RI 9241

REPORT OF INVESTIGATIONS/1989

Calamity Hollow Mine Fire Project

(In Five Parts)

2. Operation of the Burnout Control System

By Robert F. Chaiken, Louis E. Dalverny,
and Ann G. Kim

BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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PREFACE

More than 500 fires are now burning in abandoned coal waste banks and coal deposits in the United States. Once established, such fires can burn for decades, and extinguishing them by conventional methods such as surface sealing to exclude air, excavation to remove fuel, or flushing to cool the fire zone is usually difficult and always expensive. Burnout Control, a technique developed by the Bureau of Mines for the control of abandoned coal fires, involves the accelerated combustion of coal in place with total management of the heat and fumes produced. A burning waste bank or mine is placed under negative pressure relative to the atmosphere, and heat and combustion products are drawn from the combustion zone through an exhaust ventilation system. Heat produced appears as sensible heat in the exhaust, at temperatures as high as 1,000° C (1,832° F), and could be recovered for the production of steam, hot water, process heat, or electricity.

The Bureau's first field demonstration of Burnout Control was at Calamity Hollow in Allegheny County, PA (near Pittsburgh). Calamity Hollow was the site of an underground mine in the 1900's and was surface mined in the 1940's. In the winter of 1961-62, a fire of undetermined origin was discovered in the exposed coal. In 1963, the Bureau constructed a trench barrier around the fire and a surface seal over the affected area. The fire was isolated but, not completely extinguished. In 1979, when the Bureau began work on the Calamity Hollow Mine Fire Project to demonstrate controlled burnout, the fire was still smoldering on the hot side of the trench barrier. The project, which was begun in December 1979 and ended in July 1982, consisted of the design, construction, operation, and subsequent dismantling of a Burnout Control ventilation system.

This report, although considered part 2, is actually the last of a five-part series that describes the Calamity Hollow Mine Fire Project. It was written last because it involved the analysis of a substantial body of data describing in detail the results of a continuous 4-month burnout operation. The first report, part 1, describes the design and construction of the field installation. Part 3 describes the instrumentation used to control and monitor the progress of the burnout operation. Parts 4 and 5 deal with the closeout phase of the field demonstration. Part 4 describes the procedure used to quench the fire, and part 5 describes the final excavation and backfilling of the heated zones.

The reports in this series document the Calamity Hollow controlled burnout demonstration, which showed that (1) controlled in situ combustion is a feasible method for controlling underground fires in abandoned mines, (2) the resultant thermal exhaust output is sufficient for energy utilization, and (3) water injection-fume exhaustion is a potentially effective method for cooling large underground fire zones. Further investigations of both Burnout Control and the water injection-fume exhaustion quenching procedure are planned.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	kW	kilowatt
BTU/lb	British thermal unit per pound	lb	pound
BTU/(lb/°F)	British thermal unit per pound per degree Fahrenheit	lb/ft^3	pound per cubic foot
°C	degree Celsius	min	minute
cm	centimeter	mm Hg	millimeter of mercury (atmos. pressure)
cm^3	cubic centimeter	MW	megawatt
cP	centipoise	pct	percent
°F	degree Fahrenheit	ppm	part per million
ft	foot	psi	pound (force) per square inch
gpm	gallon per minute	scfm	standard cubic foot per minute
g/s	gram per second	st	short ton
h	hour	V	volt
h/d	hour per day	W•h	watt hour
in	inch	W•min/lb•°F	watt minute per pound per degree Fahrenheit
in H_2O	inch of water (pressure)		

CALAMITY HOLLOW MINE FIRE PROJECT

(In Five Parts)

2. Operation of the Burnout Control System

By Robert F. Chaiken,[1] Louis E. Dalverny,[2] and Ann G. Kim[3]

ABSTRACT

During the period from January to May 1982, the U.S. Bureau of Mines carried out a continuous field test of the Burnout Control process for controlling abandoned mined-land fires. In this process, the rate of burning of an underground mine fire is accelerated through the action of a suction fan, which pulls and collects hot combustion gases from the mine while causing air to flow over the fire. Burnout Control, thus, controls the emission of heat and fumes from the mine fire, and produces sufficient thermal power to run a small electrical generation plant.

Previous reports in this five-part series have described the design, construction, and instrumentation of the Burnout Control system at Calamity Hollow, Allegheny County, PA, and the quenching and excavation process by which the fire was cooled and finally extinguished after this particular experimental field test. This report, which completes the full description of the Calamity Hollow Coal Mine Fire Project, summarizes in detail various aspects of the operational phase of the field test. It includes a chronology of events, a discussion of the technical data, and a summary of results.

