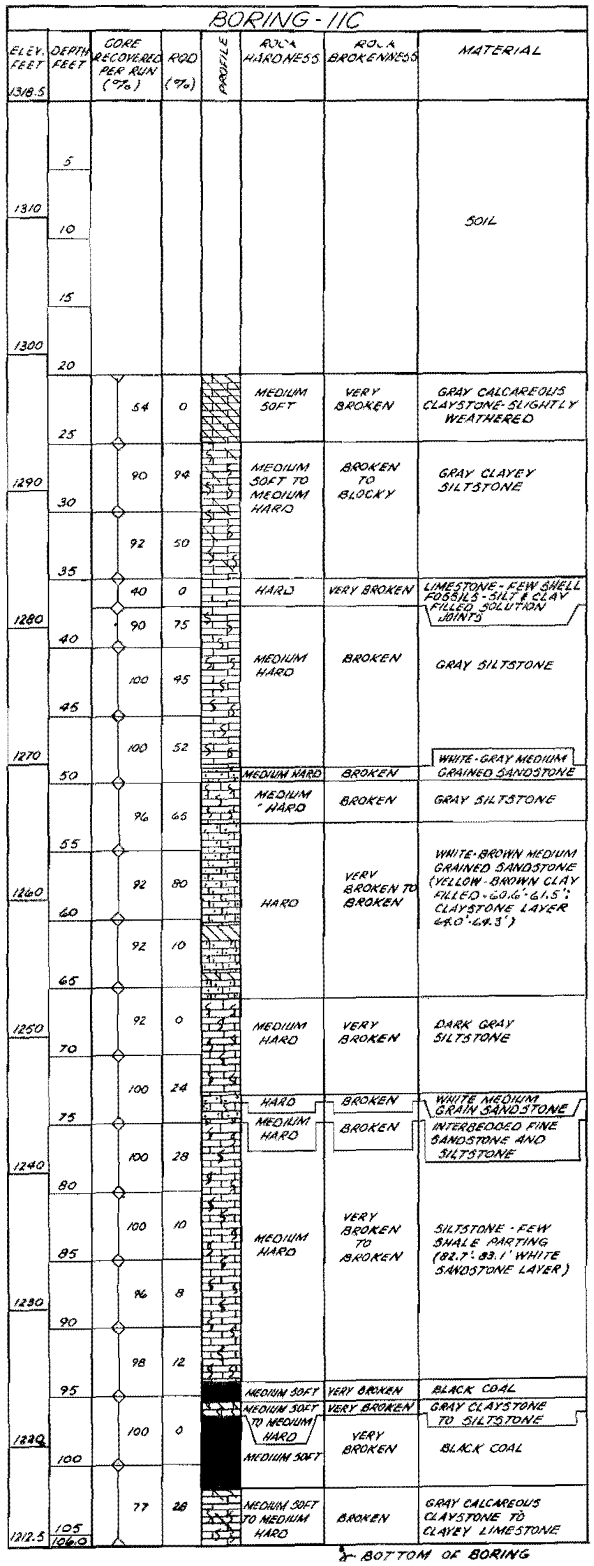

Figure 4.—Example of handwritten stratigraphic data from core boring near water tank.

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

[7]Two usually minor problems affected pressure measuring: (1) Sometimes liquid would condense behind the septum. An extraordinarily high-pressure value signaled that occurrence. A few taps on the tee fitting normally dislodged the liquid. (2) During cold weather, the Magnehelic pressure meter's response time increased, so that total measurement time also lengthened.

[8]Vacutainer glass sampling tubes with rubber stoppers are normally used for medical sampling. That use requires incomplete evacuation (e.g., to minimize likelihood of vein collapse); residual sterilizing (and other) gases remain in the tube and must be removed so as to not affect mine gas compositions (*6*).

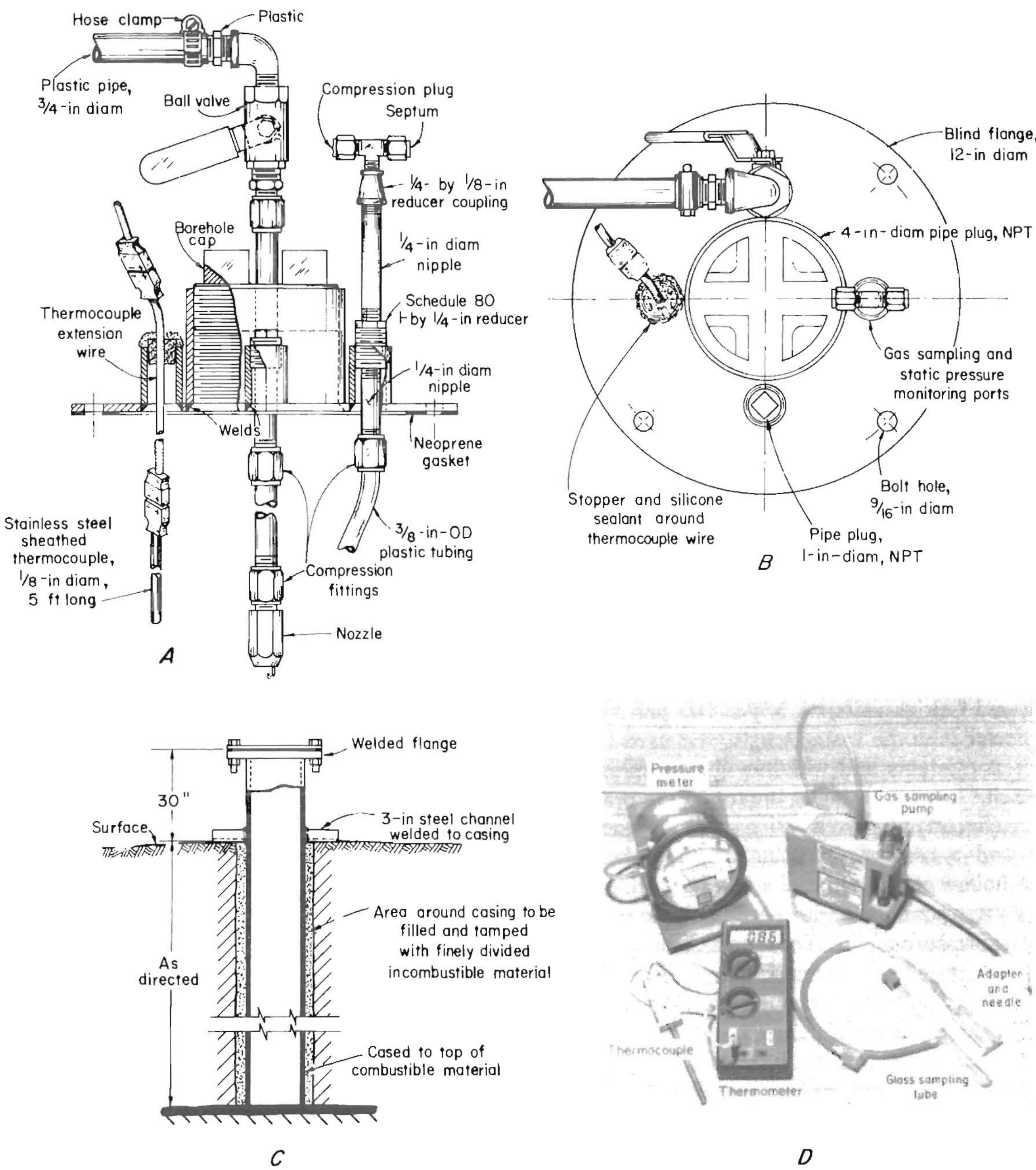

Figure 5.—Borehole casing cap (*A-C*) fitted for water injection and for monitoring, using instruments shown in inset (*D*). (NPT = National pipe thread.)

purge time was about 1 min and sampling time was about 20 s. Field trials showed that one experienced person could gather data at the rate of one borehole every 5 min or less. It was faster to have one person obtain temperature and pressure data and a second person follow to take the gas sample. The time involved was important because (1) minimizing the time provided a better "snapshot" of conditions for the monitored area; (2) eventually, at least 30 boreholes were monitored 2 or more times within 4 to 6 h by 2 persons; and (3) the data gatherers needed time between sessions to rest (especially during inclement weather). All gas samples were coded for project identifier, borehole number, Julian date,[9] and sample time. Barometric pressure and ambient temperature usually were recorded once each day on arrival at the office trailer. While all data were recorded eventually on paper logsheets (with a carbon copy), during inclement weather, use of a handheld, battery-powered miniature tape recorder for interim data storage simplified some of the data gathering. The data on the logsheets were entered into the VAX 780 mainframe computer at the Pittsburgh Research Center, sometimes through a video display terminal and telephone modem assembly in the office trailer. Subsequent computerized merging of pressures and temperatures from field data with associated gas concentration data from laboratory analyses was simplified by correlation using the coded borehole number and time data.

A customized "test fan" assembly was purchased for the initial studies. This fan is described in appendix A. The fan assembly in operation at a borehole is shown in figure 6. The small bulldozer shown in the figure was used to pull the skid-mounted fan assembly to the various borehole locations. Not shown in the figure is a portable electrical generator (33 kW) used to supply power to the test fan.

Three types of related diagnostic studies using the procedures described above were conducted throughout the project duration:

1. Baseline.—site quiescent; no exhaust fan operating;
2. Communications.—exhaust fan operating; neighboring boreholes sampled several times during study time of 4 to 6 h;
3. Extinguishment.—similar to communications study, but with water being injected into neighboring boreholes.

[9]The Julian date (JD) is the numerical representation of a specific day during the year. In this report, the letters JD precede one digit that indicates the year and three digits that indicate the day (e.g., JD4030 represents January 30, 1984).

Figure 6.—Fan assembly in operation during borehole communications study.

DIAGNOSTIC STUDIES

The diagnostic methodology evolved as more data were acquired and analytical techniques were evaluated. These evaluations are described below. By the time of the extinguishment phase, a hydrocarbon ratio, R1, became the indicator criterion of choice. This ratio, as described later in the "Temperature and Gas Analyses" section is directly related to the heating level of the carbonaceous fuel. Using only this ratio of desorbed hydrocarbon concentrations negates effects of dilution or interference from air or combustion products. The descriptions of the analytical techniques follow in generally chronological order.

COMMUNICATIONS PHASE

After accumulation of several weeks of baseline data, communications studies began in April 1984. Interborehole communication was initially determined by measuring, at neighboring boreholes, the change in static pressure caused by turning on the suction fan that was attached to one of the 8-in-ID casings. Figure 7 depicts some typical borehole vacuum levels observed over several hours during a single communications test in which borehole (BH) 21 (figure 8, Miller Farm area)[10] served as the exhaust, or suction, hole. Based on the observed vacuum and flow (21.5 in H_2O and 4,000 scfm) at the top of BH 21 (14.5 ft of 8-in casing), it can be estimated that the vacuum at mine level near BH 21 was about 12 in H_2O. It is evident from the data in figure 7 that while the vacuum dissipates rapidly through the mine, it is still sufficient to influence flows several hundred feet from the suction hole. A change in vacuum of 0.02 in H_2O or greater was taken as the criterion for communication; this value was determined from the overall uncertainty in reading the low vacuum levels with a Magnehelic pressure meter.[11] Thus, it can be seen from figure 7 that BH 12, 24, and 25 were in good communication, BH 13 was in marginal communication, and BH 2 and 22 were not communicating with the suction hole (BH 21).

[10]On maps, borehole numbers with suffix C (e.g., BH 19C) indicate holes cored to obtain stratigraphic data.

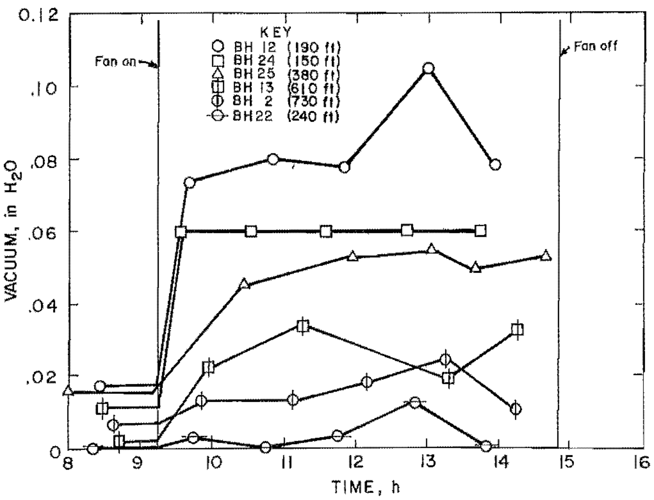

Figure 7.—Communications test borehole (BH) vacuum values and distances from exhaust BH 21 with vacuum at 21.5 in H_2O.

Table 1 lists several communications results found with the first 25 boreholes. While a number of borehole pairs communicated at an average distance of 283 ft, others did not communicate at an average separation of 315 ft. It is apparent here that separation distance alone is not the primary determinant factor in establishing communication. It is interesting to note that some of the borehole pairs communicated in one direction only. One possible reason for this noncommutative flow behavior is differences in fire activity as the mine atmosphere is drawn first in one direction and then in the other. The fire's acting as a source of gas and heat would tend to throttle the flow of gas between the boreholes, possibly more in one direction than in the other (7).

An assumption that the average communication distance (283 ft) corresponds to the radius of circular influence about a suction borehole could imply that a 250,000-ft^2 area of the mine was being sampled from a single borehole. Even if this estimate ignores the actual geometry of the mine, it is evident that the sampling area during communication is several orders of magnitude larger than the 10 ft^2 estimated for the static baseline coverage.

Four communicating boreholes (BH 16, 18, 19C, and 20), in the southern area (Danny property) shown on the map in figure 8, were used to study the use of sulfur hexafluoride (SF_6) tracer gas in determining the movement of mine gases under the influence of the underground pressure gradients generated by the exhaust fan. Several tracer tests were done during April 1984 using these four

[11]Good communication was inferred from a pressure differential of at least 0.02 in H_2O from the baseline value. The most sensitive pressure meter used had a range of 0.25 in H_2O and a specified accuracy of ±4 pct of full scale (i.e., 0.020 in H_2O).

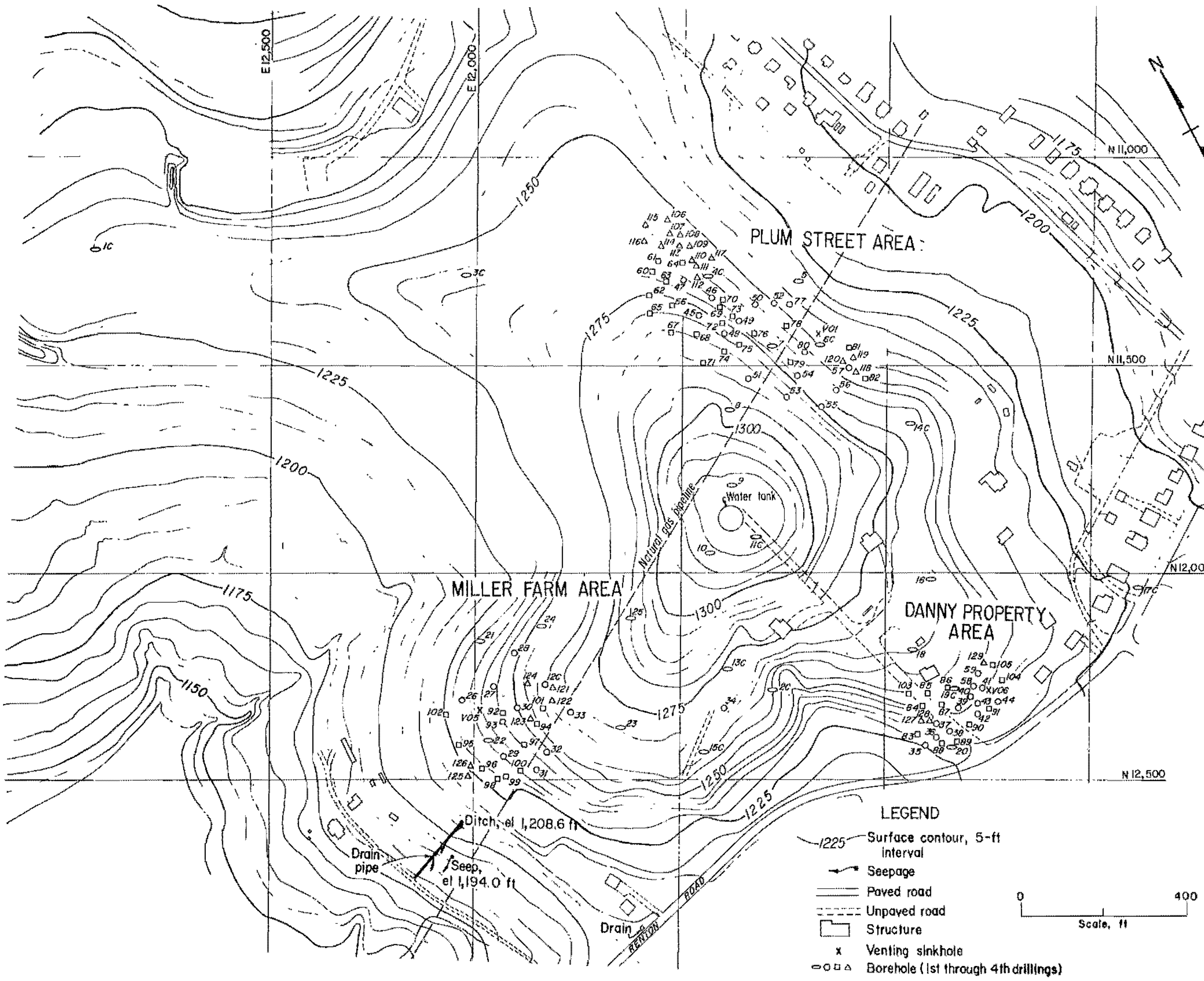

Figure 8.—Project site contour map with locations of numbered boreholes.

boreholes to try to determine travel times between boreholes. Gas samples were analyzed for the tracer using electron capture gas chromatography. The studies clearly confirmed communication among those boreholes; however, the results were inconclusive about the restrictions along possible pathways between pairs of holes. Positive gas pressure (from heated combustible materials) could act as a restriction as could a barrier of rubble from a collapsed roof or pillar. The essentially inert nature of the SF_6 allowed it to remain in the strata for long time periods so that some of the SF_6 from a previous test interfered with attempts at subsequent tracer studies unless the suction fan was operated a sufficiently long time to remove the residual gas. The necessary amount of "purge" time would be site dependent. In the meantime, two other techniques—communications testing and mine gas analysis—were combined to more effectively obtain the necessary information. Evaluation of gas chromatography analyses for the fixed gases and the hydrocarbons in the mine gas samples (initially, duplicate samples from the SF_6 work) became the preferred approach to learning more about the underground fire conditions.

Table 1.—Early borehole communications results

(Communication is taken as Δp greater than 0.02 in H_2O)

Communicating borehole pair[1]	Separation distance, ft	Δp, in H_2O	Noncommunicating borehole pair[1]	Separation distance, ft	Δp, in H_2O
2 directions:			2 directions:		
9(R) ↔ 25(S)	400	0.06	16(R) ↔ 18(R)	180	0.006
21(R) ↔ 24(R)	150	.04	16(R) ↔ 20(S)	410	.013
23(S) ↔ 25(S)	260	.042	1 direction:		
25(S) ↔ 24(R)	220	.053	18(R) → 20(S)	250	.000
1 direction:			21(R) → 23(S)	400	.005
20(S) → 18(R)	250	.10	21(R) → 25(S)	380	.013
23(S) → 21(R)	400	.024	24(R) → 23(S)	310	.012
23(S) → 24(R)	310	.029	Average	315	.009
25(S) → 21(R)	380	.032			
Average	283	.05			

[1]R and S signify borehole terminations in rubble or solid, respectively, as determined from drilling log. Arrow indicates direction toward suction borehole.

As mentioned, static pressure changes caused by the exhaust fan's suction defined communication between boreholes. Although the underground flow paths passing a borehole casing opening were unknown, for interpretive purposes it could be assumed that (1) there existed a straight path to the exhaust fan and (2) a portion of a spherical volume of influence centered at the bottom of the exhaust borehole extended beyond the neighboring boreholes' subsurface openings. Gases would flow along pressure gradients generated by the fan and intersected by the boreholes. Figure 9 depicts the mine fire diagnostics technique applied to several one-dimensional situations showing various fire locations relative to three boreholes set in a line. With the pressure gradient directed from right to left and burning occurring as illustrated in case A, combustion products (i.e., a signature) would be in evidence at all three boreholes. This is the same result as for a fire only beyond the rightmost hole. Heating between either pair of holes would not produce effects at the hole farthest from the exhaust (cases B and C). By expanding the borehole pairs into a two-dimensional network and moving the suction hole from borehole to borehole within that network, successive communications tests will produce sufficient data to permit deducing which boreholes are in the "cold" zone and which boreholes are in the "hot" zone.

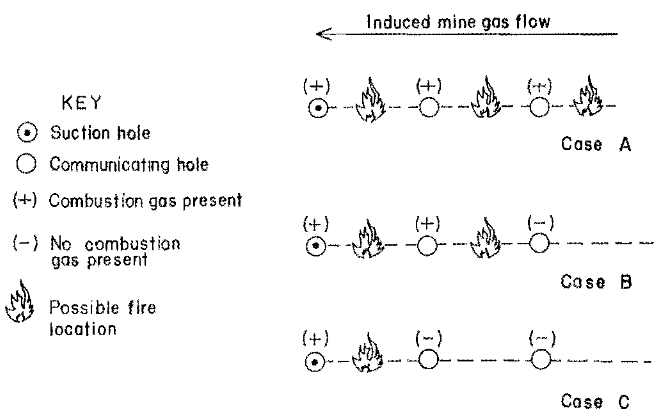

Figure 9.—Schematic of mine fire diagnostics method.

The borehole gas samples were analyzed for the following components: hydrogen (H_2), oxygen (O_2), nitrogen (N_2), CO, carbon dioxide (CO_2), methane (CH_4), and the C_2 through C_5 alkane and alkene hydrocarbons (higher hydrocarbons) except butene and pentene. Standard gas chromatography analytical techniques yielded lower detection limits for CO and the hydrocarbons of 10 ppm and 1 ppm, respectively. When CH_4 concentrations were <20 ppm, the concentration of the other higher molecular weight hydrocarbons could be below the 1-ppm limit. Concentrations of acetylene (C_2H_2) were so rarely reported that those few instances may have been gas chromatograph computer artifacts. Initial data analyses evaluated the absolute concentrations of CO and CO_2, their ratio values, and their "air-free" concentrations (i.e., effective concentrations after correction for the presence of air in the samples),[12] all with respect to elapsed time during exhaust fan operation (generally, a 4- to 6-h period).