Despite mechanical and operational problems, the field trial at Calamity Hollow demonstrated that Burnout Control is a viable method of controlling an abandoned mine fire.

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INTRODUCTION

During the period from January to May 1982, the Bureau of Mines carried out for the first time a continuous field test of a process called Burnout Control (*1*)[4] in which the rate of burning of an underground mine fire was accelerated through the action of a suction fan. The fan also pulled hot, fully combusted gases from the mine; these gases could have powered a small electrical generation plant. During the course of 102 days of fan operation, approximately 1,100 tons[5] of coal were burned, yielding hot exhaust gases whose average temperature and thermal power level were 603° C and 3.2 MW, respectively. Maximum design goals of 900° C and 5 MW output for the exhaust were exceeded at times. Subsidence, which occurred around the exhaust manifold, had no significant effect on the underground combustion, and was controlled with relatively simple remedies. Levels of pollutants in the exhaust were low, generally below air pollution standards. Despite mechanical and operational problems, the field trial at Calamity Hollow demonstrated that Burnout Control is a viable method of controlling an abandoned mine fire.

Previous reports in this series described the design, construction (*2*), and instrumentation (*3*) of the Burnout Control system at Calamity Hollow (site of the 2-acre abandoned coal mine fire) and also a description of the quenching and excavation process by which the fire was cooled and finally extinguished after the field test (*4-5*). This report, which completes the full description of the Calamity Hollow Coal Mine Fire Project, summarizes in detail various aspects of the 4 months of around-the-clock activities, and the analyses of some 100,000 data points accumulated during the operational phase of the field test.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of the following personnel to the execution of the work described in this report–from the Pittsburgh Research Center: Edward F. Divers, mining engineer; Karen E. Soroka, physical scientist; Joseph P. Slivon, physical science technician; and John R. Odoski, engineering technician. From Boeing Services International, Inc., Pittsburgh, PA: Roy Laverick, construction supervisor; Timothy Fircak, Francis T. Kelly, and Harold Smith, electromechanical technicians. These personnel carried out the day-to-day activities required for operating the Burnout Control system.

BACKGROUND

The Burnout Control process uses exhaust ventilation conditions to promote the complete burning of the underground mine fire, while allowing for total management of the hot gases produced. An artist's rendition (fig. 1) of the system at Calamity Hollow, and an oblique aerial view of the actual system (fig. 2), show its relationship to the instrumentation or office trailer and a water storage pool used during extinguishment of the fire at the end of this experimental demonstration. A plan view drawing of the site (fig. 3) shows the location of individual air inlet boreholes, the trenched incombustible fire barrier, the former highwall, and the original Pittsburgh Coalbed outcrop (*2*). Figure 4 depicts the location of various instrumentation stations on the Burnout Control system, which are referred to in the body of this report.[6]

At Calamity Hollow, a 48-in-OD double-walled, water-cooled steel pipe with a thermally insulated interior lining (26-in-ID) was set vertically 21.5 ft from the surface into the region of the mine roof. This served as a manifold into which gaseous combustion products could be drawn. A partially insulated duct system connected this combustion manifold to a fan (20,000 scfm at 25 in H_2O). The hot gases, drawn from the underground mine fire were cooled by water sprays and by introduction of cold air to mix with the hot exhaust prior to wasting the gases and heat to the atmosphere through the fan. Control of the exhaust output was achieved by opening and/or closing the fan damper near station 4, and/or altering the position of the valve on the air dilution duct near station 6 (fig. 4).

Construction on the Burnout Control system and its supporting instrumentation was completed early in December 1981. A series of daily quality assurance tests carried out during the remainder of the month helped to train those Bureau personnel who would be responsible for operating the system around-the-clock. During this phase of intermittent testing, a vacuum would often be applied to the mine for several hours. This resulted in a slow buildup of heat in the mine as evidence by the continued increase in the starting daily exhaust temperatures (*2*). Continuous 24 h/d operations were begun on January 4, 1982 and continued until May 4, 1982. This report (Part 2) deals solely with this period of operation, and is organized around a chronology of the daily events and a compilation and analysis of the results.

[4]Italic numbers in parentheses refer to items in the list of references at the end of this report.
[5]In this report, "ton" indicates 2,000 lb.
[6]Figures 1 through 4, 6, and 7 are taken from previous reports in the Calamity Hollow series. They are reproduced again in this report to help clarify the discussions.