The results for two communications test periods (in 1984 and 1985) carried out about 150 days apart are shown in appendix B, figures B-1 through B-8. These figures,

[12]Air-free concentrations are independent of air dilution. The equations for air-free CO and CO_2 concentrations, are, respectively, $[COaf] = ([CO]/(100.0 - (4.76\cdot[O_2])))\cdot 100$ pct and $[CO_2af] = (([CO_2] - 0.001\cdot[O_2]))/(100.0 - (4.76\cdot[O_2])))\cdot 100$ pct. The correction is based on the assumption that the measured oxygen in the sample comes from normal air having a composition of 20.94 pct O_2, 78.08 pct N_2, 0.0300 pct CO_2, and 0.95 pct Ar.

which tabulate the daily test data from the Danny property location, are the computerized spreadsheets used to store, recover, and manipulate data. Similar spreadsheets were compiled for every day of testing and for the other two fire locations at Renton (i.e., Miller Farm and Plum Street locations). Some of the earlier communications tests involved fewer boreholes than shown, while later tests involved more boreholes (e.g., up to 39 holes at Plum Street). The baseline and communications data shown in figures B-1 through B-8 are typical and illustrate some observations relative to the use of mine gas compositions as a fire signature:

1. Absolute values of the concentrations of CO, CO_2, CH_4, and H_2 do not yield consistent results. Figure B-2 provides some examples: (1) Some boreholes show the same CO_2 concentration levels with very different CH_4 concentration levels, e.g., BH 18 and BH 36, suction at BH 42, or (2) increasing CO concentration corresponds with increasing CH_4 concentration in one case, but with decreasing CH_4 concentration in another, e.g., BH 20 and BH 36, suction at BH 42. H_2, which is generated when coal is heated to 300° C or greater, does not appear at many boreholes. The absence of H_2 during the JD4243 to JD4256 tests, except at BH 38 in figure B-3 and BH 58 in figure B-4, prompted a time-saving decision to not analyze for H_2 in every gas sample (see later tests in figures B-5 through B-8). The H_2 concentration data of figure B-3 indicate that (1) coal is burning only near BH 38 (an unlikely event), or (2) excess air dilution has lowered the H_2 concentration below detectable limits elsewhere (a more likely event). The BH 58 data are those for the mix of mine gases drawn to that exhaust hole, so the source of the H_2 measured could be anywhere in the affected region. However, given that (1) dilution should be greatest at the suction hole, (2) none of the neighboring boreholes indicate any H_2 (because of dilution?), and (3) the BH 58 concentration is greater than or equal to 0.1 pct, quite possibly the combustion is occurring near BH 58. As indicated, the problem in utilizing absolute gas concentrations for a fire signature is that different amounts of air dilution occur at various borehole locations in the mine. This can be seen from the large variation in O_2 concentration level in the gas samples.

2. Air-free carbon monoxide (AFCO), which, in essence, should be independent of air dilution (see footnote 12), does appear to be a useful fire signature. This is supported by the observed variation in baseline AFCO concentration data with borehole temperature as depicted in figure 10. In these baseline data, both the temperature and the gas sample are expected to represent a local mine condition (i.e., near the borehole opening), whereas in communications tests, the sampled gas will have originated some distance from the borehole opening and, hence, represent some other temperature. It is evident that temperatures above 60° C are associated with significant changes in the baseline AFCO concentration. However, it should be pointed out that when the O_2 concentration exceeds 17 pct, the calculated value of AFCO concentration is inherently uncertain. This arises from the amplification of relative errors when arithmetical subtraction is carried out between two large numbers, each having a smaller relative error. This same error enhancement applies to the Jones-Trickett ratio (JTR), which is defined as (*8-9*):

$$JTR = \frac{([CO_2] + 0.75[CO] - 0.25[H_2])}{(0.265 \cdot [N_2] - [O_2])}. \qquad (1)$$

Figure 11 depicts the variation of baseline JTR (where O_2 concentration is greater than 17 pct) with borehole temperature. It is evident that, independent of a dilution problem, the JTR does not appear to be a particularly good indicator of fire and nonfire areas. Most of the reliable JTR values (i.e., when O_2 concentration is <17 pct) fall in a relatively narrow range between 0.65 and 0.85, independent of borehole temperature. There is also an apparent separate grouping of larger JTR values (2.0 to 3.0) over the temperature range 40° to 70° C. Oxygen-rich combustion of coal can be shown to yield JTR values of about 0.8, while fuel-rich combustion should produce somewhat higher values (1.0 to 1.5) (*10-12*). Mitchell (*10*) has suggested that JTR values greater than 1.6 be considered as "suspect" and not considered as valid data. However, this conclusion cannot be justified without knowing the reason for the suspect result, such as improper sampling or dilution with CO_2, which likewise would reflect

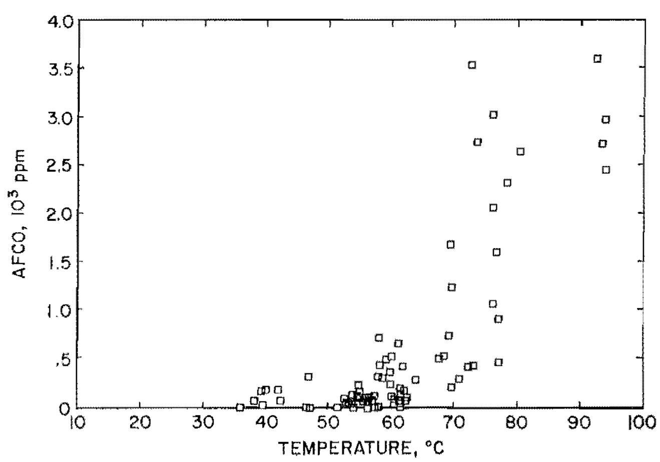

Figure 10.—Air-free carbon monoxide (AFCO) versus borehole temperature, baseline data, Danny property. AFCO (ppm) = $\frac{[\text{pct CO}]}{100.0 - 4.76 \times [\text{pct } O_2]} \times 10^4$.

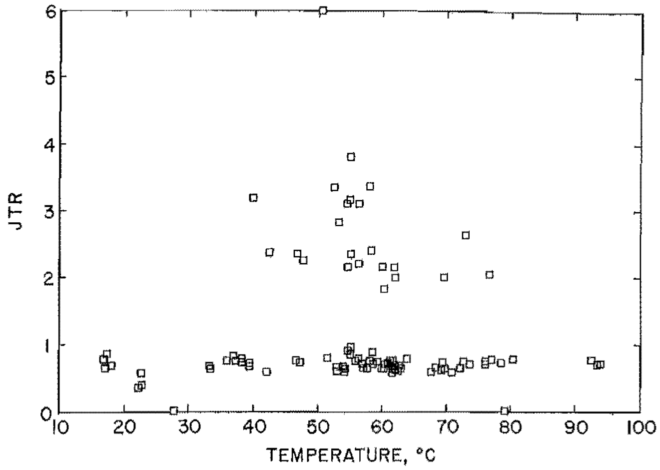

Figure 11.—Jones-Trickett ratio (JTR) versus borehole temperature, baseline data, Danny property.

$$JTR = \frac{[CO_2] + 0.75\,[CO] - 0.25\,[H_2]}{0.265\,[N_2] - [O_2]}.$$

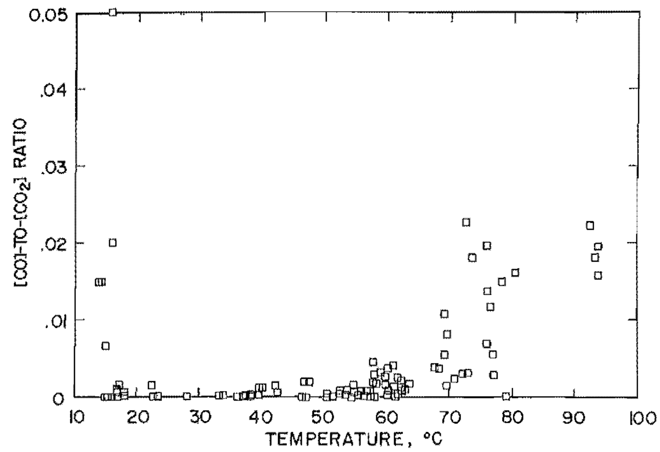

Figure 12.—Carbon monoxide-to-carbon dioxide concentration ([CO]-to-[CO_2]) ratio versus borehole temperature, baseline data, Danny property.

on the validity of all the measured JTR data. Additionally, JTR values greater than 1.6 are quite feasible for certain combustion reactions. E.g., the 50 pct conversion of CO to CO_2 would lead to JTR = 7.0.

While the JTR by itself is not dependent on temperature, it is dependent on the coal combustion process, which, in turn, is expected to raise the temperature of the surroundings. Assuming that the sampled baseline mine atmosphere (i.e., without fan suction) represents the local condition about the borehole, elevated JTR values (greater than 0.5) at elevated temperature boreholes (greater than 30° C) are consistent with active burning near these boreholes. However, figure 11 also depicts elevated JTR values at lower temperature boreholes, a fact inconsistent with a nonfire (i.e., cold) condition near the borehole. This apparent lack of consistency among the measured JTR values is not indicative of a good fire signature.

3. An examination of the CO-to-CO_2 concentration ratio (fig. 12), which is independent of air dilution, and which has been used as a fire signature, suggests that it too is not totally consistent with borehole temperatures. From the Bureau's work at the Calamity Hollow (Allegheny County, PA) abandoned mine fire (*12*), it might be expected that the combustion products from burning coal underground would yield CO-to-CO_2 concentration values between 0 (complete combustion) and 0.04 (incomplete burning). While this is the range of values observed at Renton, their relationship to the mine fire is somewhat uncertain. E.g., values of a ratio near zero can be seen for boreholes which, by all other indications, appear to represent the cold coal zone (e.g., BH 16 and 18, figures B-1 through B-8 in appendix B), while values of the ratio in the range of 0.02 to 0.04 do seem to be consistent with combustion activity. The apparent discrepancy of results between a smoldering mine fire (i.e., Renton) and an accelerated mine fire (i.e., Calamity Hollow), could be due to the air-dilution effects noted above. Other possible explanations could be the presence of CO_2 from noncombustion underground sources (e.g., bacterial decomposition) and/or the selective absorption of CO as the gases flow through the underground rubble toward the boreholes. In either case, the CO-to-CO_2 concentration ratio, while indicative of fire activity, does not by itself appear to be a definitive fire signature.

4. Previous Bureau work (*13-14*) indicated that the ratio of the concentration of higher hydrocarbon gases (C_2 to C_5) to that of CH_4 in the normal atmosphere of bituminous mines (i.e., at ambient temperature of about 18° C) is between 0.01 and 0.05, but at temperatures greater than 50° C, the ratio would increase rapidly with increasing coal temperature. It was suggested that the ratio of the sum of the C_2 to C_5 hydrocarbons concentrations to the CH_4 concentration be used as a signature of fire. The values of C_2C_5 to CH_4 shown in appendix B (figs. B-1 through B-8) and summarized in figure 13 appear to substantiate this suggestion. As will be described later (in the "Analysis of Extinguishment Effort Data" section), a somewhat different version of the ratio, R1 (equation 3), became the primary fire signature for interpreting the progress of the water injection with fume exhaustion extinguishing activities.

Interpretation of the communications data was done graphically using an enlarged section of the map of a set of boreholes and some colored ink pens. The variation over time of (1) various fire signatures, (2) O_2 concentrations, and (3) the degree of communication with a particular exhaust borehole were all considered. Three colors represented the value's having increased, decreased, or remained the same. This simple procedure generated a readily interpreted representation of the effects of suction on the concentration values at each borehole. This colored graphical approach to interpreting the communications data is represented by the symbolic format shown in figure 14, which is based on the Danny property data in figures B-1 through B-8. An increase in O_2 concentration and/or a decrease in fire signature value implied that the underground atmosphere was being diluted with gas having component concentrations more like air, while the converse (O_2 concentration decrease and/or fire signature increase) implied dilution by gas from another portion of the mine that contained more temperature-dependent desorption gases. Note also was made of the quality of communication between the exhaust hole and each neighboring borehole. Each communications study generated data for another map. By repeating the mapping analysis several times for a set of boreholes, it was possible to determine whether a cold boundary existed for that area and what changes were occurring with time.[13]

A good estimate, based on the mine atmosphere data, then could be made for the approximate location of the cold boundary within the dimensions of the borehole pattern. That boundary was taken as the line of boreholes that produced gas samples showing a time-dependent decrease in concentrations of desorbed gases and combustion products while the fan was operating. The borehole spacing defined approximately how close the combustion front was to the inferred boundary. Figures 15 and 16 depict the mapped results for the Danny property. These data are from the summary data in figure 14 and show evidence that combustion was decreasing in the vicinity of BH 20 and increasing near BH 59. Similar data interpretations were made for the other areas.

At Renton, as more data were accumulated and analyzed, new boreholes were placed to obtain a more accurate estimation of the boundaries of the heated zones. A typical radius of effect of some 250 ft would be a reasonable distance to expect to measure differential pressure changes for this type of underground mine situation (see table 1). Measurable pressure changes were observed as far as 700 ft from the exhaust hole. It was possible,

[13]Another diagnostic technique developed during this project to help map the cold boundaries involved network ventilation analysis of the measured borehole vacuum and exhaust flow values. The technique does not depend on gas composition as a fire signature, but instead uses anomalies in calculated fire resistances between borehole pairs. The theoretical basis for the method and its limited application to a portion of the Renton data are described in appendix C.

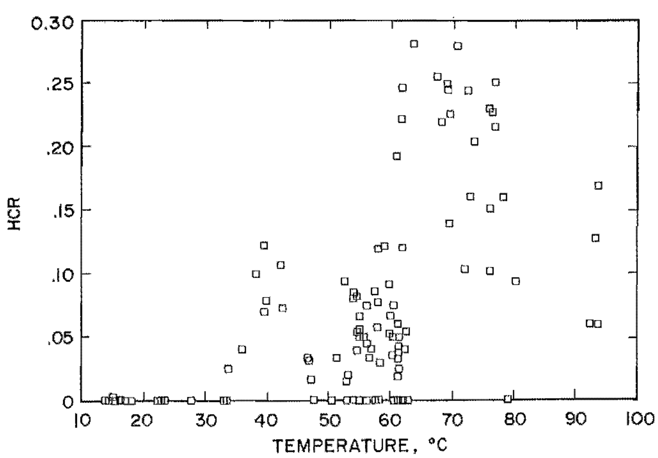

Figure 13.—Hydrocarbon ratio (HCR) versus borehole temperature, baseline data, Danny property. $HCR = \frac{\Sigma\ ([C_2H_2]\ \text{thru}\ [C_5H_{12}])}{[CH_4]}$.

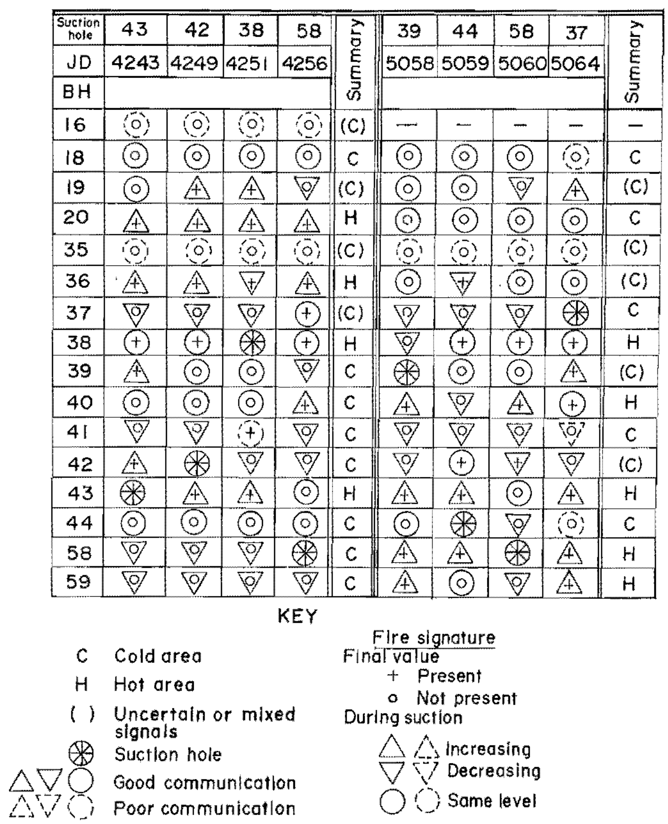

Figure 14.—Summary of fire signature information from eight borehole communications tests.

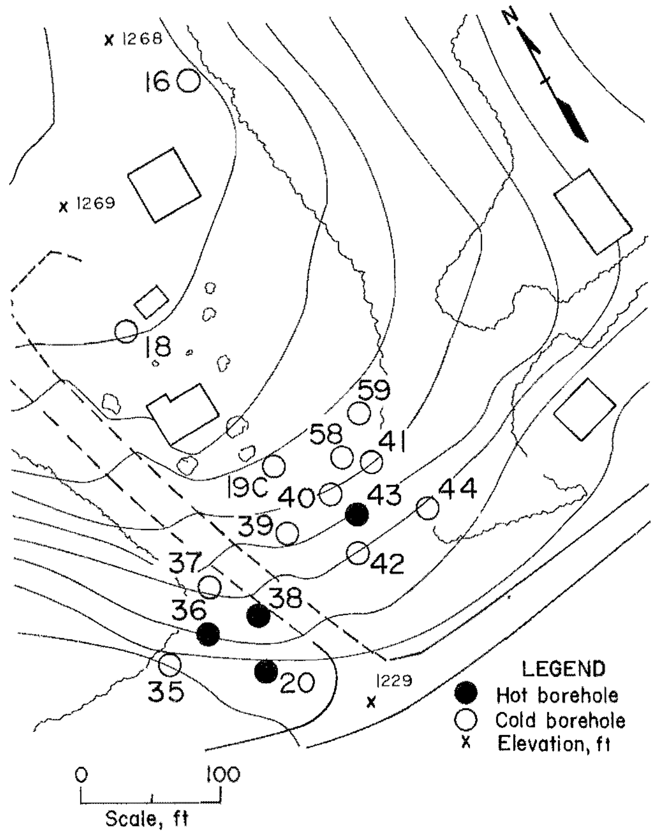

Figure 15.—Map of hot and cold boreholes determined from fire signature values, 1984 test days, Danny property.

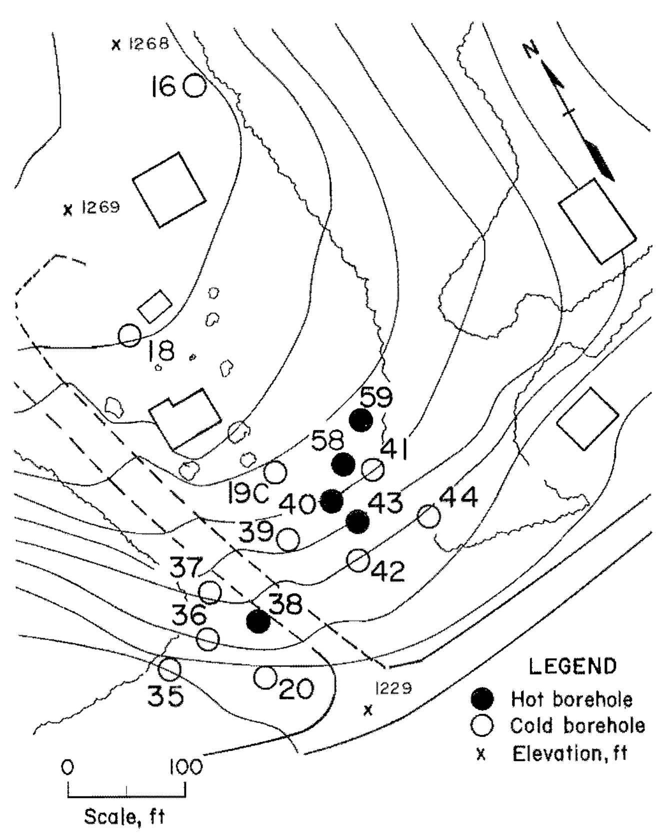

Figure 16.—Map of hot and cold boreholes determined from fire signature values, 1985 test days, Danny property.

therefore, to quickly survey about 4.5 acres from one borehole alone using the suction fan method. In contrast, a gas sampling pump might affect a 10-ft-radius area around the bottom of a casing—about one-thousandth of the area that could be affected by an exhaust fan's suction.

Most of the boreholes indicated on the map in figure 8 were drilled for use in the communications studies; some of the last ones drilled (high numbers) were added particularly for use as injection and monitoring holes during extinguishment activities described below. Monitoring of the boreholes already in place during previous months had confirmed the slow movements of the three combustion fronts and their directions of movement (as previously described in the "Site Description and History" section). Therefore, some injection boreholes were placed ahead of where each front would be expected when extinguishing began. As a result of the communications tests, three thermally noncontiguous subsites were delineated. They were designated as the Danny property area, the Miller Farm area, and the Plum Street area (fig. 8). It was significant that, while combustion products were detectable in the central part of the mine, no heating was occurring there.

EXTINGUISHMENT EFFORT

Physical Plant

The fire extinguishment phase of the work was a first-time attempt at using water injection with fume exhaustion to completely extinguish an abandoned mined land fire. The only previous field use of the water injection with fume exhaustion technique was for cooling the strata affected by a Burnout Control project fire prior to excavating the fire zone (2). That quenching action was quite successful and it was hoped that implementation of the technique would result in stopping the combustion on the three subsites at Renton.

The basic premise of water injection with fume exhaustion was to quench the fire by heat removal. At each subsite an exhaust fan connected to a borehole exerted suction on the mine network while water was injected into neighboring, communicating boreholes. These boreholes also were used as monitoring stations. The water was expected to saturate the underground gases flowing along pressure gradients generated by the fan. Previous communications studies had shown that there was gas movement through heated zones; moisture-laden gas could be expected to absorb heat energy from the hot materials. Conversion of liquid water to steam that could then be exhausted from the mine would significantly enhance heat removal. It was understood that air would be drawn into the underground system with both positive and negative effects with respect to the fire:

1. Air flowing over burning coal would tend to enhance the burning (negative);
2. Dilution of desorbed hydrocarbon gases would tend to make gas chromatographic detection of the hydrocarbons more difficult (negative);
3. Air flowing over heated, but nonburning, coal and rocks would cool those strata and act as a heat transfer medium for removing heat from the mine (positive).

The potential problem that additional air would supply more O_2 to the burning strata, and possibly spread the fire, required that the progress of the water injection with fume exhaustion technique be examined closely using the fire diagnostics technique. It was believed (at least at the start of the project) that fire quenching through widespread water injection would negate the possible fire enhancement from increased flow of air in the mine by rapid cooling of the fuel and by exclusion of air due to steam formation. Previous experience at the Calamity Hollow Burnout Control site had indicated that energy removal and subsequent cooling of the strata could be expected (*2*). In principle, once underground fuel temperatures decreased below their calorimetric self-heating point [approximately 158° F (70° C) for the case of Pittsburgh Seam coal] (*15*), plain air injection without water would suffice to further cool the mine media.