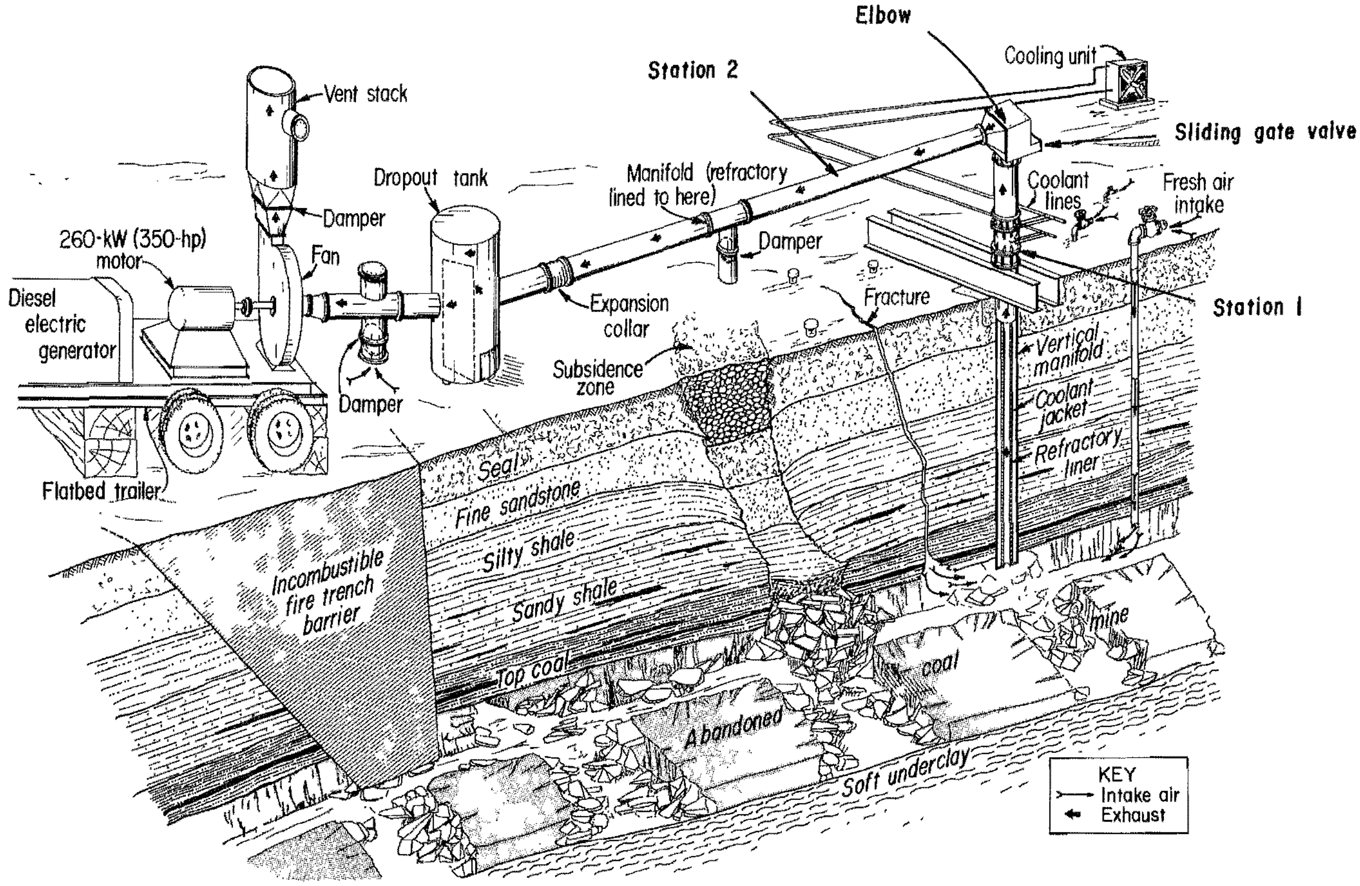

Figure 1.–Artist rendition of Burnout Control system at Calamity Hollow.