Consideration of the fact that the three subsites were thermally noncontiguous, coupled with the assumption that it might be necessary to operate each subsite independently from the others, suggested that separate fans, rather than one large, centrally located unit, be used. Each of three combustion air-type fans was driven by a 40-hp electric motor and was designed to draw 4,000 scfm of air at 70° F (21° C). Their physical design was essentially the same as that of the test fan previously used (see appendix A). Increased airflow and a slightly larger maximum differential pressure (about 40 in H_2O) were expected to enhance entrainment of moisture into the induced subterranean airflows. Based on the communications studies, a central borehole was chosen to be the exhaust fan location for each subsite: Danny—BH 39, Miller—BH 29, and Plum Street—BH 76. After about 2 months of water injection with fume exhaustion operation and the drilling of more injection boreholes, the test fan was put into service at the northern end of the Plum Street area (at BH 47) to enhance the vacuum pressure differentials at the boreholes on the cold side of the combustion front.

In consideration of the relatively long-term nature of the extinguishment effort, an electrical distribution network conveying utility mains power at 440 V ac was put in place. Each fan had a motor starter so each could be switched separately from the others even though each leg of the electrical network also had individual circuit breakers. Additionally, transformers produced 120-V-ac power for other uses such as charging pump batteries and powering space heaters and fans in small trailers on the subsites. Each trailer sheltered the water injection with fume exhaustion system operator-data gatherer during weather extremes, provided a place to store equipment, and served as an office.

A gravity-fed water distribution network consisting of about 3,400 ft of 2-in-diam and 4,500 ft of 0.75-in-diam plastic pipe was connected to a hydrant located at the municipal water tank at the top of the hill. A pilot valve shutoff system installed between the hydrant and the piping insured against uncontrolled outflow should a connection downstream break. Standard in-line water meters were placed at the hydrant and at appropriate locations in the network to monitor flow rates and record cumulative flow data. Each working day, midmorning and midafternoon readings of the flowmeters were recorded manually. At the borehole end of the network, the water flowed through a ball valve and into 0.375-in-OD polyethylene tubing extending to the bottom of the casing. The tubing terminated with a brass spray nozzle chosen to produce a conical pattern of 25- to 400-μm-sized droplets at a minimum water pressure of 10 psi. (This plumbing scheme is depicted in figure 5.) On each subsite, at least one borehole location had a pressure gauge as a monitoring point for that portion of the system. (Figure 17 is a photograph of the monitoring point near Renton Road.) An estimate of the typical pressures at the spray nozzle of 40 to 45 psi was made from the readings of the borehole water pressure gauges. The minimum regulated flow rate was about 0.6 gpm; the manufacturer's specified maximum flow rate at 50 psi was 1.22 gpm.

Figure 17.—Injection water pressure gauge, pipe, and valve at top of borehole casing.

Analysis of Extinguishment Effort Data

Temperatures and Gas Analyses

As a general measure of the effectiveness of the water injection with fume exhaustion effort, baseline temperatures for the boreholes were plotted versus time. Essentially all boreholes indicated approximately constant or increasing baseline temperatures.

The following discussion of this phase of the project refers to the data shown in figures 18 through 21 for four boreholes. The exhaust data were obtained while the fan was running during communications tests, but the borehole shown was not necessarily a suction hole. The boreholes were chosen because the data shown are representative of the different levels of activity occurring across the site. Analyses of temperature data and the associated O_2 concentration data provide some insight to the various possible results of the water injection with fume exhaustion activity occurring concurrently throughout the site. Also presented in figures 18 through 21 are plots of the ratio R1 versus time. R1 is a ratio that evolved from the previously mentioned analyses using ratios involving the sum of hydrocarbon concentrations and the CH_4 concentration derived from a gas sample analysis (*16*). As defined,

$$R1 = \frac{1.01[THC] - [CH_4]\cdot 1{,}000}{[THC] + 0.01}, \tag{2}$$

where [THC] = total volume concentration, ppm, of C_1 through C_5 hydrocarbons,

$[CH_4]$ = volume concentration, ppm, of CH_4,

and the constant 0.01 is included only to prevent attempted division by zero (by a computer) when there are no hydrocarbon values in the sample analysis. This ratio was defined to relate the quantity of desorbed hydrocarbons to the level of heating of the carbonaceous fuel. Concurrent with the latter part of the Renton activity was a laboratory study to establish a data base for correlation with field data (*16*). From experimental work on Pittsburgh Seam coal, the following inferences can be drawn.

R1 =	0	when	[THC] = 0;
	10		[THC] = $[CH_4]$;
	10-50		conditions are normal;
	50-100		there is possible heating;
	>100		heating is occurring.

A single temperature may not be associated with a specific R1 value because the ratio is derived from concentrations of hydrocarbons that are desorbing from a finite amount of coal, and therefore, those concentrations (or the ratio) could be numerically the same both at low temperature when little desorption occurs and at high temperature when most hydrocarbons are gone. This fact indicates the need for time-dependent monitoring to determine whether the fuel is heating or the combustion already has occurred.

Baseline and exhaust data for BH 14 are shown in figure 18. BH 14 was drilled into a probable entry as indicated by the drill log record of small voids and red dog (ash). The area was within a few hundred yards of the initial ignition point and may have experienced combustion as early as 1960. The top of the rubble was about 36 ft below the surface, and no water was injected into this borehole because of its low temperature. The data

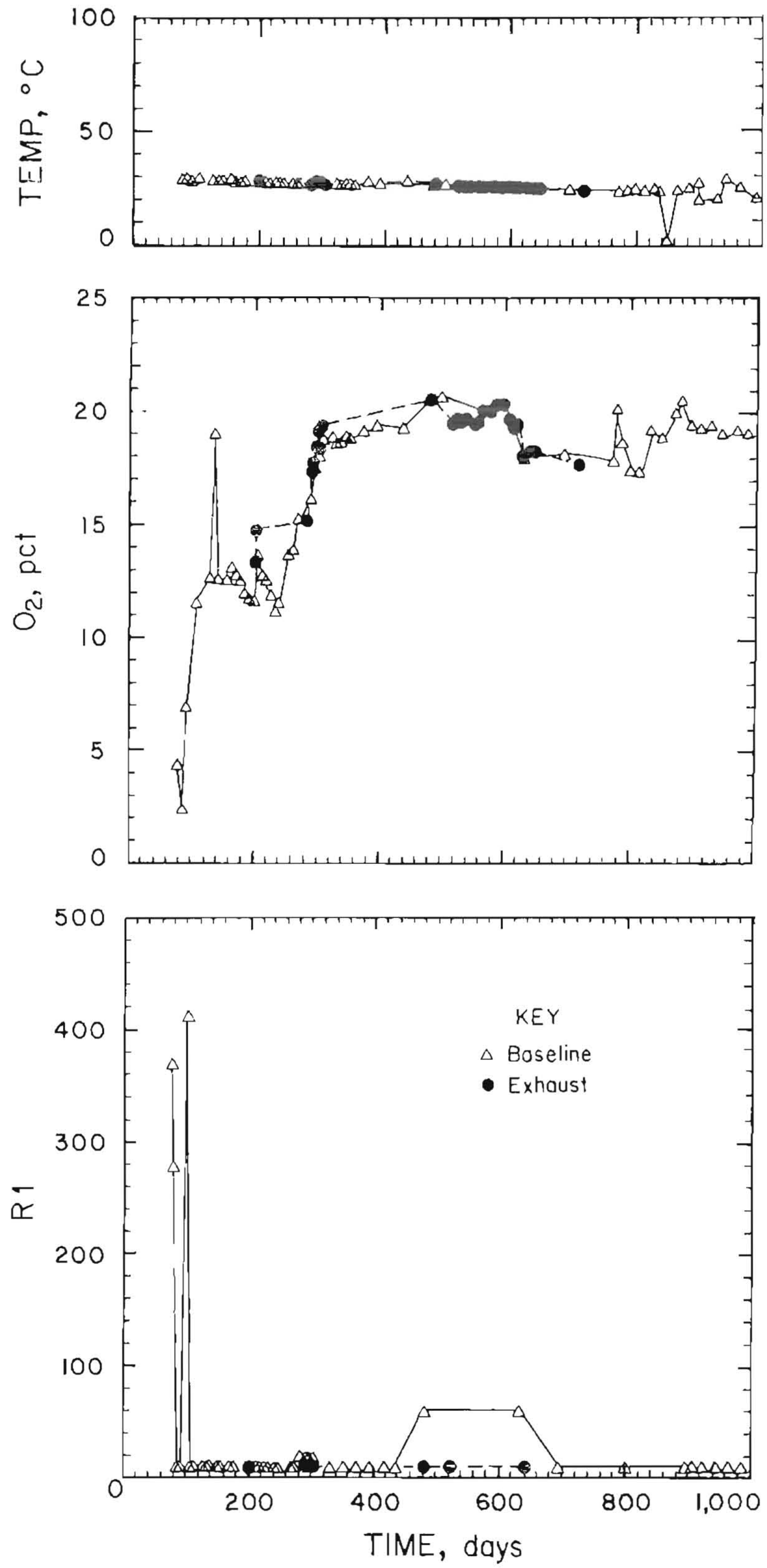

Figure 18.—Temperature, O_2 concentration, and hydrocarbon ratio R1 at bottom of BH 14 during project.

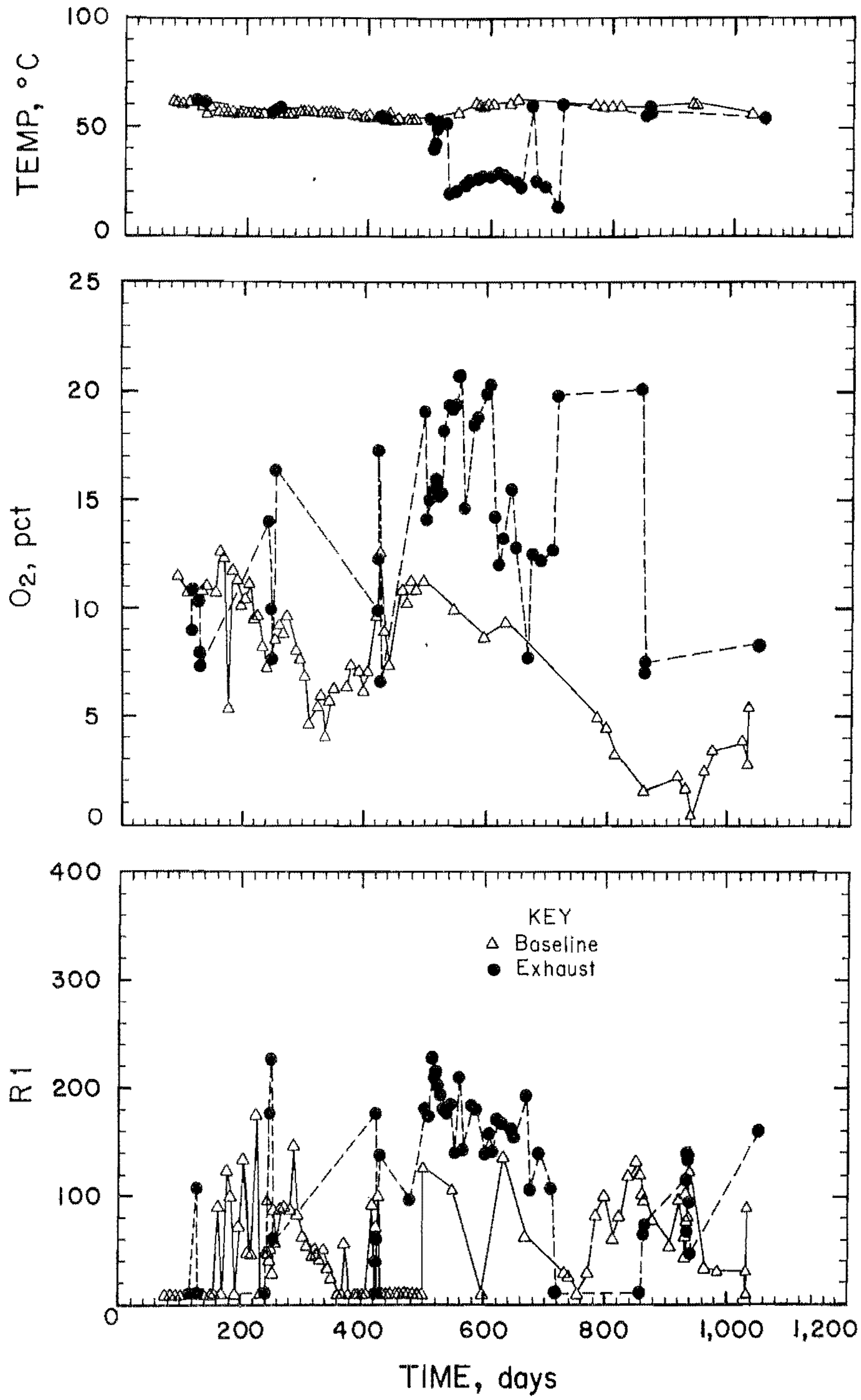

Figure 19.—Temperature, O_2 concentration, and hydrocarbon ratio R1 at bottom of BH 19C during project.

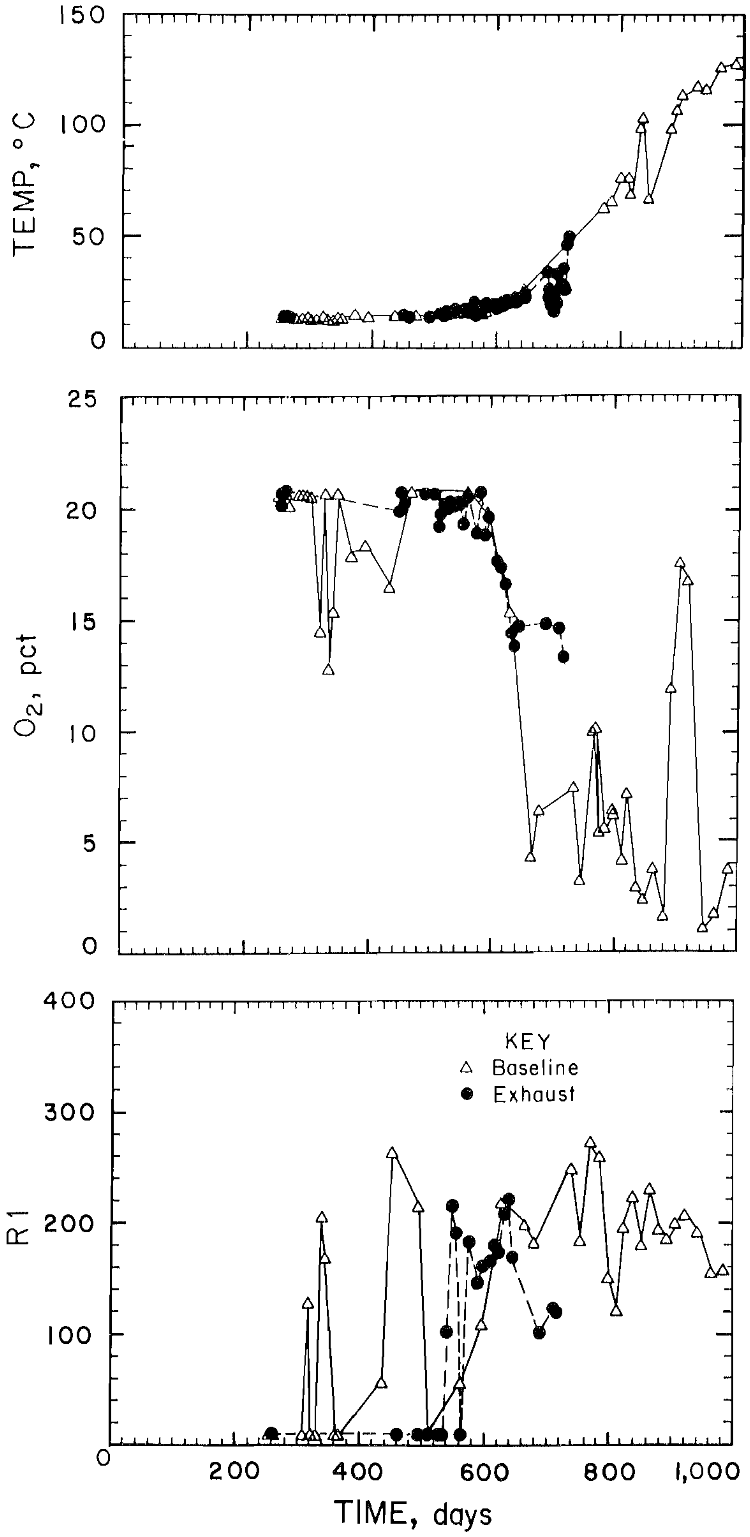

Figure 20.—Temperature, O_2 concentration, and hydrocarbon ratio R1 at bottom of BH 33 during project.

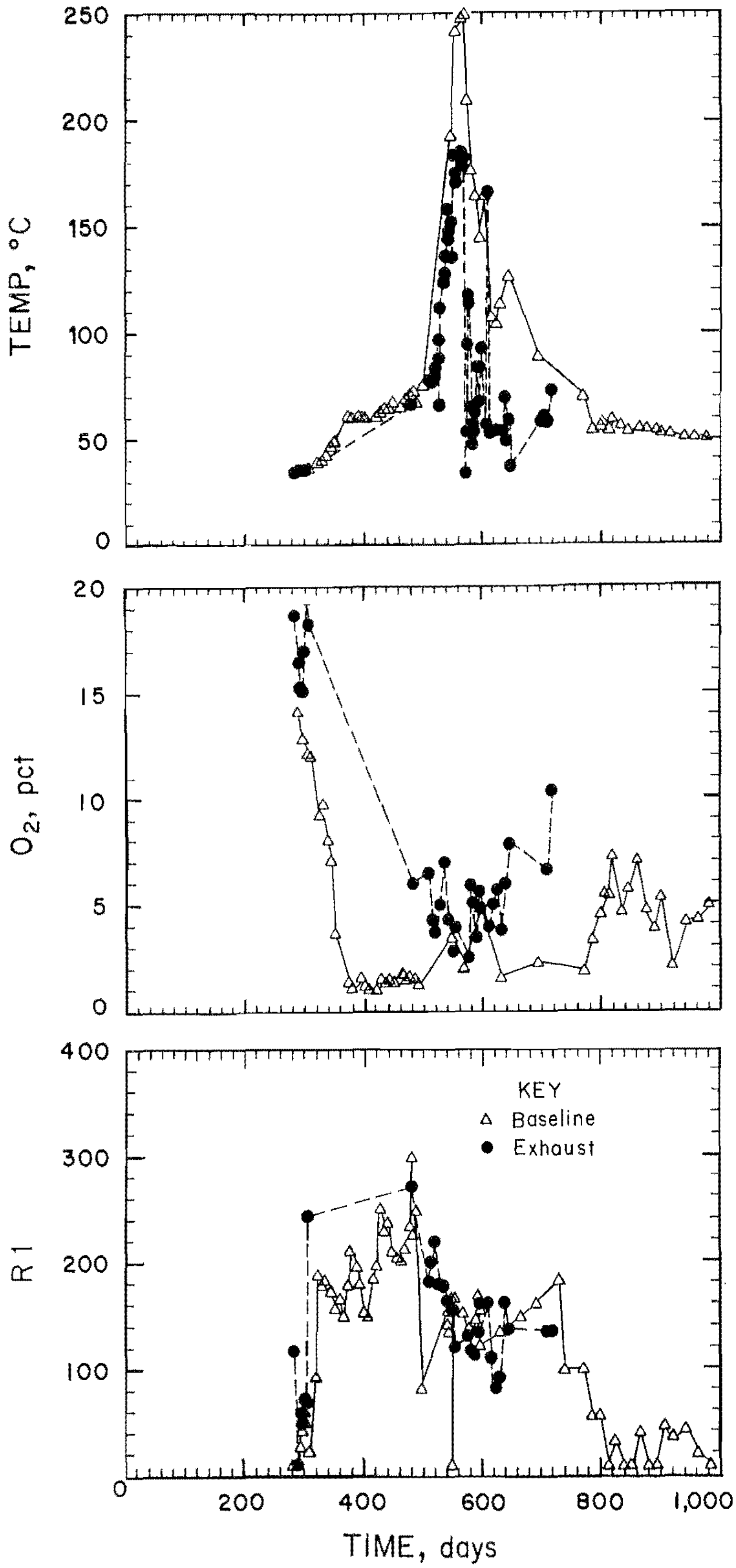

Figure 21.—Temperature, O_2 concentration, and hydrocarbon ratio R1 at bottom of BH 57 during project.

(fig. 18) show that there was less than a 5° C drop in the local temperature even with the exhaust fan drawing cooling air through the heated mass (for reference, unheated strata temperatures were 12° to 14° C). The temperature did fall while the O_2 concentration increased from the time of drilling and preliminary communications studies. Initiation of the water injection with fume exhaustion activity brought the O_2 concentration level to near the atmospheric value of 20.9 pct. Without other information, the initial, baseline R1 values for the gases sampled at the borehole would indicate heating at that location. The values calculated later imply a condition of little hydrocarbon desorption. Between days 460 and 640 and while the fan was not operating, migration of desorbed gases from heated fuel in the general vicinity may have caused the baseline R1 value to increase to the higher values calculated for those 2 days. The data comprehensively indicate that the strata around BH 14 were not reignited with the added O_2 and continued their slow cooling.

The data for BH 19C (fig. 19) indicate that prior to the "continuous" 6 h/d, 5 d/w fan operation (i.e., prior to approximately day 534 on this subsite), the baseline temperature was slowly decreasing. Water injection produced an apparent temperature decrease, which is contradicted by the baseline data for the same period. Those baseline data include a 7° C elevation from which a slight increase in combustion in the vicinity is inferred. There is the possibility that the water cooled the thermocouple while having little effect on the heated carbonaceous material. Data from communications tests run after day 700 show that those temperatures taken with the fan operating are close in value to the baseline measurements made then and some 2 years earlier. BH 19C O_2 concentrations increased toward the normal air value when the fan was operating, implying that the subsurface atmosphere drawn past this borehole was not affected substantially by any combustion in the mine area upstream on the flow path extending through BH 19C to the exhaust hole. The conclusion inferred from comparing both O_2 concentration and temperature baseline data was that heated combustion products (from accelerated burning nearby, but not on the induced flow path) migrated to the vicinity of BH 19C via natural underground flow patterns when the fan was not running. While two explanations for the temperature increase could be advanced—local combustion or movement of heated gases—the added information from the gas analyses substantiates the latter conclusion. The variation over time of the R1 values corroborates the above analysis, particularly through day 500. The exhaust data imply heated material upstream of the borehole; the baseline numbers are less straightforward in interpretation. The post day 780 data again imply possible heating in the general vicinity.

BH 33 was drilled into a probable entry more than 100 ft inside the mine and away from the apparent path of the combustion front moving northward along the western (buried) crop line. While the temperature at BH 33 initially was about 12° C (fig. 20), the temperature 50 to 100 ft to the west was about 33° C. Following initiation of water injection with fume exhaustion activity at that subsite (after day 540), there was a substantial increase in temperature both for baseline and exhaust values. These data alone could indicate one of the following two conclusions: (1) Combustion had begun at the borehole site, or (2) hot combustion products were migrating from a burning volume upstream on a natural flow path passing BH 33. The O_2 concentration data provide a more complete explanation. Drops in O_2 concentration values prior to water injection with fume exhaustion could be the result of infiltration of heated combustion products into the vicinity, perhaps as a result of communications tests. It is seen that the concentration values tend to return to the value in atmospheric air; this fact diminishes the likelihood of the borehole being on a natural flow path connected to a hot area at that time. However, concurrent with the temperature increase at water injection with fume exhaustion initiation, the O_2 baseline concentration decreases continually, thereby again implying either conclusion 1 or 2 stated above. More communications tests would be required to determine which conclusion is correct, but the higher initial temperatures and gas compositions at other boreholes closer to the outcrop support the inference of new burning near or at BH 33. Quite possibly, heated gases drawn to the vicinity during water injection with fume exhaustion conditioned the carbonaceous material toward rapid combustion by drying the fuel. Subsequently, spraying water on the material could have increased temperature via the exothermic heat of wetting reaction. R1 baseline values indicate heating whereas R1 exhaust data show normal conditions prior to day 540. A reasonable conclusion from both the O_2 concentration and R1 data is that there is combustion occurring upstream and, possibly, in the immediate vicinity of this borehole.

On the eastern side of the site, the combustion front passed through BH 57's location after traversing BH 14's site. The temperature and gas data (fig. 21) both show that an increase in local combustion was evident from the time of instrumentation cap installation. The annular space around the casing, although plugged with soil, probably acted as a chimney for the already warm gases in the rubble at the bottom of the casing. Convection then would cause more air to be drawn to the zone, thus sustaining oxidation, slowly rising temperatures, and evaporating water that sometimes condensed around the casing at the surface. The suction of the exhaust fan during water injection with fume exhaustion operation pulled even more air into the area; the results were the dramatic changes in temperature indicated on the graph. The conclusion made from these data is that the hot fuel producing the heated gases sampled at the borehole burned to completion. As the exhaust fan continued to induce cool airflow over the hot ash, temperatures decreased and less O_2 was consumed. It is of interest to note in the early baseline data that the O_2 concentration dropped, during a period of 80 days, from about 14 pct to about 1 pct and remained at that level for another 120 days while the temperature rose about 45° C (to approximately 75° C) during the whole 200-day period.

Water Injection

After about 4 months of injecting water for about 6 h/d, 5 d/w, two plumbing modifications were made to saturate the strata in the immediate vicinity of the borehole in case there was combustion above the bottom of the casing. Also, any gases flowing past the wet surfaces would become saturated with water vapor. First, a 2-week-long replumbing of injection piping was done; this task began on September 12, 1985. A substantial portion of water now bypassed the spray nozzles, flowed through 0.375-in-OD tubing placed along the outside of the casing, and exited only a foot or two beneath the surface. Water injection with fume exhaustion activity continued during the replumbing time and the following 2 weeks. Second, after a 2-week hiatus for data evaluations and to allow the Pittsburgh Research Center analytical laboratory to complete some chromatography analyses, the outside water injection tubes for 24 boreholes were modified by perforating (with eight 0.0625-in holes) the tubing, which was then looped into a ring around the casing. The revised injection methods and increased waterflow at some boreholes had no measurable effect on the general combustion activity.

During the extinguishment activity, a total of approximately 7.1 million gal of water was injected into the underground workings over a 6-1/2-month period (May 14 through December 13, 1985). Analysis of mine drainage flow rates indicated augmentation of the normal output by water injected at the boreholes. However, no new drains were observed anywhere on the site.

Figures 22 through 24 present data associated with the Miller Farm seep drain, the primary mine water monitoring point. While figure 22 indicates that flow rates varied within a range of about 2 to 56 gpm during a 3.5-year period, it is also evident that the running average, calculated using all the measurements successively, remained fairly constant at about 12 to 14 gpm from the installation of a drain pipe extension in May 1984 through the first 8 months of 1985. Subsequently, starting in late August 1985, there was a large increase in the quantity of water injected during the water injection with fume exhaustion procedure followed by about 3 weeks of rainy weather (October to November). The graph in figure 23 shows that, unless there was a long delay in the injected water's movement through the mine, the rain had a greater effect on the seep's flow rate than did the injected water.

Figure 24 shows that the temperature of the drainage water was fairly constant for each set of measurements

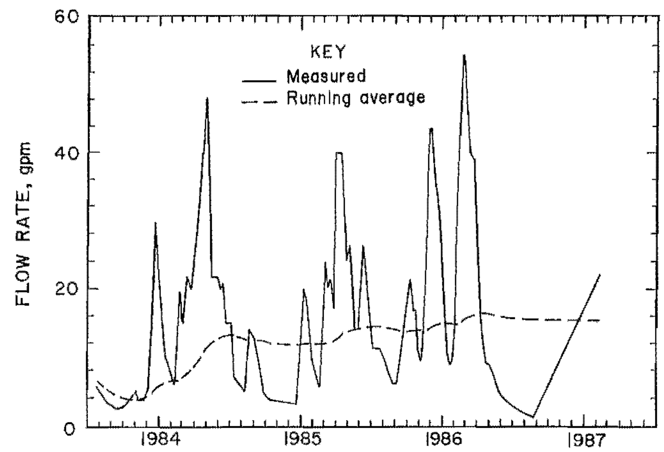

Figure 22.—Waterflow rate at Miller Farm seep drain during project.

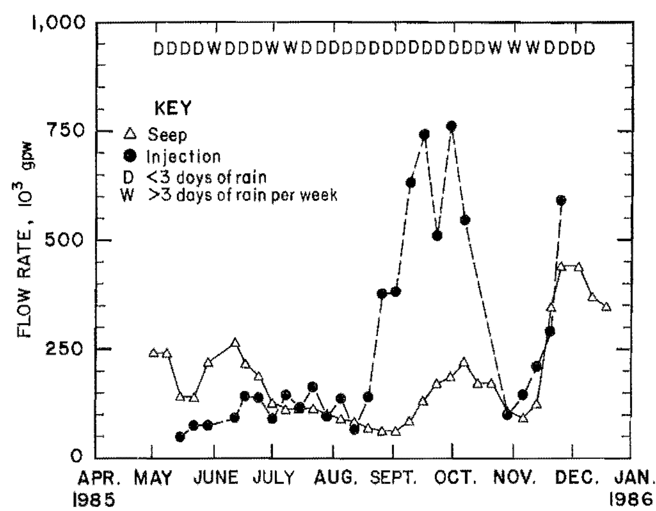

Figure 23.—Rainfall periods and flow rates for Miller Farm seep drain and for water injected into boreholes during water injection with fume exhaustion segment of project.

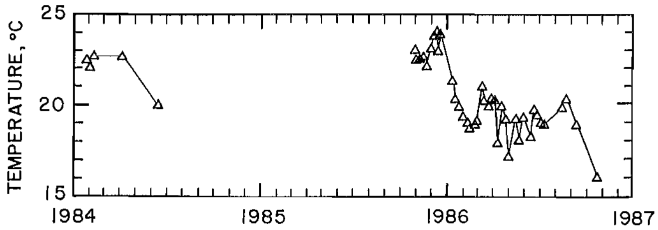

Figure 24.—Temperature of water from Miller Farm seep drain during project.

prior to and at the end of the water-injection activity. The drainage water temperature was higher than that of unheated strata (12° to 14° C) by as much as 10° C. Thermal energy was being removed from the heated strata, the ultimate goal to effect extinguishment. However, the following calculation shows that the energy removed was insufficient to achieve that goal. Based on many visual observations, the total quantity of water draining from the mine at any specific time was estimated to be about twice that from the Miller Farm seep drain in order to account both for water seeping elsewhere across the same hillside as the drain and for water exiting into the roadside catch basin mentioned earlier. A thermal energy flow calculation using an average total waterflow rate of 28 gpm and a heat capacity, C_v = 0.999 cal/g, for water at an average temperature of 22° C yields a value of approximately 25,208 Btu/h. Over a year, the energy removed approximates the energy released by complete combustion of about 8.8 st of coal with a heating value of 12,500 Btu/lb. In the abandoned mine situation, the overall heating value of the burning material (carbonaceous shale, in part) is lower, combustion is incomplete, and much of the liberated energy is stored in the adjacent strata and the fuel itself instead of heating the flowing mine water. The affected mass, therefore, is several times greater than that reflected in the quantity of energy removed by the mine drainage. For completeness, it is noted that the drainage liquid had an approximate pH 3; it was a warm acid that flowed into the environment outside the old mine.

COMPUTER-ASSISTED DATA ANALYSES—DISCUSSION

The flowchart shown in figure 25 illustrates the method used to process the data acquired during field activities. Numerical data from borehole measurements, mine gas and mine drainage water analyses, and textual information concerning drilling and other events were entered into various computer files stored on disc in the Pittsburgh Research Center's VAX 780 computer. For efficiency, analytical laboratory personnel entered the data generated from analyses of gas and water samples; these data were the primary data base used for diagnostic evaluations.

Manipulations of the data were accomplished using various packaged and in-house-produced computer programs, as indicated in the bottom row of the diagram. Numerical data from the field measurements and the laboratory analyses were sorted with respect to sample date and time and borehole number and then merged to simplify accessing the data. Graph-generating programs were also used; figures 10 through 13 and 18 through 24 are typical of the output graphs. Although the results were not used to determine actions during the field project at Renton, two other mathematical manipulation programs have been applied to the data. One program generated contour maps of a variable's value as a function of location (defined by the borehole). A matrix-solving program generated solutions used in network analyses of the effects of the heating on pressure differences between boreholes. The initial work using the extensive Renton data base and these latter two packages indicates the possiblity of new mine fire diagnostics tools to better, and more economically, define underground fire locations using the borehole and exhaust fan system.

Ongoing evaluations of data processing activities for this and two other Bureau projects indicate that a variety of data can be efficiently recorded and retrieved using spreadsheet programs designed for use with a personal computer (*17-18*). Various calculations can be done automatically by available spreadsheet software. As importantly, portable personal computers are sufficient for much of the data processing; when necessary, data can be transferred to larger capacity computers. Communication with a central computer is readily accomplished via telephone modem from field sites. The major advantage, currently, of mainframe computers is the capability to operate quickly on many large files. Data manipulation operations of this kind are done, during comparisons of (1) data describing several boreholes and/or (2) data gathered over an extended period of time. Data files in these cases may contain several thousand lines of data. A spreadsheet program on a personal computer does well at displaying and manipulating all available data for one borehole. In some cases, it may be useful to transfer consolidated data records from a mainframe machine to a

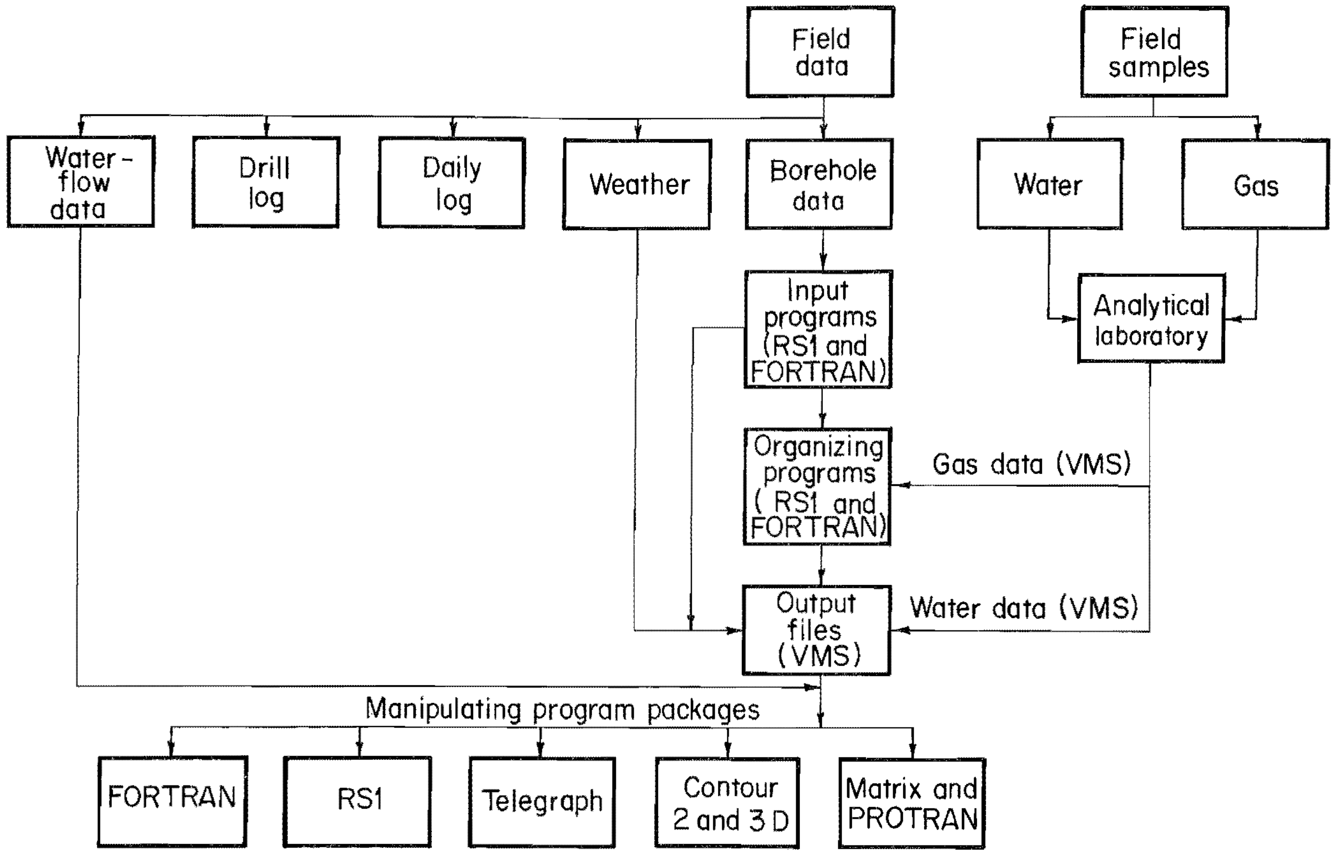

Figure 25.—Flowchart of data from field acquisition to data manipulation computer programs.

personal computer. Recent advances in graphics software allow representing spreadsheet records in various graphical formats.

It was found to be useful and convenient to store even infrequently accessed data such as borehole drilling logs and daily activity text logs in the computer. At the least, the data were available to anyone needing them even if the original logsheets were elsewhere. Proper encoding of these types of data allows easy cross-referencing with the wholly numerical data.

SUMMARY AND CONCLUSIONS

Novel mine fire diagnostics methodology for remote delineation of combustion zones in abandoned underground coal mines was developed and shown to work at a field site. The locations of three such zones were determined at the Renton, PA, abandoned mine fire site. The zones, thermally separate from each other, included a total area of approximately 11 acres out of about 60 acres of mine workings bounded by the buried outcrop. The techniques employed (1) drilled boreholes into an underground mine, (2) an exhaust fan attached to one of the boreholes, and (3) monitoring pressure, temperature, and gas concentrations at the bottoms of the boreholes. Evaluations of changes in the magnitudes of borehole pressure, temperature, and gas concentration values generated the information necessary for drawing maps of the heated areas. Long-term monitoring produced the data that confirmed the suspected movement and direction of the combustion fronts. Computerized manipulation of tens of thousands of pieces of data was carried out during the development and application of the diagnostic effort.

Exclusive of the time required to acquire and install equipment and to have boreholes drilled, the diagnostic activity required 8 to 10 months. With the knowledge now available, it is likely that the time for diagnostic work could be significantly shortened.

The water injection with fume exhaustion technique to extinguish the combustion through heat removal was tried without success. The system was not able to transport sufficient quantities of water to the burning materials to absorb and remove the thermal energy being produced and, thus, to compensate for the maintenance and probable acceleration of the combustion at some locations in all three subsites. It is suspected that the burning was occurring in the carbonaceous roof strata and that the water agglomerated and flowed away before sufficient moisture made contact with all the heated strata. Although water-saturated gases were expelled from the mine by the exhaust fans and temperature and gas concentration changes indicated that some localized regions were being cooled, the overall effect was that the combustion continued at all three subsites. A more effective delivery system for the water (perhaps foam) will be required to accomplish the required quenching and heat removal.

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APPENDIX A.—FAN ASSEMBLY DESCRIPTION

Figure A-1 is a line drawing of the test fan assembly and the flexible duct and rigid piping (detail A) containing the "test section," situated between the borehole and the fan. The test fan (combustion air type, for use in exhaust mode) was rated at 2,920 cfm at a differential pressure of 34.7 in H_2O at 70° F (21° C) and had a wheel and shaft fabricated of AISI Type 316 stainless steel to withstand temperatures to 600° F (316° C). Its 25-hp motor was powered from a separate, propane-fueled generator set. The test fan's original sled was made as a drainable water tank that could be filled to lower the center of mass to increase stability. This configuration was difficult to tow and was not needed for stability in actual field use. The original fan was placed on another sled built from approximately 10-in-diam tube skids (not shown in figure A-1); the generator set also was placed on a similarly constructed tubular sled. Both sleds were pulled about the site with a small bulldozer. The fan was equipped with

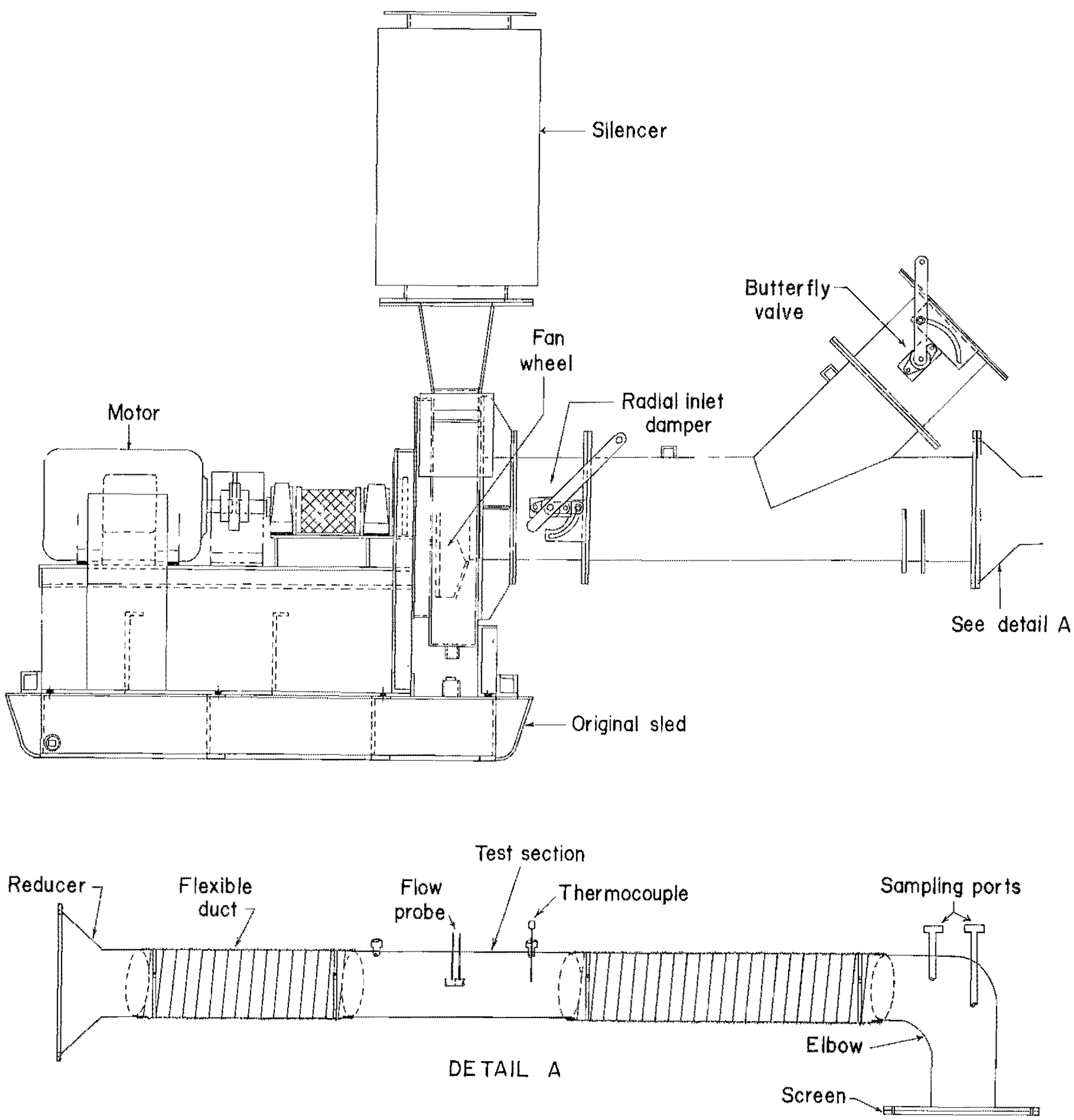


Figure A-1.—Schematic of fan assembly including test section and connecting piping.

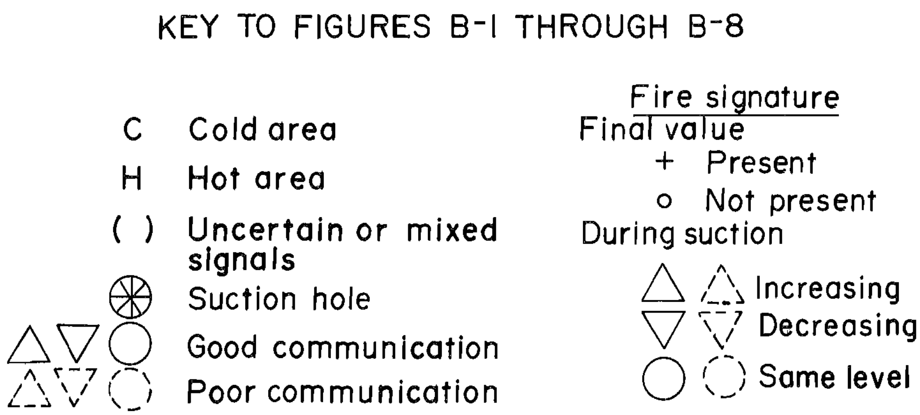
a radial inlet damper, which was used during some flow simulation tests and was closed only at fan start to minimize load. An outlet silencer reduced noise levels, but both the fan and the generator assemblies were too noisy to stand near for more than a few minutes. A plastic blind flange, used when the fan was not operating, replaced a rain hood that proved to be too heavy to be on top of the silencer. At the inlet, a Y-section was installed ahead of the damper to provide dilution or balance air, if necessary. A butterfly valve controlled flow through the screened opening of the branch. Normally, the branch was sealed with a gasket and a blind flange.

A nominal 8-in-diam, 10-ft-long steel test section, supported on two sawhorses about 3 ft high, was connected at one end to the fan with a reducer (8 by 12 in) and at the other end to a 90° elbow to be attached to the 8-in-diam borehole casing. The 3- to 5-ft-long connections were made with flexible, reinforced, vinyl-coated nylon duct. The test section had a removable bidirectional flow probe (*19*)[1] centered in the pipe plus a port near each end for installing a type-K thermocouple. The elbow was fitted with a removable metal screen between it and the casing (to prevent large solids entrained in the airstream from entering the test section), a pressure-gas sampling port, and a second port to which could be attached a tube extending to the bottom of the casing for other pressure measurements.

[1]Italic numbers in parentheses refer to items in the list of references preceding this appendix.