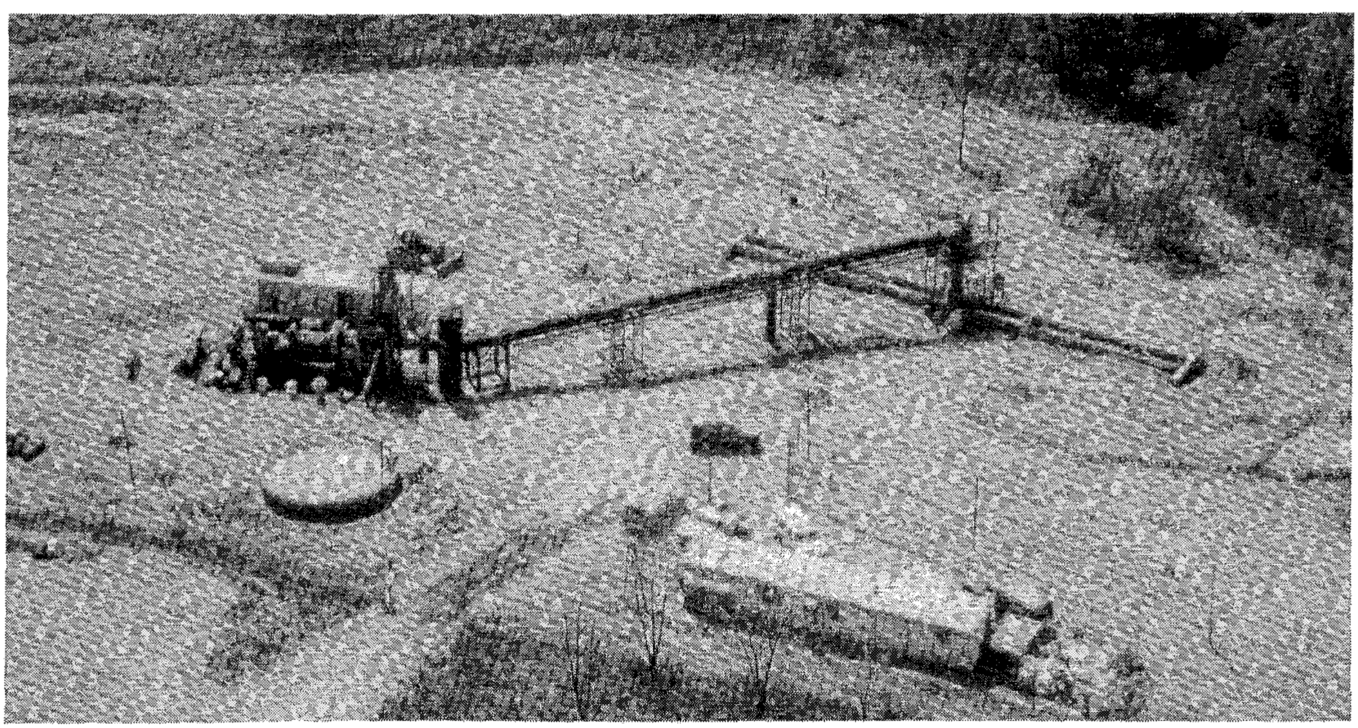

Figure 2.–Aerial view of Calamity Hollow site.