APPENDIX B.—LOTUS 1-2-3 SPREADSHEET TABULATIONS OF RESULTS FOR TWO BOREHOLE COMMUNICATIONS TEST PERIODS

Computerized spreadsheets are shown in figures B-1 through B-8. The symbols in the last column of each tabulation are explained below.



Mine Fire RENTON (JD4243) EXHAUST BOREHOLE = #43 FAN ON AT 1007

BH:	TIME:	DEGC TEMP:	INH2O PRES:	PCT H2:	PCT CO2:	PCT O2:	PCT N2:	PCT CO:	PCT CH4:	PPM C2H6:	PPM C2H4:	PPM C3H8:	PPM C3H6:	PPM xC4H10:	PPM xC5H12:	C2C5/CH4:	CO/CO2:	JTR:	PPM AFCO:	SUMMARY CONCLUSION
16	931	16.1	-0.004	0.0000	0.05	20.90	78.12	0.0010	0.0005	0	0	0	0	0	0	0.000	0.0200	-0.256	4093	
16	1237	16.0	-0.014	0.0000	0.05	20.90	78.12	0.0015	0.0005	0	0	0	0	0	0	0.000	0.0300	-0.258	6140	
16	1421	15.6	0.000	0.0000	0.05	20.90	78.12	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	-0.252	0	
18	926	17.1	-0.015	0.0000	4.90	13.70	80.40	0.0005	0.0003	0	0	0	0	0	0	0.000	0.0001	0.644	14	
18	1232	17.8	-0.056	0.0000	4.50	14.90	79.60	0.0010	0.0003	0	0	0	0	0	0	0.000	0.0002	0.727	35	
18	1417	17.6	-0.041	0.0000	4.10	16.20	78.80	0.0005	0.0002	0	0	0	0	0	0	0.000	0.0001	0.876	22	
19	916	56.9	0.027	0.0000	9.80	6.90	82.30	0.0050	0.0025	1	0	0	0	0	0	0.040	0.0005	0.658	75	
19	1214	58.2	-0.125	0.0000	8.00	10.10	80.90	0.0080	0.0020	0	0	0	0	0	0	0.000	0.0010	0.706	154	
19	1406	57.8	-0.100	0.0000	6.30	13.60	79.10	0.0115	0.0015	0	0	0	0	0	0	0.000	0.0018	0.857	328	
19	1458	56.7	-0.113	0.0000	6.00	14.00	79.00	0.0085	0.0015	0	0	0	0	0	0	0.000	0.0014	0.866	256	
20	816	33.4	0.000	0.0000	9.10	7.20	82.70	0.0010	0.0015	0	0	0	0	0	0	0.000	0.0001	0.618	15	
20	1054	34.3	-0.340	0.0000	7.80	11.40	79.80	0.0325	0.0485	45	3	10	1	5	2	0.136	0.0042	0.803	713	
20	1308	33.9	-0.215	0.0000	5.00	15.30	78.60	0.1000	0.0655	115	7	30	4	12	5	0.264	0.0200	0.918	3707	
20	1440	35.9	-0.210	0.0000	4.50	16.00	78.20	0.1200	0.1800	175	15	50	7	18	11	0.153	0.0267	0.972	5078	
35	821	22.4	0.000	0.0000	1.80	16.30	80.90	0.0025	0.0010	0	0	0	0	0	0	0.000	0.0014	0.351	113	
35	1100	23.4	-0.001	0.0000	1.60	16.40	81.00	0.0025	0.0010	0	0	0	0	0	0	0.000	0.0016	0.316	115	
35	1315	22.3	-0.001	0.0000	1.60	16.70	80.70	0.0015	0.0010	0	0	0	0	0	0	0.000	0.0009	0.342	74	
36	828	76.1	0.000	0.0000	15.50	0.50	82.80	0.1040	0.1000	155	5	40	4	17	9	0.230	0.0067	0.727	1065	
36	1105	77.8	-0.126	0.0000	9.40	7.00	82.40	0.1020	0.0585	110	7	30	5	13	8	0.296	0.0109	0.639	1532	
36	1321	77.6	-0.120	0.0000	5.10	11.90	81.80	0.1600	0.0495	95	13	25	4	10	6	0.309	0.0314	0.534	3704	
37	837	69.3	0.016	0.0000	10.30	7.30	81.30	0.1100	0.1000	155	8	50	6	16	10	0.245	0.0107	0.729	1688	
37	1116	68.1	-0.104	0.0000	0.95	20.10	78.00	0.0035	0.0040	5	0	1	0	0	0	0.150	0.0037	1.671	861	
37	1325	66.3	-0.087	0.0000	0.50	20.60	77.97	0.0015	0.0000	0	0	0	0	0	0	ERR	0.0030	8.076	895	
37	1443	66.7	-0.100	0.0000	0.40	20.70	78.00	0.0000	0.0005	0	0	0	0	0	0	0.000	0.0000	-13.333	0	
38	841	69.6	0.020	0.0000	14.00	0.20	84.70	0.0205	0.0470	70	2	20	3	7	4	0.226	0.0015	0.630	207	
38	1121	62.0	-0.155	0.0000	0.60	20.35	78.11	0.0040	0.0035	4	0	1	0	0	0	0.143	0.0067	1.727	1394	
38	1330	59.2	-0.133	0.0000	0.60	20.40	78.05	0.0095	0.0100	17	0	5	0	0	0	0.220	0.0158	2.143	3611	
39	912	62.4	0.027	0.0000	5.30	12.60	81.10	0.0105	0.0015	0	0	0	0	0	0	0.000	0.0020	0.597	263	
39	1127	63.0	-0.212	0.0000	0.65	20.35	78.06	0.0075	0.0010	0	0	0	0	0	0	0.000	0.0115	1.952	2614	
39	1401	62.7	-0.195	0.0000	0.55	20.40	78.10	0.0170	0.0030	3	0	1	0	0	0	0.133	0.0309	1.898	6462	
40	908	62.4	0.019	0.0000	11.00	4.10	83.90	0.0060	0.0025	1	0	0	0	0	0	0.040	0.0005	0.607	75	
40	1136	61.6	-0.500	0.0000	0.55	20.25	78.27	0.0020	0.0005	0	0	0	0	0	0	0.000	0.0036	1.122	598	
40	1357	61.1	0.000	0.0000	0.30	20.65	78.12	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	5.792	0	
41	901	93.8	0.040	0.0000	13.90	1.90	82.90	0.2700	0.0135	7	0	1	0	0	0	0.059	0.0194	0.703	2969	
41	1141	94.2	-0.178	0.0000	4.00	17.50	77.60	0.0020	0.0010	0	0	0	0	0	0	0.000	0.0005	1.306	121	
41	1346	91.2	-0.150	0.0000	2.50	19.00	77.60	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	1.598	0	
41	1451	92.1	-0.131	0.0000	2.20	19.30	77.60	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	1.741	0	
42	847	27.9	0.000	0.0000	0.25	20.70	78.12	0.0000	0.0008	0	0	0	0	0	0	0.000	0.0000	138.889	0	
42	1148	33.5	-0.440	0.0000	0.20	20.80	78.07	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	-1.795	0	
42	1335	32.4	-0.420	0.0000	0.30	20.70	78.07	0.0035	0.0007	0	0	0	0	0	0	0.000	0.0117	-26.430	2919	
42	1505	33.1	-0.419	0.0000	0.25	20.70	78.11	0.0015	0.0030	2	0	1	0	0	0	0.100	0.0060	-295.441	1251	
43	851	55.8	0.023	0.0000	3.40	16.40	79.20	0.0015	0.0040	1	0	1	0	0	0	0.050	0.0004	0.741	69	
43	944	53.5	-6.000	0.0000	8.50	8.70	81.80	0.0510	0.0100	7	0	2	0	0	0	0.090	0.0060	0.658	872	
43	1012	54.9	-23.900	0.0000	0.05	20.90	78.12	0.0015	0.0000	5	0	0	0	0	0	ERR	0.0300	-0.258	6140	
43	1047	57.0	-24.400	0.0000	0.10	20.85	78.12	0.0015	0.0005	0	0	0	0	0	0	0.000	0.0150	-0.682	3106	
43	1154	57.5	-24.700	0.0000	0.05	20.85	78.17	0.0035	0.0005	0	0	0	0	0	0	0.000	0.0700	-0.390	7247	
43	1304	57.6	-24.400	0.0000	0.05	20.85	78.17	0.0040	0.0005	0	0	0	0	0	0	0.000	0.0800	-0.393	8282	
43	1345	42.6	-24.200	0.0000	0.05	20.85	78.17	0.0035	0.0005	0	0	0	0	0	0	0.000	0.0700	-0.390	7247	
43	1435	58.2	-22.400	0.0000	0.05	20.90	78.12	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	-0.252	0	
43	1509	56.9	-21.800	0.0000	0.05	20.90	78.12	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	-0.252	0	
44	856	35.8	-0.002	0.0000	0.65	20.15	78.27	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	1.099	0	
44	1159	36.1	-0.101	0.0000	2.40	19.00	77.70	0.0015	0.0000	0	0	0	0	0	0	ERR	0.0006	1.510	161	
44	1341	35.1	-0.088	0.0000	2.20	19.30	77.60	0.0015	0.0000	0	0	0	0	0	0	ERR	0.0007	1.741	190	
44	1447	35.7	-0.100	0.0000	2.10	19.10	77.90	0.0005	0.0000	0	0	0	0	0	0	ERR	0.0002	1.361	57	
58	905	62.7	0.022	0.0000	10.50	5.90	82.60	0.0070	0.0055	2	0	1	0	0	0	0.055	0.0007	0.657	97	
58	1205	62.1	-0.205	0.0000	4.00	16.70	78.40	0.0010	0.0010	0	0	0	0	0	0	0.000	0.0003	0.982	49	
58	1352	60.0	0.000	0.0000	2.90	18.50	77.70	0.0010	0.0005	0	0	0	0	0	0	0.000	0.0003	1.388	85	
59	921	60.1	0.035	0.0000	11.60	3.90	83.50	0.0430	0.0060	3	0	1	0	0	0	0.067	0.0037	0.638	528	
59	1221	60.8	-0.100	0.0000	1.60	19.00	78.50	0.0035	0.0010	0	0	0	0	0	0	0.000	0.0022	0.889	376	
59	1412	59.4	-0.085	0.0000	1.00	19.80	78.30	0.0030	0.0007	0	0	0	0	0	0	0.000	0.0030	1.056	546	
59	1454	58.5	-0.086	0.0000	0.55	20.20	78.32	0.0015	0.0000	0	0	0	0	0	0	ERR	0.0027	0.993	418	

Figure B-1.—Borehole communications test data, JD4243.

Mine Fire RENTON (JD4249) EXHAUST BOREHOLE = #42 FAN ON AT 952

BH:	TIME:	DEGC TEMP:	INH2O PRES:	PCT H2:	PCT CO2:	PCT O2:	PCT N2:	PCT CO:	PCT CH4:	PPM C2H6:	PPM C2H4:	PPM C3H8:	PPM C3H6:	PPM xC4H10:	PPM xC5H12:	C2C5/CH4:	CO/CO2:	JTR:	PPM AFCO:	SUMMARY CONCLUSION
16	920	15.8	0.000	0.0000	0.05	20.90	78.12	0.0000	0.0003	0	0	0	0	0	0	0.000	0.0000	-0.252	0	◌
16	1104	15.7	-0.010	0.0000	0.05	20.90	78.12	0.0000	0.0004	0	0	0	0	0	0	0.000	0.0000	-0.252	0	
16	1309	15.3	-0.003	0.0000	0.05	20.90	78.12	0.0000	0.0003	0	0	0	0	0	0	0.000	0.0000	-0.252	0	
16	1428	16.7	-0.006	0.0000	0.05	20.90	78.12	0.0000	0.0002	0	0	0	0	0	0	0.000	0.0000	-0.252	0	
18	917	16.9	0.000	0.0000	4.60	15.10	79.30	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	0.778	0	⊙
18	1101	17.1	-0.024	0.0000	4.60	15.00	79.40	0.0000	0.0003	0	0	0	0	0	0	0.000	0.0000	0.761	0	
18	1307	17.4	-0.028	0.0000	4.60	15.10	79.30	0.0000	0.0002	0	0	0	0	0	0	0.000	0.0000	0.778	0	
18	1425	18.1	-0.038	0.0000	4.50	15.50	79.10	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	0.824	0	
19	913	56.6	0.013	0.0000	9.30	8.20	81.50	0.0060	0.0030	1	0	0	0	0	0	0.033	0.0006	0.694	99	△+
19	1055	56.9	-0.024	0.0000	9.70	7.50	81.80	0.0390	0.0055	6	0	3	0	0	0	0.164	0.0040	0.686	607	
19	1303	58.1	-0.025	0.0000	9.10	8.80	81.10	0.0415	0.0040	5	0	3	0	0	0	0.200	0.0046	0.719	716	
19	1420	57.8	-0.052	0.0000	8.60	9.90	80.50	0.0470	0.0035	4	0	3	0	0	0	0.200	0.0055	0.755	891	
20	927	33.0	-0.018	0.0000	6.40	12.20	80.40	0.0000	0.0010	0	0	0	0	0	0	0.000	0.0000	0.703	0	△+
20	1120	33.3	-0.205	0.0000	6.10	13.80	79.00	0.0910	0.0600	62	3	13	1	5	3	0.145	0.0149	0.865	2666	
20	1318	34.1	-0.210	0.0000	4.90	15.50	78.30	0.1600	0.1600	245	21	50	6	16	7	0.216	0.0327	0.956	6149	
20	1439	35.3	-0.217	0.0000	4.80	15.80	78.10	0.1600	0.1600	225	20	60	6	20	11	0.214	0.0333	1.005	6508	
35	926	22.7	0.000	0.0000	2.60	14.80	81.60	0.0000	0.0010	0	0	0	0	0	0	0.000	0.0000	0.381	0	◌
35	1119	22.9	0.000	0.0000	2.50	15.20	81.30	0.0000	0.0008	0	0	0	0	0	0	0.000	0.0000	0.394	0	
35	1317	23.0	-0.005	0.0000	2.40	15.70	80.90	0.0000	0.0007	0	0	0	0	0	0	0.000	0.0000	0.418	0	
35	1437	23.5	0.000	0.0000	2.40	15.90	80.70	0.0000	0.0007	0	0	0	0	0	0	0.000	0.0000	0.438	0	
36	924	77.1	0.015	0.0000	16.60	0.10	82.10	0.0465	0.1400	210	10	50	7	14	12	0.216	0.0028	0.768	467	△+
36	1117	76.2	-0.105	0.0000	7.30	10.40	81.10	0.1500	0.0630	93	7	24	3	10	6	0.227	0.0205	0.668	2979	
36	1315	77.4	-0.100	0.0000	4.70	13.20	80.80	0.2400	0.0580	108	15	27	4	10	5	0.291	0.0511	0.594	6487	
36	1434	76.5	-0.150	0.0000	4.30	13.90	80.50	0.2500	0.0630	120	15	35	3	12	7	0.305	0.0581	0.604	7428	
37	922	72.6	0.022	0.0000	9.30	8.50	80.90	0.2100	0.0825	125	15	36	5	12	9	0.245	0.0226	0.731	3534	▽o
37	1115	70.2	-0.070	0.0000	1.20	20.00	77.90	0.0075	0.0035	3	0	1	0	0	0	0.114	0.0063	1.874	1652	
37	1313	69.2	-0.070	0.0000	0.60	20.60	77.90	0.0020	0.0010	0	0	0	0	0	0	0.000	0.0033	13.828	1193	
37	1431	69.3	-0.065	0.0000	0.55	20.60	77.90	0.0020	0.0010	0	0	0	0	0	0	0.000	0.0036	12.678	1193	
38	929	68.3	0.010	0.0000	14.20	0.10	84.60	0.0525	0.0650	100	3	26	2	9	3	0.220	0.0037	0.638	528	⊕
38	1122	60.2	-0.135	0.0000	0.95	19.90	78.20	0.0220	0.0165	20	1	5	0	2	0	0.170	0.0232	1.174	4385	
38	1321	59.0	-0.129	0.0000	0.85	20.00	78.10	0.0285	0.0310	40	3	11	1	4	0	0.190	0.0335	1.251	6278	
38	1442	58.2	-0.130	0.0000	0.85	20.00	78.10	0.0320	0.0370	50	3	14	1	5	0	0.197	0.0376	1.255	7048	
39	911	62.9	0.015	0.0000	12.50	2.50	84.00	0.0115	0.0015	0	0	0	0	0	0	0.000	0.0009	0.633	131	⊙
39	1053	62.3	-0.132	0.0000	1.50	19.30	78.30	0.0025	0.0008	0	0	0	0	0	0	0.000	0.0017	1.036	317	
39	1301	64.0	-0.129	0.0000	0.90	20.20	78.00	0.0080	0.0006	0	0	0	0	0	0	0.000	0.0089	1.928	2231	
39	1417	63.0	-0.128	0.0000	0.70	20.30	78.10	0.0080	0.0006	0	0	0	0	0	0	0.000	0.0114	1.781	2574	
40	909	61.4	0.013	0.0000	12.00	3.10	83.90	0.0045	0.0025	0	0	0	0	0	0	0.000	0.0004	0.627	53	⊙
40	1051	61.2	-0.133	0.0000	1.40	19.20	78.50	0.0005	0.0005	0	0	0	0	0	0	0.000	0.0004	0.874	60	
40	1257	62.0	-0.125	0.0000	0.35	20.60	78.10	0.0003	0.0003	0	0	0	0	0	0	0.000	0.0009	3.629	179	
40	1415	62.0	-0.137	0.0000	0.25	20.70	78.10	0.0003	0.0003	0	0	0	0	0	0	0.000	0.0012	-71.493	250	
41	906	93.8	0.045	0.0000	14.00	2.10	82.70	0.2200	0.0065	7	2	2	0	0	0	0.169	0.0157	0.715	2445	▽o
41	1047	93.0	-0.034	0.0000	8.20	10.80	80.00	0.0140	0.0090	2	0	1	0	1	0	0.044	0.0017	0.789	289	
41	1241	96.7	-0.030	0.0000	5.50	14.60	78.90	0.0035	0.0065	1	0	0	0	0	0	0.015	0.0006	0.872	115	
41	1412	96.5	-0.016	0.0000	4.50	15.90	78.60	0.0030	0.0020	0	0	0	0	0	0	0.000	0.0007	0.913	124	
42	856	36.0	0.008	0.0000	4.80	14.70	79.50	0.0000	0.0025	1	0	0	0	0	0	0.040	0.0000	0.754	0	⊛
42	1003	36.3	-29.700	0.0000	0.05	20.90	78.12	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	-0.252	0	
42	1034	36.6	-29.200	0.0000	0.05	20.90	78.12	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	-0.252	0	
42	1135	39.1	-30.000	0.0000	0.05	20.90	78.12	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	-0.252	0	
42	1230	39.1	-30.000	0.0000	0.05	20.90	78.12	0.0025	0.0000	0	0	0	0	0	0	ERR	0.0500	-0.262	10233	
42	1332	40.4	-29.800	0.0000	0.05	20.90	78.12	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	-0.252	0	
42	1449	40.5	-29.500	0.0000	0.05	20.90	78.12	0.0020	0.0000	0	0	0	0	0	0	ERR	0.0400	-0.260	8187	
42	1457	40.2	99.999	0.0000	3.90	16.60	78.40	0.1000	0.0500	50	4	10	0	3	0	0.134	0.0256	0.952	4815	
43	902	60.2	0.000	0.0000	14.30	1.40	83.30	0.0010	0.0020	1	0	0	0	0	0	0.050	0.0001	0.692	11	△+
43	1041	56.9	-0.218	0.0000	5.00	15.20	78.80	0.0470	0.0045	5	0	2	0	0	0	0.156	0.0094	0.886	1712	
43	1233	60.0	-0.235	0.0000	5.70	14.10	79.10	0.1100	0.0065	10	0	2	0	0	0	0.185	0.0193	0.843	3364	
43	1406	60.6	-0.219	0.0000	4.30	16.30	78.40	0.0945	0.0075	7	0	1	0	0	0	0.107	0.0220	0.977	4257	
44	904	37.0	-0.004	0.0000	3.70	16.40	79.00	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	0.816	0	⊙
44	1045	35.9	-0.045	0.0000	2.80	18.10	78.20	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	1.067	0	
44	1237	37.6	-0.050	0.0000	2.30	19.30	77.50	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	1.859	0	
44	1409	37.4	-0.042	0.0000	2.00	19.70	77.40	0.0015	0.0000	0	0	0	0	0	0	ERR	0.0008	2.467	251	
58	908	61.3	0.029	0.0000	10.50	6.70	81.80	0.0030	0.0030	1	0	0	0	0	0	0.033	0.0003	0.701	44	▽o
58	1049	62.0	-0.042	0.0000	5.80	13.30	79.90	0.0000	0.0010	0	0	0	0	0	0	0.000	0.0000	0.737	0	
58	1255	62.3	-0.020	0.0000	4.40	15.70	79.00	0.0000	0.0005	0	0	0	0	0	0	0.000	0.0000	0.840	0	
58	1413	62.4	-0.035	0.0000	4.10	16.40	78.60	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	0.926	0	
59	914	58.1	0.033	0.0000	12.10	4.50	82.40	0.0345	0.0050	5	0	1	0	0	0	0.120	0.0029	0.699	439	▽o
59	1058	58.6	-0.004	0.0000	11.30	5.50	82.20	0.0090	0.0040	2	0	0	0	0	0	0.050	0.0008	0.694	122	
59	1305	59.4	-0.016	0.0000	9.20	9.90	79.90	0.0015	0.0015	0	0	0	0	0	0	0.000	0.0002	0.816	28	
59	1422	59.6	-0.010	0.0000	8.30	11.60	79.20	0.0000	0.0010	0	0	0	0	0	0	0.000	0.0000	0.884	0	

Figure B-2.—Borehole communications test data, JD4249.