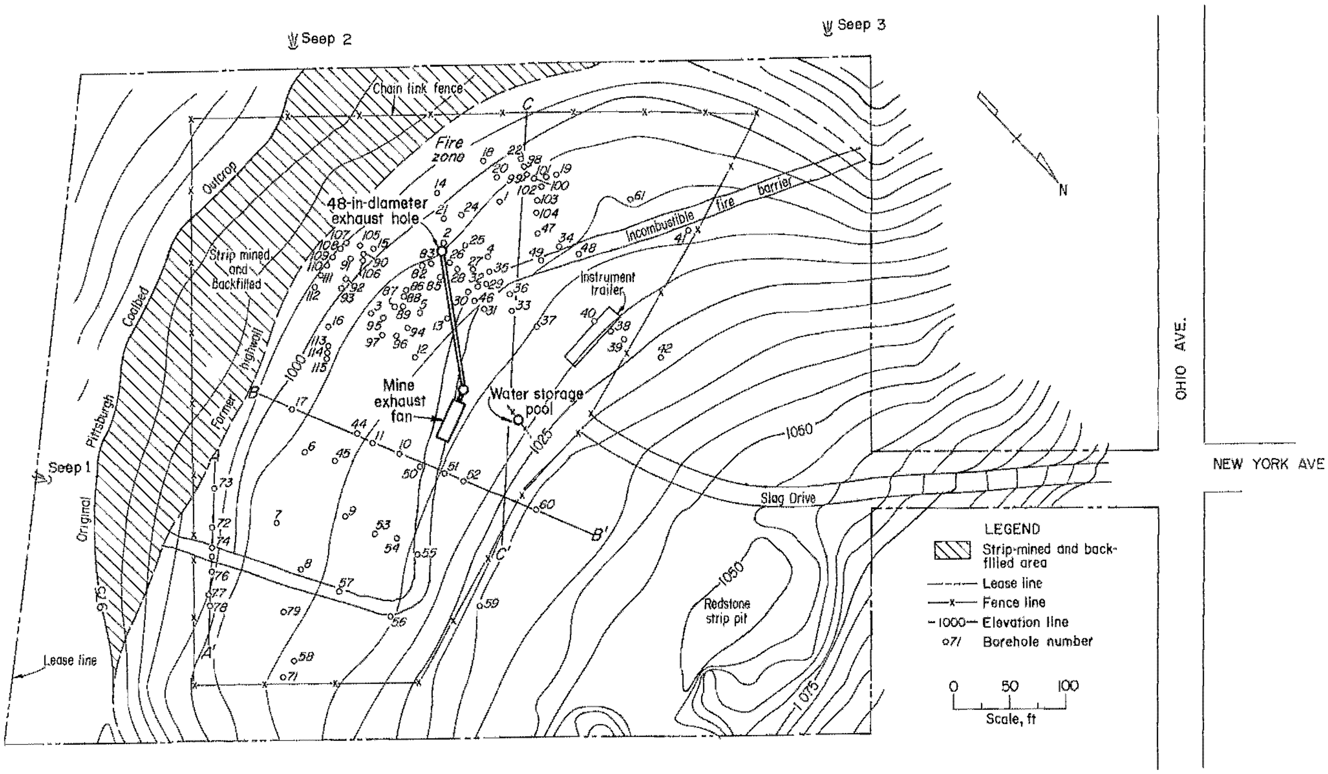

Figure 3.–Calamity Hollow site plan.

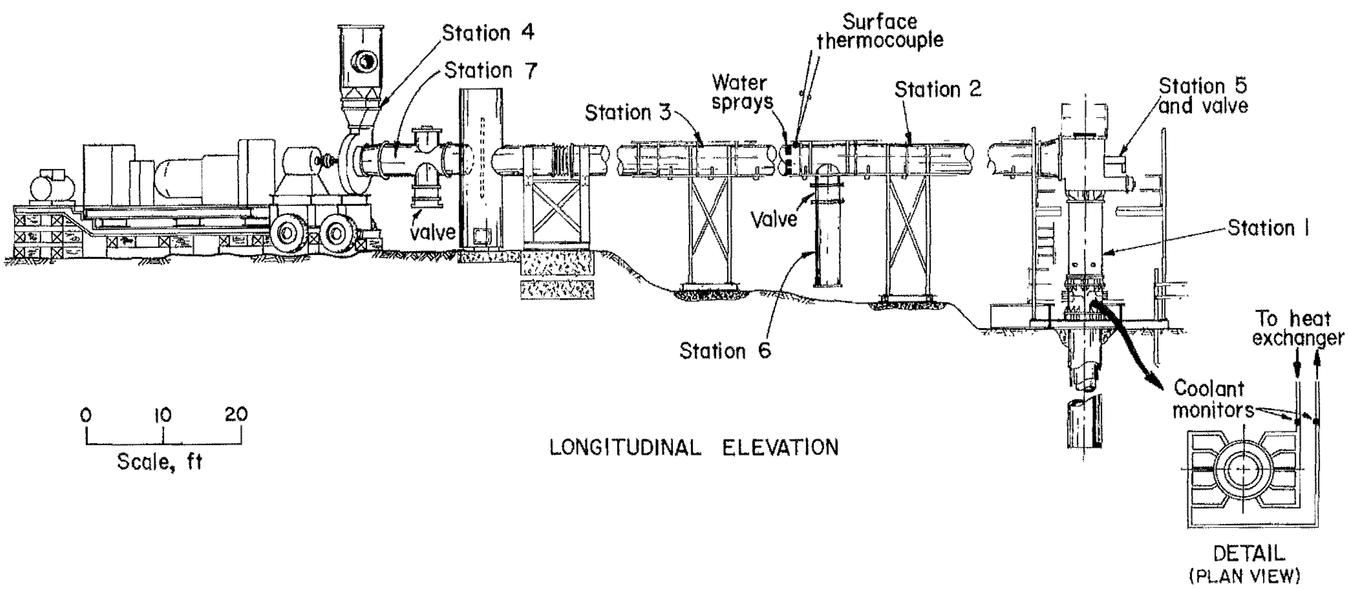

Figure 4.–Instrumentation station locations on Burnout Control system.

CHRONOLOGY OF OPERATIONAL PHASE

Julian Day 4: -3° to 14° C; 749 mm Hg[7]

Monday, January 4, 1982, was the first day of the continuous operations. After resolving a problem with a partially blocked diesel fuel line, the generator and fan were started at 0855 h. The manifold temperature at station 1 quickly rose to 210° C with the carbon monoxide [CO][8] greater than 1,000 ppm[9] and the oxygen [O_2] at 10.4 pct.