Mine Fire RENTON (JD4251) EXHAUST BOREHOLE = #38 FAN ON AT 1001

BH:	TIME:	DEGC TEMP:	INH2O PRES:	PCT H2:	PCT CO2:	PCT O2:	PCT N2:	PCT CO:	PCT CH4:	PPM C2H6:	PPM C2H4:	PPM C3H8:	PPM C3H6:	PPM xC4H10:	PPM xC5H12:	C2C5/CH4:	CO/CO2:	JTR:	PPM AFCD:	SUMMARY CONCLUSION
16	952	16.2	0.000	0.0000	0.05	20.90	78.12	0.0000	0.0003	0	0	0	0	0	0	0.000	0.0000	-0.252	0	(⊙)
16	1137	16.3	-0.011	0.0000	0.05	20.90	78.12	0.0000	0.0003	0	0	0	0	0	0	0.000	0.0000	-0.252	0	
16	1306	17.1	-0.013	0.0000	0.05	20.90	78.12	0.0000	0.0003	0	0	0	0	0	0	0.000	0.0000	-0.252	0	
16	1443	16.0	-0.013	0.0000	0.05	20.90	78.12	0.0000	0.0003	0	0	0	0	0	0	0.000	0.0000	-0.252	0	
18	954	17.3	-0.003	0.0000	4.40	15.70	79.00	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	0.840	0	◎
18	1135	17.9	-0.059	0.0000	4.40	15.50	79.20	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	0.802	0	
18	1304	18.3	-0.056	0.0000	4.30	15.70	79.10	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	0.817	0	
18	1448	18.0	-0.055	0.0000	4.10	16.00	79.00	0.0020	0.0010	0	0	0	0	0	0	0.000	0.0005	0.831	85	
19	947	56.2	0.026	0.0000	8.70	9.20	81.10	0.9700	0.0045	1	0	1	0	0	0	0.044	0.1115	0.767	17294	△+
19	1129	57.3	-0.115	0.0000	10.50	6.80	81.60	0.0875	0.0155	30	0	6	1	3	0	0.258	0.0083	0.713	1295	
19	1259	58.2	-0.160	0.0000	11.00	6.50	81.40	0.1100	0.0155	35	0	8	1	3	0	0.303	0.0100	0.735	1595	
19	1438	58.0	-0.104	0.0000	10.40	7.60	80.90	0.1200	0.0130	25	0	7	1	3	0	0.277	0.0115	0.758	1883	
20	921	33.3	-0.043	0.0000	5.50	12.90	80.60	0.0000	0.0015	0	0	0	0	0	0	0.000	0.0000	0.650	0	△+
20	1108	33.6	-0.860	0.0000	2.60	18.60	77.70	0.0650	0.0730	22	2	2	0	0	0	0.036	0.0250	1.331	5792	
20	1235	33.0	-0.880	0.0000	1.70	19.70	77.50	0.0590	0.0950	32	6	2	0	0	0	0.042	0.0347	2.083	9880	
20	1407	32.9	-0.885	0.0000	1.30	19.90	77.70	0.0470	0.0950	32	6	3	0	0	0	0.043	0.0362	1.934	9368	
35	923	22.7	0.000	0.0000	2.40	16.80	79.80	0.0000	0.0005	0	0	0	0	0	0	0.000	0.0000	0.552	0	(⊙)
35	1106	23.9	-0.002	0.0000	2.20	17.20	79.60	0.0000	0.0005	0	0	0	0	0	0	0.000	0.0000	0.565	0	
35	1237	23.4	0.000	0.0000	2.10	17.60	79.30	0.0000	0.0005	0	0	0	0	0	0	0.000	0.0000	0.615	0	
35	1410	23.7	0.000	0.0000	1.90	18.00	79.20	0.0000	0.0005	0	0	0	0	0	0	0.000	0.0000	0.636	0	
36	925	77.0	0.015	0.0000	16.60	0.10	81.90	0.0910	0.2200	385	17	95	11	27	18	0.251	0.0055	0.772	914	▽+
36	1110	78.1	-0.760	0.0000	2.40	18.40	78.20	0.0145	0.0165	15	0	5	1	0	1	0.133	0.0060	1.038	1191	
36	1239	80.4	-0.760	0.0000	1.50	19.50	78.00	0.0110	0.0055	6	0	2	1	1	0	0.182	0.0073	1.289	1588	
36	1412	75.5	-0.760	0.0000	1.20	19.80	78.00	0.0110	0.0040	3	0	1	0	0	0	0.100	0.0092	1.389	2002	
37	927	73.6	0.018	0.0000	8.90	8.70	81.20	0.1600	0.0680	90	7	25	4	9	4	0.204	0.0180	0.704	2736	▽o
37	1112	67.9	-0.480	0.0000	0.65	20.55	77.90	0.0035	0.0015	0	0	0	0	0	0	0.000	0.0054	6.980	1828	
37	1241	65.1	-0.480	0.0000	0.30	20.70	78.10	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	-85.714	0	
37	1415	63.7	-0.485	0.0000	0.10	20.85	78.12	0.0000	0.0010	0	0	0	0	0	0	0.000	0.0000	-0.675	0	
38	843	67.6	0.018	0.0000	13.30	0.10	85.40	0.0510	0.0800	140	4	40	2	13	5	0.255	0.0038	0.592	512	⊛
38	1030	64.4	-23.500	0.0000	7.50	11.10	80.30	0.1200	0.0415	50	5	11	0	4	0	0.169	0.0160	0.746	2552	
38	1102	63.6	-23.800	0.1000	5.90	13.80	79.00	0.1800	0.0880	100	10	20	0	6	0	0.155	0.0305	0.849	5274	
38	1141	63.7	-23.500	0.1000	5.20	14.60	78.70	0.2300	0.2400	170	19	45	10	13	5	0.109	0.0442	0.863	7587	
38	1231	63.2	-23.500	0.1000	5.20	14.60	78.70	0.2300	0.2400	220	25	60	15	17	7	0.143	0.0442	0.863	7587	
38	1313	62.6	-23.700	0.1500	4.70	15.20	78.40	0.2600	0.3200	250	35	70	17	21	10	0.126	0.0553	0.885	9472	
38	1352	64.1	-23.900	0.1800	4.60	15.30	78.30	0.2600	0.3300	300	38	75	18	24	11	0.141	0.0565	0.888	9639	
38	1503	61.9	-23.800	0.2000	4.50	15.60	78.10	0.2600	0.3500	340	42	80	18	25	11	0.147	0.0578	0.931	10180	
39	930	61.5	0.032	0.0000	11.20	3.00	84.80	0.0140	0.0040	2	0	0	0	0	0	0.050	0.0013	0.576	163	◎
39	1114	61.8	-0.260	0.0000	1.00	19.70	78.40	0.0005	0.0010	0	0	0	0	0	0	0.000	0.0005	0.930	84	
39	1243	62.1	-0.278	0.0000	0.70	20.10	78.30	0.0005	0.0010	0	0	0	0	0	0	0.000	0.0007	1.078	123	
39	1417	60.6	-0.270	0.0000	0.60	20.30	78.20	0.0005	0.0010	0	0	0	0	0	0	0.000	0.0008	1.419	161	
40	933	61.5	0.022	0.0000	10.90	4.60	83.50	0.0065	0.0070	2	0	1	0	0	0	0.043	0.0006	0.622	83	◎
40	1116	62.8	-0.138	0.0000	1.40	19.20	78.50	0.0015	0.0090	0	0	0	0	0	0	0.000	0.0011	0.874	179	
40	1245	62.4	-0.139	0.0000	0.50	20.40	78.20	0.0000	0.0005	0	0	0	0	0	0	0.000	0.0000	1.548	0	
40	1419	61.1	-0.136	0.0000	0.30	20.70	78.10	0.0000	0.0005	0	0	0	0	0	0	0.000	0.0000	-85.714	0	
41	937	92.5	0.054	0.0000	14.40	2.30	82.00	0.3200	0.0300	14	1	3	0	0	0	0.060	0.0222	0.753	3595	(+)
41	1120	94.4	-0.019	0.0000	6.20	13.20	79.60	0.0275	0.0240	11	0	3	0	0	0	0.058	0.0044	0.788	743	
41	1250	97.9	-0.020	0.0000	4.90	15.00	79.10	0.0245	0.0190	8	0	2	0	0	0	0.053	0.0050	0.825	863	
41	1425	95.6	-0.020	0.0000	5.90	13.50	79.50	0.0765	0.0220	10	0	2	0	0	0	0.055	0.0130	0.787	2151	
42	944	38.2	-0.005	0.0000	9.90	8.00	81.10	0.0045	0.0210	15	3	3	0	0	0	0.100	0.0005	0.734	73	▽o
42	1127	37.7	-0.255	0.0000	0.75	20.50	77.80	0.0015	0.0010	0	0	0	0	0	0	0.000	0.0020	6.420	697	
42	1257	37.8	-0.255	0.0000	0.40	20.65	78.00	0.0030	0.0010	0	0	0	0	0	0	0.000	0.0075	20.112	2087	
42	1432	37.8	-0.250	0.0000	0.35	20.70	78.00	0.0050	0.0010	0	0	0	0	0	0	0.000	0.0143	-11.792	4170	
43	941	61.3	0.013	0.0000	13.50	2.70	82.80	0.0040	0.0220	3	0	1	0	0	0	0.018	0.0003	0.702	46	△+
43	1124	61.0	-0.144	0.0000	5.50	14.70	78.70	0.1200	0.0250	25	1	6	0	3	0	0.140	0.0218	0.908	4022	
43	1254	63.1	-0.147	0.0000	8.70	10.70	79.20	0.4300	0.0540	50	2	11	0	3	0	0.122	0.0494	0.877	8788	
43	1427	61.9	-0.149	0.0000	6.70	13.60	78.40	0.3300	0.0520	45	2	8	0	3	0	0.112	0.0493	0.968	9405	
44	939	37.3	0.000	0.0000	3.20	16.70	79.20	0.0005	0.0000	0	0	0	0	0	0	ERR	0.0002	0.746	25	◎
44	1122	37.1	-0.041	0.0000	2.60	18.20	78.30	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	1.020	0	
44	1252	38.5	-0.045	0.0000	2.20	19.20	77.70	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	1.582	0	
44	1430	37.5	-0.042	0.0000	1.80	19.80	77.50	0.0000	0.0000	0	0	0	0	0	0	ERR	0.0000	2.441	0	
58	936	60.7	0.037	0.0000	10.00	7.70	83.30	0.0055	0.0080	5	0	1	0	0	0	0.075	0.0006	0.696	87	▽o
58	1118	62.9	-0.056	0.0000	5.70	13.60	79.70	0.0003	0.0055	1	0	0	0	0	0	0.018	0.0001	0.758	9	
58	1248	62.4	-0.060	0.0000	4.40	15.80	78.90	0.0000	0.0040	1	0	0	0	0	0	0.025	0.0000	0.861	0	
58	1422	61.2	-0.059	0.0000	3.70	17.10	78.30	0.0000	0.0025	0	0	0	0	0	0	0.000	0.0000	1.014	0	
59	949	58.0	0.035	0.0000	11.20	6.40	81.40	0.0500	0.0180	8	3	3	0	0	0	0.078	0.0045	0.741	720	▽o
59	1132	59.7	-0.024	0.0000	10.70	6.60	81.70	0.0170	0.0195	8	2	2	0	2	0	0.072	0.0016	0.712	248	
59	1301	59.7	-0.022	0.0000	9.70	8.10	81.20	0.0135	0.0140	4	2	1	0	0	0	0.050	0.0014	0.724	220	
59	1441	60.1	-0.026	0.0000	9.00	10.00	80.00	0.0090	0.0105	2	0	0	0	0	0	0.019	0.0010	0.804	172	

Figure B-3.—Borehole communications test data, JD4251.

Mine Fire RENTON (JD4256)   EXHAUST BOREHOLE = #58   FAN ON AT 1033

BH:	TIME:	DEGC TEMP:	INH2O PRES:	PCT H2:	PCT CO2:	PCT O2:	PCT N2:	PCT CO:	PCT CH4:	PPM C2H6:	PPM C2H4:	PPM C3H8:	PPM C3H6:	PPM xC4H10:	PPM xC5H12:	C2C5/CH4:	CO/CO2:	JTR:	PPM AFCO:	SUMMARY CONCLUSION
16	1015	17.2	0.000	0.0000	0.05	20.90	78.12	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	-0.252	0	◌
16	1142	16.3	-0.015	0.0000	0.05	20.90	78.12	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	-0.252	0	
16	1351	17.1	-0.010	0.0000	0.05	20.90	78.12	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	-0.252	0	
16	1507	18.3	-0.015	0.0000	0.05	20.90	78.12	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	-0.252	0	
18	1018	18.1	-0.003	0.0000	4.50	14.70	79.80	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	0.698	0	◎
18	1151	18.0	-0.063	0.0000	4.30	15.40	79.30	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	0.766	0	
18	1353	18.5	-0.058	0.0000	3.30	17.40	78.40	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	0.977	0	
18	1509	19.0	-0.057	0.0000	3.00	17.80	78.30	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	1.017	0	
19	1011	57.4	0.025	0.0000	8.60	9.30	81.10	0.0065	0.0035	2	0	1	0	0	0	0.086	0.001	0.706	117	▽
19	1134	58.4	-0.143	0.0000	7.00	12.20	79.80	0.0035	0.0090	3	0	1	0	0	0	0.044	0.001	0.783	84	
19	1347	59.0	-0.140	0.0000	4.40	16.60	78.00	0.0100	0.0095	4	0	1	0	0	0	0.053	0.002	1.083	482	
19	1503	58.9	-0.128	0.0000	4.40	16.40	78.20	0.0110	0.0100	4	0	1	0	0	0	0.050	0.003	1.020	506	
20	1007	33.8	-1.320	0.0000	5.60	12.00	81.40	0.0000	0.0040	1	0	0	0	0	0	0.025	0.000	0.585	0	△
20	1125	33.8	-0.940	0.0000	4.50	14.60	79.90	0.0000	0.0045	3	0	0	0	0	0	0.067	0.000	0.685	0	
20	1340	34.1	-0.115	0.0000	4.10	16.20	78.70	0.0300	0.0400	20	0	3	0	0	0	0.058	0.007	0.886	1323	
20	1458	34.6	-0.111	0.0000	4.20	16.30	78.40	0.0500	0.0600	41	5	6	1	1	1	0.092	0.012	0.947	2252	
35	841	23.4	0.000	0.0000	2.10	18.40	78.60	0.0000	0.0005	0	0	0	0	0	0	0.000	0.000	0.865	0	◌
35	1127	25.0	-0.002	0.0000	1.60	19.00	78.50	0.0000	0.0005	0	0	0	0	0	0	0.000	0.000	0.888	0	
35	1338	25.3	0.000	0.0000	1.50	18.80	78.80	0.0000	0.0005	0	0	0	0	0	0	0.000	0.000	0.720	0	
35	1459	25.3	-0.002	0.0000	1.60	19.20	78.30	0.0015	0.0010	0	0	0	0	0	0	0.000	0.001	1.033	179	
36	915	79.1	0.033	0.0000	0.05	20.90	78.12	0.0000	0.0005	0	0	0	0	0	0	0.000	0.000	-0.252	0	△
36	1130	80.1	-0.060	0.0000	11.60	5.30	81.70	0.1600	0.2100	325	11	75	6	15	14	0.212	0.014	0.717	2142	
36	1335	80.2	-0.060	0.0000	7.50	10.40	80.60	0.2800	0.2100	290	10	52	3	13	14	0.182	0.037	0.704	5560	
36	1500	80.6	-0.058	0.0000	6.80	11.30	80.30	0.3100	0.2500	315	19	65	4	12	14	0.172	0.046	0.705	6730	
37	1009	76.1	0.039	0.0000	8.10	9.80	81.00	0.1100	0.0520	36	2	10	2	3	0	0.102	0.014	0.701	2067	⊕
37	1132	75.5	-0.041	0.0000	2.30	18.60	78.10	0.0220	0.0125	15	0	2	0	0	0	0.136	0.010	1.105	1960	
37	1333	74.3	-0.043	0.0000	1.00	20.10	78.00	0.0170	0.0115	13	0	2	0	0	0	0.130	0.017	1.777	4184	
37	1507	74.2	-0.037	0.0000	0.80	20.20	78.00	0.0170	0.0115	10	0	2	0	0	0	0.104	0.021	1.729	4741	
37	1540	73.9	-0.032	0.0000	0.80	20.20	78.00	0.0175	0.0115	11	0	2	0	0	0	0.113	0.022	1.730	4881	
38	927	69.2	0.018	0.0000	13.60	0.20	85.00	0.0725	0.0925	160	9	41	4	11	6	0.250	0.005	0.612	732	⊕
38	1123	65.6	-0.071	0.0000	2.60	17.80	78.60	0.0170	0.0250	32	0	7	0	0	0	0.156	0.007	0.863	1130	
38	1331	63.3	-0.075	0.0000	3.00	16.90	79.00	0.0790	0.0830	115	8	27	2	6	2	0.193	0.026	0.758	4086	
38	1456	63.2	-0.066	0.0000	3.20	16.50	79.10	0.1000	0.1100	165	10	40	3	10	4	0.211	0.031	0.734	4707	
39	1004	62.0	0.030	0.0000	12.10	2.60	84.30	0.0150	0.0025	3	0	0	0	0	0	0.120	0.001	0.614	171	▽
39	1121	63.7	-0.105	0.0000	1.20	19.50	78.40	0.0010	0.0000	0	0	0	0	0	0	ERR	0.001	0.941	144	
39	1329	62.4	-0.106	0.0000	0.30	20.70	78.10	0.0005	0.0005	0	0	0	0	0	0	0.000	0.002	-85.821	417	
39	1453	62.5	-0.104	0.0000	0.20	20.75	78.12	0.0005	0.0005	0	0	0	0	0	0	0.000	0.003	-4.157	521	
40	953	60.6	0.023	0.0000	11.00	4.90	83.10	0.0035	0.0025	0	0	0	0	0	0	0.000	.000	0.643	46	△
40	1108	61.9	-0.255	0.0000	1.50	19.00	78.60	0.0010	0.0010	0	0	0	0	0	0	0.000	0.001	0.821	107	
40	1320	60.1	-0.255	0.0000	0.50	20.30	78.30	0.0000	0.0035	2	0	0	0	0	0	0.057	0.000	1.112	0	
40	1444	57.7	-0.252	0.0000	0.60	20.40	78.00	0.0145	0.0140	4	0	1	0	0	0	0.036	0.024	2.262	5512	
40	1533	60.1	-0.228	0.0000	0.40	20.50	78.10	0.0110	0.0065	3	0	1	0	0	0	0.062	0.028	2.078	5108	
41	956	93.4	0.052	0.0000	13.90	1.70	83.40	0.2500	0.0180	16	1	6	0	0	0	0.128	0.018	0.691	2721	▽
41	1110	94.5	-0.243	0.0000	4.80	17.00	77.30	0.0100	0.0030	2	0	0	0	0	0	0.067	0.002	1.380	530	
41	1316	88.4	-0.239	0.0000	1.30	20.00	77.80	0.0005	0.0005	0	0	0	0	0	0	0.000	.000	2.108	110	
41	1446	88.7	-0.230	0.0000	0.80	20.40	77.90	0.0005	0.0005	0	0	0	0	0	0	0.000	0.001	3.287	190	
41	1543	89.0	-0.219	0.0000	0.70	20.40	78.00	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	2.593	0	
42	1002	39.5	-0.002	0.0000	10.70	6.40	81.90	0.0020	0.0100	7	0	0	0	0	0	0.070	.000	0.699	29	▽
42	1118	39.3	-0.155	0.0000	1.30	19.50	78.30	0.0005	0.0005	0	0	0	0	0	0	0.000	.000	1.041	72	
42	1326	39.4	-0.155	0.0000	0.45	20.50	78.12	0.0010	0.0010	0	0	0	0	0	0	0.000	0.002	2.234	464	
42	1452	40.9	-0.151	0.0000	0.40	20.60	78.07	0.0010	0.0005	0	0	0	0	0	0	0.000	0.003	4.526	597	
42	1538	39.1	-0.131	0.0000	0.25	20.75	78.07	0.0005	0.0005	0	0	0	0	0	0	0.000	0.002	-4.074	521	
43	1000	61.5	0.014	0.0000	13.10	3.10	82.80	0.0000	0.0080	2	0	0	0	0	0	0.025	0.000	0.695	0	◎
43	1115	59.4	-0.250	0.0000	1.60	19.70	77.80	0.0010	0.0007	0	0	0	0	0	0	0.000	0.001	1.746	167	
43	1324	58.0	-0.260	0.0000	0.65	20.40	78.00	0.0035	0.0007	0	0	0	0	0	0	0.000	0.005	2.417	1330	
43	1450	58.4	-0.234	0.0000	0.50	20.55	78.00	0.0040	0.0010	0	0	0	0	0	0	0.000	0.008	4.192	2089	
43	1536	56.4	-0.223	0.0000	0.80	20.20	78.10	0.0115	0.0025	1	0	0	0	0	0	0.040	0.014	1.629	3207	
44	958	38.2	0.001	0.0000	3.40	16.60	79.10	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	0.780	0	◎
44	1113	38.4	-0.149	0.0000	2.50	18.60	78.00	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	1.208	0	
44	1322	39.1	-0.151	0.0000	1.20	20.10	77.80	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	2.321	0	
44	1448	38.6	-0.145	0.0000	0.90	20.40	77.80	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	4.147	0	
44	1535	37.9	-0.143	0.0000	0.80	20.50	77.80	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	6.838	0	
58	932	61.4	0.042	0.0000	9.70	8.30	81.00	0.0040	0.0050	3	0	0	0	0	0	0.060	.000	0.737	66	⊛
58	1100	59.9	-24.500	0.0000	9.90	8.40	80.60	0.0735	0.0125	11	0	3	0	2	0	0.128	0.007	0.768	1227	
58	1217	60.1	-24.600	0.0000	7.10	13.30	78.40	0.1700	0.0335	30	0	5	0	2	0	0.110	0.024	0.967	4655	
58	1300	60.2	-24.600	0.0000	6.40	14.40	78.00	0.1700	0.0460	30	4	7	1	3	0	0.098	0.027	1.041	5437	
58	1402	60.2	-24.400	0.1000	2.90	18.10	77.90	0.0765	0.0280	28	0	4	1	2	0	0.125	0.026	1.173	5621	
58	1439	60.1	-24.400	0.1000	5.60	15.10	78.00	0.1900	0.0720	43	4	10	1	4	0	0.086	0.034	1.035	6803	
58	1515	59.4	-24.500	0.1500	5.40	15.30	77.90	0.1900	0.0795	51	4	11	1	4	0	0.089	0.035	1.044	7044	
58	1542	59.1	-24.600	0.1500	5.30	15.40	77.90	0.1900	0.0835	53	4	12	1	4	0	0.089	0.036	1.045	7171	
59	1013	59.1	0.027	0.0000	11.50	5.70	81.80	0.0360	0.0230	21	0	5	0	2	0	0.122	0.003	0.721	495	▽
59	1137	59.3	-0.265	0.0000	1.90	18.80	78.40	0.0020	0.0015	0	0	0	0	0	0	0.000	0.001	0.962	195	
59	1349	59.2	-0.250	0.0000	1.40	19.60	78.10	0.0005	0.0005	0	0	0	0	0	0	0.000	.000	1.277	78	
59	1505	59.1	-0.245	0.0000	1.20	19.90	78.00	0.0000	0.0005	0	0	0	0	0	0	0.000	0.000	1.558	0	

Figure B-4.—Borehole communications test data, JD4256.

Mine Fire RENTON (JD5058) EXHAUST BOREHOLE = #39 FAN ON AT 1040

BH:	TIME:	DEGC TEMP:	INH2O PRES:	PCT H2:	PCT CO2:	PCT O2:	PCT N2:	PCT CO:	PCT CH4:	PPM C2H6:	PPM C2H4:	PPM C3H8:	PPM C3H6:	PPM xC4H10:	PPM xC5H12:	C2C5/CH4:	CO/CO2:	JTR:	PPM AFCO:	SUMMARY CONCLUSION
18	1006	18.0	0.003		2.70	17.70	78.70	0.0015	0.0010	0	0	0	0	0	0	0.000	0.001	0.856	97	◎
18	1247	16.6	-0.052		2.90	17.30	78.90	0.0010	0.0000	0	0	0	0	0	0	ERR	.000	0.804	57	
18	1426	16.9	-0.057		2.70	17.50	78.90	0.0012	0.0000	0	0	0	0	0	0	ERR	.000	0.792	73	
19	1002	56.2	0.025		8.70	10.30	80.00	0.0050	0.0020	0	0	0	0	0	0	0.000	0.001	0.799	98	◎
19	1243	54.3	-0.023		11.20	7.70	80.10	0.0550	0.0035	5	0	2	0	0	0	0.200	0.005	0.831	870	
19	1422	54.5	-0.229		10.10	9.90	79.00	0.0600	0.0025	0	0	0	0	0	0	0.000	0.006	0.919	1137	
20	1014	15.0	-0.019		1.20	19.10	78.80	0.0000	0.0005	0	0	0	0	0	0	0.000	0.000	0.673	0	◎
20	1254	13.7	-0.420		0.35	20.55	78.20	0.0000	0.0005	0	0	0	0	0	0	0.000	0.000	2.023	0	
20	1432	14.5	-0.450		0.45	20.50	78.10	0.0000	0.0005	0	0	0	0	0	0	0.000	0.000	2.290	0	
35	1012	14.4	0.010		0.10	17.30	81.60	0.0015	0.0005	0	0	0	0	0	0	0.000	0.015	0.023	86	(◎)
35	1252	13.7	0.075		0.10	17.60	81.30	0.0020	0.0000	0	0	0	0	0	0	ERR	0.020	0.026	125	
35	1430	14.5	-0.020		0.10	17.60	81.30	0.0015	0.0005	0	0	0	0	0	0	0.000	0.015	0.026	94	
36	1010	60.2	0.003		14.50	0.50	83.90	0.0110	0.0735	20	0	3	0	3	0	0.035	0.001	0.668	113	◎
36	1251	58.0	-0.360		0.70	20.20	78.20	0.0025	0.0050	2	0	0	0	0	0	0.040	0.004	1.342	697	
36	1429	58.2	-0.360		0.60	20.30	78.20	0.0020	0.0030	0	0	0	0	0	0	0.000	0.003	1.422	643	
37	1009	76.6	0.034		10.80	4.60	83.60	0.1250	0.0075	10	0	4	0	3	0	0.227	0.012	0.621	1602	▽
37	1249	70.9	-0.320		0.70	20.40	78.00	0.0030	0.0010	0	0	0	0	0	0	0.000	0.004	2.601	1140	
37	1428	70.1	-0.320		0.50	20.60	78.00	0.0020	0.0005	0	0	0	0	0	0	0.000	0.004	7.164	1193	
38	1017	42.5	0.000		9.00	7.40	82.00	0.0045	0.0165	9	0	2	0	1	0	0.073	0.001	0.628	70	▽
38	1256	31.0	-0.420		0.20	20.60	78.30	0.0025	0.0010	0	0	0	0	0	0	0.000	0.013	1.350	1491	
38	1433	29.9	-0.429		0.20	20.60	78.30	0.0045	0.0015	0	0	0	0	0	0	0.000	0.022	1.360	2685	
39	959	55.0	0.012		10.90	6.30	81.50	0.0015	0.0015	0	0	0	0	0	0	0.000	.000	0.713	21	⊛
39	1058	47.7	-28.700		8.00	6.30	81.50	0.0085	0.0040	3	0	0	0	0	0	0.075	0.001	0.523	122	
39	1151	47.2	-28.300		6.60	12.70	79.70	0.0510	0.0375	45	0	8	0	0	0	0.141	0.008	0.788	1295	
39	1239	47.5	-28.300		5.50	14.30	79.10	0.1200	0.0575	64	0	13	0	0	0	0.134	0.022	0.839	3780	
39	1420	47.5	-28.900		4.70	15.50	78.60	0.1300	0.1300	98	0	17	0	0	0	0.088	0.028	0.900	4996	
39	1458	47.9	-28.600		1.80	19.40	77.90	0.0050	0.0075	102	0	19	0	0	0	1.613	0.003	1.451	675	
40	1026	54.6	0.003		12.70	4.20	82.10	0.0025	0.0025	1	0	0	0	0	0	0.040	.000	0.723	31	△+
40	1308	50.1	-0.330		0.70	20.30	78.10	0.0010	0.0015	0	0	0	0	0	0	0.000	0.001	1.767	322	
40	1441	49.2	-0.320		1.80	19.40	77.90	0.0050	0.0075	10	0	2	0	0	0	0.160	0.003	1.451	675	
41	1024	69.6	0.040		13.80	2.40	82.70	0.1100	0.0115	13	0	3	0	0	0	0.139	0.008	0.711	1242	▽
41	1302	75.1	-0.090		3.50	18.10	77.50	0.0025	0.0085	4	0	0	0	0	0	0.047	0.001	1.437	184	
42	1019	61.9	0.025		16.20	1.00	81.70	0.0165	0.0450	88	0	16	0	7	0	0.247	0.001	0.785	173	▽
42	1257	62.3	-0.320		0.30	20.60	78.20	0.0015	0.0005	0	0	0	0	0	0	0.000	0.005	2.448	895	
42	1434	62.0	-0.320		2.20	19.30	77.60	0.0015	0.0075	4	0	0	0	0	0	0.053	0.001	1.741	190	
43	1020	47.6	-0.005		12.20	5.10	81.70	0.0230	0.0020	0	0	0	0	0	0	0.000	0.002	0.738	304	△+
43	1258	46.6	-0.280		3.00	17.40	78.40	0.1400	0.0650	85	4	17	2	5	0	0.174	0.047	0.920	8260	
43	1435	48.6	-0.260		3.00	17.50	78.30	0.2000	0.0870	120	6	23	3	7	2	0.185	0.067	0.969	12141	
44	1022	50.5	-0.002		3.70	16.20	79.20	0.0015	0.0010	0	0	0	0	0	0	0.000	.000	0.773	66	◎
44	1300	47.1	-0.089		2.40	19.10	77.60	0.0000	0.0025	2	0	0	0	0	0	0.080	0.000	1.639	0	
44	1437	46.6	-0.090		1.80	19.70	77.60	0.0000	0.0025	1	0	0	0	0	0	0.040	0.000	2.083	0	
58	1025	58.1	0.024		11.30	6.40	81.30	0.0000	0.0020	0	0	0	0	0	0	0.000	0.000	0.746	0	△+
58	1307	55.6	-0.150		5.80	15.20	78.10	0.0000	0.0060	4	0	1	0	0	0	0.083	0.000	1.055	0	
58	1439	55.2	-0.145		4.50	17.20	77.40	0.0000	0.0045	3	0	0	0	0	0	0.067	0.000	1.359	0	
59	1003	56.2	0.025		13.30	4.20	81.50	0.0035	0.0040	3	0	0	0	0	0	0.075	.000	0.765	44	△+
59	1245	54.4	-0.087		6.20	12.80	80.00	0.0030	0.0325	32	0	7	0	2	0	0.126	.000	0.738	77	
59	1424	54.6	-0.082		2.80	17.20	79.00	0.0020	0.0130	14	0	3	0	0	0	0.131	0.001	0.750	112	

Figure B-5.—Borehole communications test data, JD5058.

Mine Fire RENTON (JD5059) EXHAUST BOREHOLE = #44 FAN ON AT 1100

BH:	TIME:	DEGC TEMP:	INH2O PRES:	PCT H2:	PCT CO2:	PCT O2:	PCT N2:	PCT CO:	PCT CH4:	PPM C2H6:	PPM C2H4:	PPM C3H8:	PPM C3H6:	PPM xC4H10:	PPM xC5H12:	C2C5/CH4:	CO/CO2:	JTR:	PPM AFCO:	SUMMARY CONCLUSION
18	904	17.0	0.014		2.60	17.40	79.10	0.0015	0.0005	0	0	0	0	0	0	0.000	0.001	0.730	88	⊙
18	1243	17.1	-0.032		2.40	17.90	78.80	0.0010	0.0005	0	0	0	0	0	0	0.000	.000	0.805	69	
18	1425	17.1	-0.031		2.00	18.70	78.40	0.0020	0.0005	0	0	0	0	0	0	0.000	0.001	0.964	186	
19	857	55.1	0.032		6.90	13.50	78.60	0.0050	0.0020	0	0	0	0	0	0	0.000	0.001	0.942	141	⊙
19	1239	55.2	-0.065		6.60	12.50	79.90	0.0030	0.0070	2	0	0	0	0	0	0.029	.000	0.761	74	
19	1421	55.2	-0.056		6.90	12.30	79.80	0.0040	0.0070	2	0	0	0	0	0	0.029	0.001	0.780	97	
20	918	15.1	-0.034		1.80	18.80	78.40	0.0120	0.0340	1	0	0	0	0	0	0.003	0.007	0.915	1169	⊙
20	1249	15.1	-0.107		2.10	18.50	78.40	0.0030	0.0080	0	0	0	0	0	0	0.000	0.001	0.924	256	
20	1430	15.3	-0.106		1.90	18.80	78.40	0.0030	0.0040	0	0	0	0	0	0	0.000	0.002	0.963	292	
35	914	13.9	0.030		0.10	17.90	81.00	0.0015	0.0005	0	0	0	0	0	0	0.000	0.015	0.028	103	(⊙)
35	1248	15.0	0.015		0.10	17.90	81.00	0.0020	0.0005	0	0	0	0	0	0	0.000	0.020	0.028	137	
35	1429	14.6	-0.005		0.10	18.10	80.80	0.0015	0.0005	0	0	0	0	0	0	0.000	0.015	0.031	110	
36	911	59.8	-0.004		10.60	5.20	83.00	0.0275	0.1900	150	0	14	0	9	0	0.091	0.003	0.632	366	▽+
36	1247	61.0	-0.063		2.20	17.90	78.90	0.0085	0.0300	20	0	2	0	0	0	0.073	0.004	0.733	584	
36	1428	60.1	-0.055		1.00	19.40	78.60	0.0080	0.0130	8	0	1	0	0	0	0.069	0.008	0.704	1081	
37	908	72.1	0.023		8.10	9.10	81.80	0.0240	0.0320	26	0	6	0	1	0	0.103	0.003	0.645	424	▽○
37	1246	77.4	-0.032		1.00	19.60	78.40	0.0085	0.0050	4	0	1	0	0	0	0.100	0.009	0.856	1318	
37	1427	77.0	-0.040		0.50	20.20	78.40	0.0080	0.0040	2	0	0	0	0	0	0.050	0.016	0.878	2231	
38	922	39.5	-0.015		6.50	11.50	81.00	0.0075	0.0475	49	0	9	0	0	0	0.122	0.001	0.653	166	⊕
38	1250	37.0	-0.055		1.90	18.10	79.00	0.0045	0.0240	20	0	3	0	0	0	0.096	0.002	0.671	331	
38	1432	36.3	-0.063		1.80	18.20	79.00	0.0070	0.0370	39	0	5	0	0	0	0.119	0.004	0.660	533	
39	854	52.8	0.012		7.60	9.80	81.60	0.0025	0.0340	5	0	0	0	0	0	0.015	.000	0.643	47	⊙
39	1238	51.3	-0.065		1.00	19.90	78.20	0.0015	0.0015	0	0	0	0	0	0	0.000	0.002	1.216	299	
39	1420	50.2	-0.067		0.60	20.60	77.90	0.0015	0.0005	0	0	0	0	0	0	0.000	0.003	13.819	895	
40	851	54.9	0.015		9.80	9.50	79.60	0.0050	0.0900	41	2	5	0	2	0	0.056	0.001	0.846	91	▽○
40	1237	52.5	-0.139		1.30	19.70	78.10	0.0000	0.0035	2	0	0	0	0	0	0.057	0.000	1.305	0	
40	1418	51.3	-0.136		0.80	20.40	77.90	0.0000	0.0010	0	0	0	0	0	0	0.000	0.000	3.285	0	
41	845	80.4	0.030		13.10	4.30	81.30	0.2100	0.0650	45	2	10	1	3	0	0.094	0.016	0.769	2642	▽○
41	1235	77.6	-0.282		1.90	19.90	77.30	0.0025	0.0010	0	0	0	0	0	0	0.000	0.001	3.254	498	
41	1415	75.4	-0.260		0.90	20.50	77.70	0.0015	0.0005	0	0	0	0	0	0	0.000	0.002	9.957	697	
42	924	61.1	0.012		14.90	2.10	81.80	0.0600	0.1600	210	18	48	5	15	12	0.193	0.004	0.763	667	⊕
42	1251	62.8	-0.094		5.30	14.20	79.40	0.0400	0.1300	200	20	54	9	20	12	0.242	0.008	0.779	1241	
42	1433	63.2	-0.084		5.60	14.10	79.10	0.0540	0.1600	210	25	52	9	20	12	0.205	0.010	0.822	1651	
43	927	47.2	0.000		11.80	5.40	81.80	0.0000	0.0300	5	0	0	0	0	0	0.017	0.000	0.725	0	△+
43	1253	45.7	-0.194		1.60	19.60	77.80	0.0180	0.0080	5	0	1	0	0	0	0.075	0.011	1.587	2791	
43	1434	45.7	-0.175		1.30	19.90	77.80	0.0180	0.0075	5	0	1	0	0	0	0.080	0.014	1.832	3588	
44	841	50.5	-0.010		2.70	17.10	79.30	0.0000	0.0005	0	0	0	0	0	0	0.000	0.000	0.690	0	⊛
44	1108	48.4	-25.700		9.60	9.30	79.90	0.0900	0.0870	185	9	45	5	15	6	0.305	0.009	0.814	1618	
44	1232	50.4	-28.300		5.90	14.70	78.20	0.1500	0.0775	99	7	25	4	8	4	0.190	0.025	0.998	5027	
44	1322	51.8	-28.300		5.30	15.20	78.30	0.1700	0.0920	112	12	26	5	10	3	0.183	0.032	0.978	6193	
44	1413	52.9	-28.300		5.00	15.50	78.30	0.1900	0.1000	125	15	30	5	11	4	0.190	0.038	0.980	7302	
44	1452	53.8	-27.900		4.20	16.60	78.00	0.1600	0.0950	112	12	27	5	10	4	0.179	0.038	1.061	7704	
58	848	58.4	0.033		10.00	9.50	79.50	0.0170	0.0430	11	0	2	0	0	0	0.030	0.002	0.866	311	△+
58	1236	56.9	-0.210		4.10	17.00	77.90	0.0060	0.0120	3	0	1	0	0	0	0.033	0.001	1.127	318	
58	1416	55.6	-0.190		2.80	18.70	77.60	0.0025	0.0075	5	0	1	0	0	0	0.080	0.001	1.503	233	
59	900	54.7	0.047		10.50	9.30	79.20	0.0060	0.0260	12	0	2	0	0	0	0.054	0.001	0.899	108	⊙
59	1241	55.3	-0.218		2.60	18.70	77.80	0.0015	0.0030	0	0	0	0	0	0	0.000	0.001	1.357	140	
59	1423	54.0	-0.187		1.60	20.00	77.50	0.0030	0.0030	0	0	0	0	0	0	0.000	0.002	2.981	661	

Figure B-6.—Borehole communications test data, JD5059.

Mine Fire RENTON (JD5060) EXHAUST BOREHOLE = #58 FAN ON AT 1000

BH:	TIME:	DEGC TEMP:	INH2O PRES:	PCT H2:	PCT CO2:	PCT O2:	PCT N2:	PCT CO:	PCT CH4:	PPM C2H6:	PPM C2H4:	PPM C3H8:	PPM C3H6:	PPM xC4H10:	PPM xC5H12:	C2C5/CH4:	CO/CO2:	JTR	PPM AFCO:	SUMMARY CONCLUSION
18	816	17.2	0.010		1.90	19.30	77.90	0.0030	0.0015	0	0	0	0	0	0	0.000	0.002	1.416	381	
18	1234	17.0	-0.060		1.30	19.90	77.90	0.0015	0.0005	0	0	0	0	0	0	0.000	0.001	1.750	299	
18	1418	16.9	-0.060	0.0000	1.10	20.10	77.90	0.0015	0.0005	0	0	0	0	0	0	0.000	0.001	2.026	369	
19	810	55.0	0.033		7.30	12.50	79.20	0.0070	0.0045	3	0	0	0	0	0	0.067	0.001	0.861	174	
19	1230	54.8	-0.240	0.0000	4.80	16.10	78.20	0.0040	0.0065	4	0	0	0	0	0	0.062	0.001	1.039	173	
19	1414	54.4	-0.240		4.20	17.30	77.60	0.0040	0.0060	3	0	0	0	0	0	0.050	0.001	1.288	230	
20	831	15.3	-0.034		1.80	18.70	78.60	0.0000	0.0030	0	0	0	0	0	0	0.000	0.000	0.845	0	
20	1241	15.3	-0.185		2.40	17.80	78.80	0.0240	0.0250	3	0	0	0	0	0	0.012	0.010	0.785	1596	
20	1424	15.3	-0.207		2.50	17.90	78.60	0.0500	0.0340	5	0	0	0	0	0	0.015	0.020	0.866	3433	
35	827	14.2	0.015		0.10	18.10	80.80	0.0015	0.0005	0	0	0	0	0	0	0.000	0.015	0.031	110	
35	1239	15.1	-0.024		0.10	18.00	80.90	0.0015	0.0005	0	0	0	0	0	0	0.000	0.015	0.029	106	
35	1423	14.9	-0.004		0.10	18.10	80.80	0.0015	0.0005	0	0	0	0	0	0	0.000	0.015	0.031	110	
36	824	59.9	0.000		11.00	5.20	82.60	0.0175	0.1600	69	2	7	0	6	0	0.053	0.002	0.660	233	
36	1237	60.2	-0.140		0.65	20.10	78.30	0.0030	0.0050	2	0	0	0	0	0	0.040	0.005	1.004	738	
36	1421	59.6	-0.128		0.50	20.30	78.30	0.0040	0.0040	1	0	0	0	0	0	0.025	0.008	1.119	1287	
37	822	73.0	0.020		8.00	9.10	81.90	0.0245	0.0180	20	0	6	0	3	0	0.161	0.003	0.636	433	
37	1236	74.7	-0.105	0.0020	0.50	20.50	78.10	0.0030	0.0010	0	0	0	0	0	0	0.000	0.006	2.559	1393	
37	1420	73.6	-0.085	0.0015	0.40	20.60	78.10	0.0030	0.0010	0	0	0	0	0	0	0.000	0.008	4.172	1790	
38	833	40.0	-0.015		6.40	11.60	81.00	0.0080	0.0330	20	0	4	0	2	0	0.079	0.001	0.649	179	
38	1242	33.6	-0.174	0.0000	0.70	20.10	78.30	0.0045	0.0070	6	0	1	0	0	0	0.100	0.006	1.083	1108	
38	1425	32.3	-0.160	0.0000	0.70	20.10	78.30	0.0080	0.0085	8	0	1	0	0	0	0.106	0.011	1.087	1969	
39	807	53.1	0.009		6.90	10.40	81.70	0.0020	0.0050	1	0	0	0	0	0	0.020	.000	0.613	40	
39	1228	46.0	-0.215		0.40	20.70	78.00	0.0020	0.0010	0	0	0	0	0	0	0.000	0.005	-13.383	1668	
39	1412	44.1	-0.212	0.0000	0.20	20.80	78.10	0.0015	0.0005	0	0	0	0	0	0	0.000	0.008	-1.943	2079	
40	804	54.8	0.013		7.30	11.10	80.60	0.0110	0.0200	9	0	1	0	0	0	0.050	0.002	0.712	234	
40	1227	49.7	-0.390		2.20	18.60	78.20	0.0175	0.0230	12	0	2	0	0	0	0.061	0.008	1.042	1559	
40	1411	48.4	-0.380		2.10	18.70	78.20	0.0650	0.0290	30	0	4	0	0	0	0.117	0.031	1.062	6049	
41	845	78.4	0.042	0.0130	12.10	4.70	82.00	0.1800	0.0380	47	1	10	0	3	0	0.161	0.015	0.719	2321	
41	1247	73.5	-0.400	0.0005	0.65	20.60	77.80	0.0020	0.0005	0	0	0	0	0	0	0.000	0.003	38.331	1193	
41	1430	72.4	-0.400	0.0005	0.40	20.70	78.00	0.0020	0.0005	0	0	0	0	0	0	0.000	0.005	-13.388	1668	
42	837	61.8	0.018		13.80	3.60	81.50	0.0350	0.1000	180	0	32	0	10	0	0.222	0.003	0.768	423	
42	1244	65.0	-0.216		0.90	19.50	78.60	0.0110	0.0175	12	0	3	0	2	0	0.097	0.012	0.683	1588	
42	1426	64.7	-0.213		0.70	19.80	78.50	0.0120	0.0125	10	0	2	0	0	0	0.096	0.017	0.707	2184	
43	839	46.8	0.007		11.50	6.00	81.50	0.0230	0.0160	5	0	0	0	0	0	0.031	0.002	0.738	322	
43	1245	44.4	-0.420		1.10	19.90	78.00	0.0350	0.0230	8	0	1	0	0	0	0.039	0.032	1.463	6976	
43	1428	43.9	-0.430		0.70	20.60	77.70	0.0250	0.0140	4	0	1	0	0	0	0.036	0.036	-75.658	14915	
44	842	52.5	-0.016		5.70	12.30	81.00	0.0040	0.0170	13	0	3	0	0	0	0.094	0.001	0.622	97	
44	1246	47.4	-0.260		1.10	20.30	77.70	0.0000	0.0000	0	0	0	0	0	0	ERR	0.000	3.787	0	
44	1429	46.7	-0.260		0.80	20.50	77.80	0.0000	0.0005	0	0	0	0	0	0	0.000	0.000	6.838	0	
58	758	57.9	0.028		8.00	11.30	79.70	0.0150	0.0225	11	0	2	0	0	0	0.058	0.002	0.816	326	
58	1026	53.3	-23.500	0.0050	7.60	11.60	79.70	0.0325	0.0540	65	3	15	1	5	2	0.169	0.004	0.801	728	
58	1134	53.1	-26.200	0.0220	5.00	15.70	78.20	0.1000	0.0500	61	4	13	2	5	1	0.172	0.020	1.011	3990	
58	1226	54.5	-25.800	0.0205	5.10	15.80	77.90	0.1400	0.0700	80	4	17	2	5	2	0.157	0.027	1.076	5694	
58	1410	54.2	-25.900	0.0550	4.40	16.80	77.60	0.1400	0.0800	90	6	21	3	7	3	0.163	0.032	1.201	7066	
58	1448	54.1	-25.800	0.0435	4.20	16.90	77.70	0.1400	0.0825	94	6	22	3	7	3	0.164	0.033	1.169	7240	
59	813	54.5	0.040		9.20	10.10	79.70	0.0060	0.0160	11	0	2	0	0	0	0.081	0.001	0.835	116	
59	1231	53.4	-0.370		1.80	19.10	78.20	0.0015	0.0010	0	0	0	0	0	0	0.000	0.001	1.110	170	
59	1416	53.0	-0.375	0.0000	1.70	19.30	78.10	0.0015	0.0010	0	0	0	0	0	0	0.000	0.001	1.218	190	

Figure B-7.—Borehole communications test data, JD5060.