Changing the setting of the station 6 valve, which controlled both the dilution air and applied vacuum, varied the station 1 exhaust flows during the day to between 3,000 and 6,000 scfm. By 1400 h a manifold exhaust temperature of 678° C was achieved. Boreholes 1 (93° C), 4 (34° C), 14 (200° C), and 20 (48° C) were opened to enhance the fire in that area. No immediate effects of this action were noted at station 1; however, the exhaust temperature continued to rise throughout the day while the [CO] concentration, decreased, so that by 2100 h, the station 1 temperature was 837° C and [CO] was 60 ppm.

A routine site inspection revealed the following: (1) numerous surface ground cracks, which were formed during the previous month's trials (*2*), remained the same; (2) the thermal expansion bellows, which was to absorb movement of the horizontal ducting, indicated that the duct had shifted slightly towards the manifold;[10] and (3) excessive vibration was noted at the fan exhaust stack and nearby catwalks.

During the day, the remote gas sampling line from station 2 became plugged, apparently by some type of solid buildup in the heated tube bundle, which carries gases from the various sampling stations in the duct directly to the analyzers in the instrumentation trailer. The process control analyzers were turned off, while the involved heated tube bundle was cooled down, and hot water was poured into it, followed by 60 psi of air. This succeeded in clearing one of the two plugged lines; however, the sample gas flow to the process control units was still not satisfactory. It also appeared that one of the solenoids in the gas lines became inoperative - also presumably due to the excess moisture.[11] Vacutainer[12] samples (batch samples) for gas chromatographic (GC) analysis were taken directly from the various stations on the duct.

At 2400 h of this first day of operation, the manifold temperature was 933° C, the [CO] was 61 ppm, the [O_2] was 7.5 pct, the carbon dioxide concentration, [CO_2], was 11.5 pct, and the exhaust gas flow was 4,150 scfm corresponding to a thermal output of 3 MW.

Julian Day 5: -3° to 2° C; 762 mm Hg

Morning activities began at 0700 with the station 1 temperature at 941° C, the exhaust flow at 4,000 scfm and [CO] at 100 ppm. Problems of excessive moisture in the gas sample lines continued. Throughout the morning, changes in open-borehole configuration were made. Boreholes 1 and 14, which were at significantly elevated temperatures (90° to +200° C), were no longer drawing in air. Borehole 2 (within 5 ft of the manifold and at +276° C) had excellent suction, and opening it to the atmosphere caused the manifold temperature to decrease by about 5° C.

The external pipe temperature at station 3 was drifting upward to its warning limit of 270° C, which prompted opening the station 6 valve further to allow more cold dilution air. At 1200 h, the station 1 conditions remained about as before, but the station 3 external pipe temperature continued to increase (195° C). It was decided to cool the exhaust partially with the installed water sprays (at 7 gpm), which resulted in a drop in stack temperature well below the dew point. Adjusting the water sprays to about 4 gpm raised the stack temperature sufficiently to completely evaporate the water in the exhaust, producing a perfectly clear stack plume.

The Burnout Control system was shutdown temporarily at 1415 h for replacement of a leaky diesel fuel line to the generator. Upon starting the system at 1500 h, the station 1 temperature quickly climbed to over 1,100° C, probably as a result of burning pyrolysis gases that had accumulated underground. The station 7 temperature warning device alarmed at well above its set point of 200° (set to protect the fan), which according to previously established operational rules, required immediate corrective action. Stations 5 and 6 valves were quickly opened full, and the water sprays turned on maximum output. These procedures quickly brought the temperature at station 7 below 200° C and the manifold temperature to about 1,000° C. After this event, it was concluded that such rapid corrective actions were probably not necessary; however, it was useful to realize that the preestablished emergency procedures led to the desired result.

During the next few hours, various vacuum levels and control conditions were set to observe the overall response of the manifold output.

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[7] Ambient atmospheric conditions for the Julian day or range of days: temperatures are the recorded lowest to highest values; barometric pressures are those recorded at 0600 h.

[8] Brackets indicate mole concentration.

[9] Maximum scale on the CO analyzer was 1,000 ppm.

[10] This movement, which expanded the bellows rather than compressing it, was indicative of a ground stability problem at the manifold that eventually required attention.

[11] These types of difficulties with the on-line remote gas sampling system were to plague the researchers for the next 2 months.

[12] Evacuated test tubes (25 cm^3) sealed with a rubber septum. Reference to specific products does not imply endorsement by the Bureau of Mines.

Julian Day 6: -3° to 9° C; 759 mm Hg

At 0100 h, the manifold temperature had dropped to 921° C; it continued its slow decrease during the day. Work continued on the malfunctioning remote gas sampling system, which had allowed moisture to condense in all the instruments of the air pollution cabinet (i.e., the SOX and NOX analyzers).