Mine Fire RENTON (JD5064) EXHAUST BOREHOLE = #37 FAN ON AT 1030

BH:	TIME:	DEGC TEMP:	INH2O PRES:	PCT H2:	PCT CO2:	PCT O2:	PCT N2:	PCT CO:	PCT CH4:	PPM C2H6:	PPM C2H4:	PPM C3H8:	PPM C3H6:	PPM xC4H10:	PPM xC5H12:	C2C5/CH4:	CO/CO2:	JTR:	PPM AFCO:	SUMMARY CONCLUSION
18	942	16.7	0.018	0.0000	2.20	18.30	78.60	0.0020	0.0005	0	0	0	0	0	0	0.000	0.001	0.871	158	(O)
18	1251	16.7	-0.005	0.0000	2.10	18.50	78.50	0.0025	0.0005	0	0	0	0	0	0	0.000	0.001	0.913	214	
18	1439	16.8	-0.025	0.0000	2.20	18.30	78.60	0.0025	0.0005	0	0	0	0	0	0	0.000	0.001	0.871	198	
19	934	54.2	0.038		8.30	8.50	82.20	0.0000	0.0015	0	0	0	0	0	0	0.000	0.000	0.625	0	△+
19	1435	54.6	-0.105		10.60	6.60	81.70	0.0550	0.0225	24	2	5	0	2	0	0.147	0.005	0.707	803	
20	858	17.2	-0.025	0.0000	1.10	19.40	78.60	0.0000	0.0005	0	0	0	0	0	0	0.000	0.000	0.770	0	⊚
20	1227	15.7	-0.560	0.0120	4.50	15.80	78.30	0.3700	0.1100	37	3	8	2	4	2	0.051	0.082	0.966	15049	
35	854	16.0	0.000	0.0000	0.05	18.00	81.00	0.0025	0.0005	0	0	0	0	0	0	0.000	0.050	0.015	177	(O)
35	1225	14.7	-0.029	0.0015	0.10	18.10	80.80	0.0025	0.0005	0	0	0	0	0	0	0.000	0.025	0.031	184	
35	1418	14.4	0.000	0.0015	0.05	18.20	80.80	0.0025	0.0005	0	0	0	0	0	0	0.000	0.050	0.016	190	
36	849	61.4	-0.005	0.0085	13.70	1.60	83.50	0.0180	0.1300	40	1	5	0	3	0	0.038	0.001	0.668	195	⊚
36	1224	57.6	-0.620	0.0005	0.50	20.50	78.10	0.0040	0.0025	1	0	0	0	0	0	0.040	0.008	2.560	1857	
36	1416	55.9	-0.590	0.0010	0.40	20.70	78.00	0.0030	0.0010	0	0	0	0	0	0	0.000	0.008	-13.417	2502	
37	845	70.8	0.026	0.0115	9.50	5.40	84.00	0.0220	0.0200	37	0	12	0	7	0	0.280	0.002	0.565	296	⊛
37	1056	60.8	-25.000	0.0095	9.60	6.40	82.80	0.1200	0.5600	70	4	16	0	5	4	0.018	0.013	0.624	1728	
37	1112	63.2	-26.400	0.0230	7.30	10.20	81.40	0.1000	0.0370	50	2	11	0	4	4	0.192	0.014	0.649	1949	
37	1222	63.4	-25.900	0.0450	4.70	14.90	79.10	0.2200	0.0650	96	8	15	0	4	4	0.195	0.047	0.804	7617	
37	1308	62.8	-26.200	0.0685	5.50	13.80	79.30	0.2800	0.1100	125	15	25	0	6	6	0.161	0.051	0.794	8203	
37	1415	62.9	-26.200	0.0535	3.60	16.60	78.50	0.1800	0.0900	96	9	21	0	6	6	0.153	0.050	0.892	8667	
37	1501	62.5	-26.000	0.0850	3.70	16.40	78.50	0.1900	0.1200	125	12	25	0	6	6	0.145	0.051	0.878	8747	
38	903	42.1	-0.009	0.0015	8.00	8.20	82.80	0.0110	0.0355	29	0	7	0	2	0	0.107	0.001	0.583	181	⊕
38	1229	33.7	-0.620	0.0000	2.00	18.80	78.20	0.0400	0.0070	6	0	1	0	0	0	0.100	0.020	1.056	3896	
38	1422	32.5	-0.610	0.0005	0.30	20.75	78.00	0.0095	0.0025	2	0	0	0	0	0	0.080	0.032	-3.841	9893	
39	931	53.0	0.000	0.0025	9.30	6.40	83.30	0.0010	0.0020	0	0	0	0	0	0	0.000	.000	0.593	14	△+
39	1244	48.4	-0.240	0.0015	3.40	17.00	78.60	0.0280	0.0170	17	0	3	0	0	0	0.118	0.008	0.894	1485	
39	1434	47.4	-0.250	0.0025	2.80	17.70	78.50	0.0490	0.0320	32	1	5	0	0	0	0.119	0.018	0.915	3158	
40	928	54.0	0.008		10.50	4.60	83.90	0.0000	0.0035	3	0	0	0	0	0	0.086	0.000	0.595	0	⊕
40	1242	52.5	-0.110		2.40	18.30	78.40	0.0000	0.0015	0	0	0	0	0	0	0.000	0.000	0.969	0	
40	1432	51.9	-0.115		1.80	19.20	78.10	0.0000	0.0035	3	0	0	0	0	0	0.086	0.000	1.203	0	
41	922	76.0	0.050	0.0320	13.30	2.90	82.50	0.2600	0.0290	35	0	7	0	2	0	0.152	0.020	0.712	3018	▽O
41	1238	76.0	-0.025	0.0030	6.40	13.80	78.80	0.0050	0.0180	4	0	0	0	0	0	0.022	0.001	0.904	146	
41	1429	77.8	-0.018	0.0025	5.20	14.90	78.90	0.0035	0.0600	13	0	1	0	0	0	0.023	0.001	0.866	121	
42	906	63.8	0.016	0.0015	13.70	3.80	81.40	0.0230	0.0790	156	5	40	0	12	9	0.281	0.002	0.772	281	▽O
42	1230	63.0	-0.165	0.0000	0.50	20.60	78.00	0.0025	0.0005	0	0	0	0	0	0	0.000	0.005	7.170	1491	
43	910	46.6	0.000		12.30	5.30	81.40	0.0000	0.0060	2	0	0	0	0	0	0.033	0.000	0.756	0	△+
43	1234	45.9	-0.140		2.80	18.40	77.80	0.0600	0.0130	12	0	0	0	0	0	0.092	0.021	1.283	4927	
43	1426	46.0	-0.120	0.0115	4.00	16.90	77.90	0.1500	0.0490	45	2	8	1	2	0	0.118	0.038	1.099	7757	
44	919	51.4	0.000		4.80	14.90	79.30	0.0000	0.0030	1	0	0	0	0	0	0.033	0.000	0.785	0	(O)
44	1236	49.6	-0.055	0.0000	2.10	19.20	77.80	0.0000	0.0020	0	0	0	0	0	0	0.000	0.000	1.482	0	
44	1427	49.2	-0.037		1.80	19.60	77.70	0.0000	0.0045	0	0	0	0	0	0	0.000	0.000	1.817	0	
58	925	57.6	0.030		9.90	6.30	82.80	0.0000	0.0035	0	0	0	0	0	0	0.000	0.000	0.633	0	△+
58	1241	56.9	-0.045		8.20	10.50	80.30	0.0000	0.0080	0	0	0	0	0	0	0.000	0.000	0.761	0	
58	1431	56.2	-0.050		6.80	12.80	79.40	0.0025	0.0240	13	0	1	0	0	0	0.058	.000	0.825	64	
59	938	53.8	0.036	0.0005	10.90	5.30	82.80	0.0095	0.0100	7	0	1	0	0	0	0.080	0.001	0.655	127	△+
59	1249	53.6	-0.015	0.0015	11.30	5.10	82.40	0.0160	0.1900	210	10	38	0	12	6	0.145	0.001	0.676	211	
59	1437	54.1	-0.045	0.0015	10.00	7.40	81.40	0.0140	0.1800	185	9	36	0	12	4	0.137	0.001	0.706	216	

Figure B-8.—Borehole communications test data, JD5064.

APPENDIX C.—VENTILATION NETWORK ANALYSIS FOR ABANDONED MINES

Problem

The Bureau's mine fire diagnostics methodology involves, in part, communications studies between boreholes set from the surface into the mine area. One borehole (the suction hole) is exhausted while the gas composition and vacuum developed at the bottom of all the other boreholes are noted; these boreholes are capped from the atmosphere. The measurements of vacuum and gas exhaust flow rate are made where each borehole in the communicating network takes a turn at being the suction hole. With these sets of data and some simplfying assumptions regarding the flow, it is possible to calculate a value for the effective resistance to flow between any two boreholes in the network. This information could be very helpful in locating an abandoned coal mine fire.

Solution

Consider n cased boreholes in an area that communicates to a suction hole, s.

Let $_sQ_{ij}$ = positive flow from borehole i to borehole j while sucking at suction hole s (i,j,s = 1,2,3,....,n),

$_sQ_{xs}$ = flow from unknown regions, x to suction hole s,

$_sQ_{xi}$ = flow from unknown regions, x to borehole i while sucking at suction hole s.

Q_s = total flow exhausted from suction hole s.

For steady flow developed at each communications test involving a different suction hole s,

$$\sum_i {_sQ_{ij}} + {_sQ_{xj}} = 0, \qquad \text{(C-1)}$$

for all j ≠ s, for all boreholes i including suction hole s.

I.e., the sum of all underground flows into and out of borehole j is zero; noting that it was assumed here that $Q_{ij} = -Q_{ji}$ and $Q_{jj} = 0$. In general, it can be written that

$$Q_{ij} = \left[\frac{P_i - P_j}{R_{ij}}\right]^{1/N}, \qquad \text{(C-2)}$$

where P_i = static pressure at borehole i,

P_j = static pressure at borehole j,

R_{ij} = flow resistance along pathway between borehole i and borehole j,

and N = a constant related to type of flow (e.g., N = 1 for Darcy flow; N = 2 for pipe flow).

The resistances R_{xi} and R_{ij} are to be determined so as to evaluate the extent of communication between borehole pairs. Under ideal conditions of no heat or mass addition in the mine, R_{ij} would be a material property and hence equal to R_{ji}.

Now at the suction hole s, there is a net flow out of the mine, Q_s,

where
$$Q_s = \sum_j {_sQ_{js}} + {_sQ_{xs}}, \qquad \text{(C-3)}$$

for all boreholes j.

Equation C-1 is summed over all j ≠ s to obtain

$$\sum_{j \neq s} \sum_i {_sQ_{ij}} + \sum_{j \neq s} {_sQ_{xj}} = 0,$$

or
$$\sum_{j \neq s} \sum_{i \neq s} {_sQ_{ij}} + \sum_{j \neq s} {_sQ_{sj}} + \sum_{j \neq s} {_sQ_{xj}} = 0.$$

However, $_sQ_{ij} = -{_sQ_{ji}}$ and $_sQ_{ii} = 0$; therefore,

$$\sum_{j \neq s} \sum_{i \neq s} {_sQ_{ij}} = 0,$$

and
$$\sum_{j \neq s} [{_sQ_{sj}} + {_sQ_{xj}}] = 0.$$

Since $_sQ_{ss} = 0$, it can be written that

$$\sum_j {_sQ_{sj}} + \sum_{j \neq s} {_sQ_{xj}} = 0. \qquad \text{(C-4)}$$

From equation C-3,

$$\sum_j {_sQ_{js}} = -\sum_j {_sQ_{sj}} = Q_s - {_sQ_{xs}},$$

which, when substituted into equation C-4, yields

$$-Q_s + {}_sQ_{xs} + \sum_{j \neq s} {}_sQ_{xj} = 0,$$

or

$$Q_s = \sum_{j \neq s} {}_sQ_{xj} + {}_sQ_{xs} = \sum_{j} {}_sQ_{xj}, \qquad \text{(C-5)}$$

for all boreholes j including suction hole s.

I.e., the exhausted flow from the mine is the sum of all flows from unknown regions into each of the holes communicating with suction hole s. If it can now be assumed that the unknown regions represent all zones that are just in communication with borehole j (i.e., the maximum extent), this would yield P_x = atmospheric pressure, P_0, and

$$Q_{xj} = \left[\frac{P_x - P_j}{R_{xj}}\right]^{1/N} = \left[\frac{P_0 - P}{R_{xj}}\right]^{1/N}.$$

Thus, equation C-5 becomes

$$Q_s = \sum_{\text{all } j} \left[P_0 - \frac{{}_sP_j}{R_{xj}}\right]^{1/N}. \qquad \text{(C-6)}$$

The quantity $(P_0 - {}_sP_j)$ is identified as ${}_sP_{0j}$, which, in turn, is equal to $-{}_sP_{j0}$, the negative of the vacuum (itself a negative quantity) measured at borehole j while sucking at suction hole s. In the communications studies involving n boreholes, Q_s and ${}_sP_{0j}$ are determined by direct measurement, while the constant N can be evaluated from separate tests where Q_s is determined as a function of ${}_sP_{j0}$. Alternatively, a value for N can be assumed (e.g., N = 1 for complete Darcy flow). Underground heat addition with its effect of temperature throttling can be accounted for by correcting the measured vacuum back to ambient temperature conditions, i.e.,

$${}_sP_{j0} = ({}_sP_{j0})_{\text{measured}} \cdot ({}_sT_0 / {}_sT_j),$$

where ${}_sT_0$ = ambient temperature,

and ${}_sT_j$ = downhole temperature at borehole j while sucking at suction hole s.

Equation C-6 is a set of n equations containing the n unknown resistances, which can be solved for simultaneously. The resultant values for each of the R_{xj}'s, should be material constants that describe the underground ventilation system. It is also noted that equation C-1, along with the same data from the communications studies, likewise forms a set of equations, i.e.,

$$\sum_i \frac{{}_sP_{ij}}{R_{ij}}^{1/N} = -\frac{{}_sP_{0j}}{R_{xj}}^{1/N}, \qquad \text{(C-7)}$$

for all j ≠ s.

Since ${}_sP_{0j}$, N, R_{xj}, and ${}_sP_{ij}$ are known, and since $P_{jj} = 0$, each value of j ≠ s leads to a set of (n - 1) equations with (n - 1) unknowns (the R_{ij}'s), which can be solved simultaneously to yield values for the effective R_{ij}. E.g., in case of Darcy flow, the equations can be written in the following form:

Taking j = 1; i,s = 2,3,4,....,n,

$$({}_2P_{21}/R_{21}) + ({}_2P_{31}/R_{31}) + \ldots + ({}_2P_{n1}/R_{n1}) = -({}_2P_{01}/R_{x1})$$
$$\vdots \qquad \vdots \qquad \vdots \qquad \vdots$$
$$({}_nP_{21}/R_{21}) + ({}_nP_{31}/R_{31}) + \ldots + ({}_nP_{n1}/R_{n1}) = -({}_nP_{01}/R_{x1})$$

Taking j = 2; i,s = 1,3,4,....,n

$$({}_1P_{12}/R_{12}) + ({}_1P_{32}/R_{32}) + \ldots + ({}_1P_{n2}/R_{n2}) = -({}_1P_{02}/R_{x2})$$
$$\vdots \qquad \vdots \qquad \vdots \qquad \vdots$$
$$({}_nP_{12}/R_{12}) + ({}_nP_{32}/R_{32}) + \ldots + ({}_nP_{n2}/R_{n2}) = -({}_nP_{02}/R_{x2})$$

Taking j = 3, i,s = 1,2,4,.....n, a similar set of n - 1 equations is obtained, and so on, for each value of j.

An interesting aspect of the solutions for the effective resistance between borehole pairs is that values are calculated explicitly for R_{ij} and R_{ji}. Under the assumptions of an ideal ventilation network (i.e., no gaseous mass additions from burning coal), the R_{ij}'s would simply be material properties whose calculated values should not change when flow is reversed between borehole i and borehole j. On the other hand, if the solutions to the ideal network model give rise to values of R_{ij} and R_{ji}, which are not equal, it is likely that heat and/or gaseous mass is being added to the network in a nonuniformly distributed manner (e.g., between one or more borehole pairs). The noncommutative behavior of the effective resistances at Renton can be seen from figures C-1 through C-3, which list the calculated values based upon field measurements

i/j	43	42	38	39	44	58	37
43	0.0088	0.49	1.06	0.75	1.55	0.64	2.33
42	1.10	0.0127	1.61	1.76	5.84	6.51	5.55
38	1.18	0.91	0.0046	0.57	4.19	2.53	0.47
39	0.70	0.89	0.35	0.0084	2.21	1.10	0.86
44	1.14	3.70	2.92	3.02	0.0088	0.87	9.43
58	0.37	1.20	0.85	0.69	0.64	0.0071	2.72
37	1.53	1.91	0.24	0.69	5.29	3.52	0.0118

Figure C-1.—Danny property site R_{ij} and R_{ji} values, inches of water per standard cubic foot, JD4134 to JD5064. R_{xi} values are listed in the R_{ii} boxes.

i/j	56	53	7	45	47	50	51
56	0.0074	0.040	-8.33	40.00	7.35	-4.02	0.337
53	0.028	0.0003	0.028	0.061	0.063	3.61	0.004
7	1.64	0.020	0.0052	0.782	0.729	-9.43	0.111
45	10.1	0.034	-5.18	0.0025	0.108	-8.70	0.133
47	4.27	0.026	-2.44	0.098	0.0014	-2.34	0.118
50	27.8	0.082	-7.81	1.079	0.998	0.0092	0.429
51	0.430	0.003	0.432	0.119	0.160	14.9	0.0013

Figure C-2.—Plum Street site R_{ij} and R_{ji} values, inches of water per standard cubic foot, JD4284 to JD4307. R_{xi} values are listed in the R_{ii} boxes.

i/j	12	27	29	32	34
12	-0.0836	0.08	13.27	2.21	451
27	-12.06	0.0014	1.32	19.3	24.3
29	-93.65	-1.08	0.0097	31.1	119
32	90.96	-1.77	1961	0.0183	139
34	-24870	-2.62	-40.18	139	0.0492

Figure C-3.—Miller Farm site R_{ij} and R_{ji} values, inches of water per standard cubic foot, JD4258 to JD4269. R_{xi} values are listed in the R_{ii} boxes.

of flow and vacuum for the three separate fire zones: Danny (seven boreholes), Plum Street (seven boreholes) and Miller Farm (five boreholes).[1] The noncommutative behavior of some of the R_{ij} pairs (factor differences ranging up to more than 100), along with calculated negative values for many of the R_{ij}'s, do indeed strongly suggest that the areas encompassed by each of the borehole networks do contain regions having nonideal behavior, presumably the underground fire.

Assuming ad hoc that ideal conditions (i.e., no fire) are still reflected by those borehole pairs whose resistances do commutate (at least to some "reasonable" factor to account for the many uncertainties that exist in the measurement and treatment of data), then those borehole pairs would be communicating through the nonfire regions of the mine. This is approximately the case of figures C-4 and C-5,

[1]It is noteworthy that the positive values of R_{xj} (0.0003 to 0.0492 in H_2O/scfm with an average of 0.0093 in H_2O/scfm) are somewhat higher, but still in keeping with the value of Darcy flow resistance (0.00098±0.00011 in H_2O/scfm) determined for the Calamity Hollow mine fire site (*12*, p. 21).

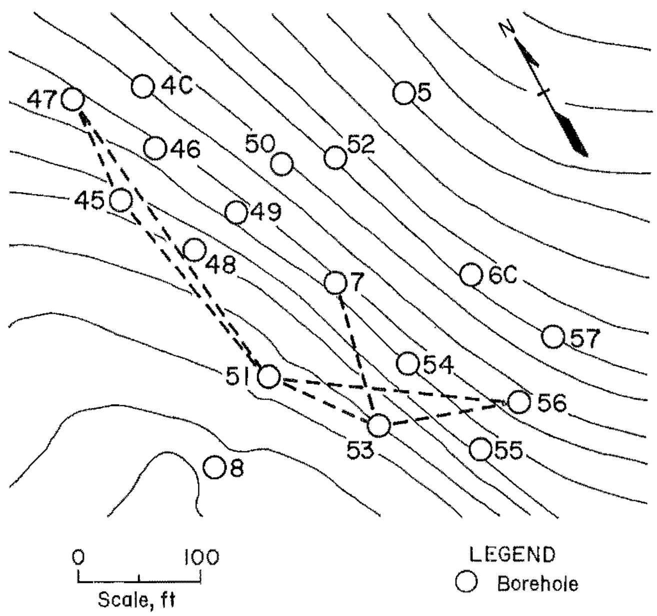


Figure C-4.—Map of cold boundary from network ventilation analysis, Plum Street area.

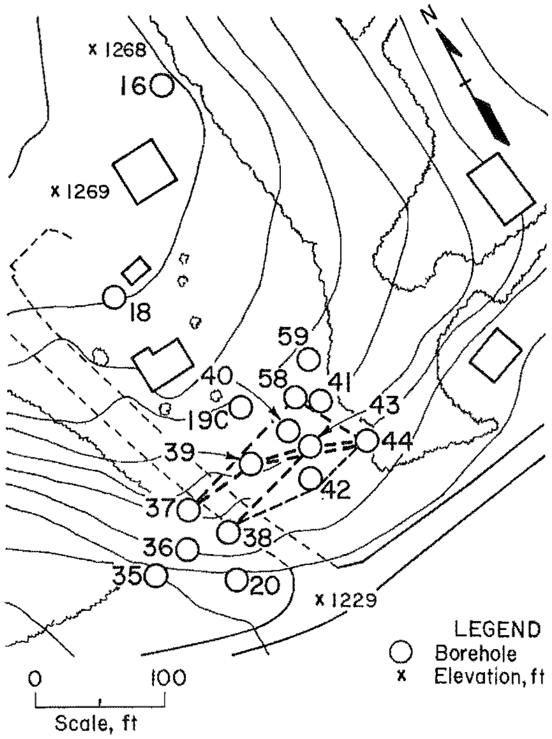


Figure C-5.—Map of cold boundary from network ventilation analysis, Danny property area.

where the "cold" borehole pairs (taken as those for which the resistances are positive and commutate within a factor of 1.5) are connected by dashed straight lines. In the case of the Plum Street and Danny sites, the dashed lines suggest outer cold boundaries that are in rough agreement with those surmised from analysis of the fire signatures, at least for the specific boreholes and Julian dates involved. In the case of the Miller Farm site, no commutating resistances can be observed (see figure C-3). This suggests that the cold boundary is exterior to the area covered by the five boreholes involved, an interpretation which is again approximately consistent with the fire signature results for the specific boreholes and dates involved.

The possibility of accurately defining fire zones through this type of network analysis is intriguing because it could save the need for sampling and analysis of the composition of the mine atmosphere, the current basis of the Bureau's mine fire diagnostics. However, correlating experimental ventilation network data for a mine fire (i.e., a nonideal network) by utilizing a theory based on an ideal network is highly questionable. The assumptions made above regarding the significance of the commutative (or noncommutative) character of the calculated R_{ij} values would have to be tested against a more rigorous theoretical analysis of the actual network conditions.