Julian Day 7: -8° to 4° C; 761 mm Hg

Subsidence effects were observed during the site inspection. The electrical junction box at station 3 had broken away from its support. The electrical conduit attached to the dropout tank had pulled apart, although the wires remained intact. The ground surface crack at the south end of the I-beams supporting the manifold stack had enlarged in width and depth while the ground itself showed evidence of dropping several inches away from the I-beams. Surface cracks were observed in increasing numbers.

New water-spray heads were installed to better direct the water to the inside duct surface near station 3. Suitable cooling of the steel duct surface was achieved at a spray rate of 2.2 gpm.

Julian Day 8: -12° to -4° C; 769 mm Hg

The morning began with evidence of continued gas sample line plugging and new surface crack formations. The manifold temperature was 943° C. The moisture problem hampered the on-line gas analyses to the point that it was decided to operate the sample gas pumps only periodically.

Julian Day 9: -18° to -4° C; 754 mm Hg

Problems with gas sampling increased with the discovery that one of the stainless steel tubes conducting gases to the pollution monitoring system had corroded to the point of leaking air. A back-flushing routine was put into effect in an attempt to prevent this from occurring again.

The manifold temperature had slowly decreased during the day to 904° C at 1930 h.

Julian Day 10: -23° to -18° C; 757 mm Hg

Excessive vibration was noted in the vicinity of station 4. Platform grating welds had come apart and several flood lights had shaken loose from their mounts. Borehole temperatures were monitored as well as the effect on the station 1 readings of opening and closing selected holes. The manifold temperature continued its slow decline during the day reaching a temperature of 841° C at 1550 h.

Julian Day 11: -22° to -16° C; 757 mm Hg

The ground continued to show evidence of subsidence under the I-beam support for the manifold stack. Slag was used to fill in some large cracks. The interior of the afterburner section exhibited a less intense orange glow than previously with the manifold temperature at 790° C at 1400 h.

Julian Day 12: -16° to -9° C; 768 mm Hg

It was decided to extend the I-beam supports for the manifold stack. The decision was based on several factors:

1. The gap between the ground and the I-beams, which had grown up to 7 in near the stack.

2. The expansion of the bellows whose, length changed from 22.7 in on December 14, 1981 to 24.2 in on January 9, 1982.

3. Visual observation of a slight tilt of the manifold to the south, which indicated a possible ground slide movement (downhill) in that direction.

Julian Days 13 and 14: -11° to -6° C; 759 to 756 mm Hg

The manifold temperature remained in the range of 720° to 730° C. Various modifications were made to the water-spray system and preparations made for the additional I-beam supports. A cracked water jacket coolant line (probably due to subsidence-shift of the manifold) was replaced with a flexible hose connection.

Julian Day 15: -17° to -8° C; 756 mm Hg

The manifold temperature was 717° C at 0600 h. At 0855 strange noises emanated from the diesel generator, accompanied by a loss of power to the system. This required emergency shutdown of the entire Burnout Control system, including capping all boreholes and closing the large gate valve at station 1. It was determined that the crankshaft in the generator had broken. The entire emergency shutdown procedures were carried out without incident and the site secured without any problems. Minimal venting to the surface was observed. While searching for a replacement generator, the auxiliary 75 kW generator was used to operate the cooling pumps and facility lights.

Julian Days 16 through 20: -28° to 1° C; 764 to 767 mm Hg

The system remained completely shutdown. Some steam and/or smoke was observed only around the manifold stack. Throughout this period, severe freezing required the extensive installation of heating tapes. Fabrication and installation of the additional I-beam supports (40 ft onto each end of the existing girders) were completed.

Julian Days 21 through 24: -9° to 10° C; 763 to 752 mm Hg

A rental diesel generator (1,000 kW) was delivered and put on-line. Shortly after startup, the system had to be turned off because of excessive fan vibration. It was surmised that during the long shutdown, corrosion from condensed steam unbalanced the fan blades. While the fan was being balanced, borehole temperatures were recorded.

Julian Day 25: -15° to 10° C; 762 mm Hg

After spending 3 h thawing out various valves, dampers, and pipes, the generator and fan was started at 1425 h. The system functioned well except for noticeable vibrations around the fan housing. Control adjustments were made to achieve a rapid rise to an elevated manifold temperature (580° C at 2100 h).

Julian Day 26: -17° to -9° C; 766 mm Hg

At 0900 h the manifold temperature was 644° C. Minor problems of an electrical and mechanical nature continued. Electrical fluctuations originating in the rental generator resulted in periodic shutdowns in the water-coolant pump. The station 7 actuator ceased to function due to broken wires. The system was shutdown for the repairs and restarted without incident.

In an attempt to obtain a more symmetrical burn zone around the manifold location, several things were done: (1) plastic sheets and gravel were inserted in cracks in the ground around the manifold; (2) burning charcoal was dropped into some of the boreholes in the eastern field.[13] By completely surrounding the exhaust manifold with burning coal, it was hoped to decrease the amount of dilution air that was flowing into the exhaust manifold.

Julian Days 27 through 29: -17° to 8° C; 771 to 772 mm Hg

The manifold temperature continued to slowly decline; it was at 595° C at 0900 h. The Burnout Control system was completely shutdown to replace the rented 1,000 kW generator with a government-owned generator (675 kW) that had become available. The change was made to reduce costs. The new generator was installed, but failed to function properly (blowing safety fuses) when the fan was started. This resulted in the system being down until the problem could be diagnosed and corrected. In the meantime, new water-spray heads were installed to replace several that had eroded, and repairs attempted on the station 6 actuator controls, which also were apparently damaged by vibration. The latter repairs could not be completed at this time.

Julian Day 30: -2° to 11° C; 763 mm Hg

The starting problem with the new generator was traced to the two-voltage-step starting switch. Increasing the time of operation at 220 V before automatic switching to high voltage (480 V) apparently resolved the blown fuse problem. However, minutes after startup of the fan, the whole system had to be shutdown again because of failure of two holddown bolts on the fan shaft bearings accompanied by excessive vibration. The system was shutdown until a serviceperson could balance the fan (see JD032).[14]

Julian Day 31: 1° to 11° C; 761 mm Hg

Shutdown of the Burnout Control system continued. Borehole temperatures were monitored. The gas sample system was replumbed to allow for back flushing of the remote sampling lines and the replacement of copper lines with stainless steel or plastic.

Julian Day 32: -6° to 3° C; 765 mm Hg

The fan was balanced and the system started by 1500 h. The actuators at both stations 6 and 7 required manual control due to continued malfunction of the electrical controls. The addition of burning charcoal through boreholes 3 and 15 was continued. At 1900 h, the manifold temperature was 432° C.

Julian Day 33: -6° to 6° C; 772 mm Hg

Burning charcoal additions were continued through boreholes 3, 5, and 15. Permeation tube dryers were installed in the gas sampling system to aid in removal of moisture, which was still plaguing the on-line gas analyses. The manifold temperature was 525° C at 1700 h.

Julian Days 34 through 36: -8° to -1° C; 762 to 770 mm Hg

Burning charcoal additions were continued; the manifold temperature was 550° to 580° C. To determine the effect of airflow through surface cracks, many of the larger ones were filled with gravel-grout-sand mixtures and covered with a plastic sheet. No significant changes in station 1 temperature or gas flow (approx 4,500 scfm) were noted.

[13] Over the course of the next 3 weeks, a total of approximately 1,000 lb of burning charcoal briquets were dropped into various boreholes in the eastern field.

[14] "JD" refers to Julian Day.

Julian Days 37 through 42: -19° to 1° C; 768 to 768 mm Hg

All systems were running smoothly. Charcoal additions were continued sporadically. Manifold temperature increased to about 600° C. Borehole studies were carried out to evaluate their influence on the exhaust output. Setting the vacuum level at station 1 first at 4.5 in H_2O and then at 14.5 in H_2O, each borehole was individually opened and closed to see its effect on manifold temperature and flow. Little effect was observed. This prompted the decision that additional boreholes be drilled in a pattern chosen to promote more uniform fire propagation around the manifold. The first of these holes (borehole 82) was drilled and cased about 20 ft from the manifold. It demonstrated good suction with a downhole temperature of 23° C.

Several times during JD042, the diesel generator shutdown for no apparent reason. In each case, the startup was accomplished within a few minutes.[15]

Julian Day 43: -14° to 0° C; 772 mm Hg

At 0500 h the manifold temperature was 613° C; boreholes 3, 5, 15, and 27 each showed temperatures greater than 200° C. Borehole 83 was drilled and cased accompanied by the emission of yellow smoke from the opening. When the drill bit was removed, flames were visible at the bottom of the hole, 35 ft below the surface. At 1730 h, the manifold temperature had risen to 704° C.

Julian Days 44 through 49: -8° to 5° C; 765 to 762 mm Hg

The manifold temperature varied slowly between 600° and 700° C. Boreholes 84 and 85 were drilled as part of the continuing effort to obtain a symmetrical burn pattern about the manifold. Likewise, burning charcoals were dropped down nine boreholes.

Julian Days 50 through 53: 0° to 6° C; 759 to 760 mm Hg

Manifold temperatures varied about the 600° C value during JD050 through JD053. A series of borehole temperatures were taken. Problems encountered with the fan damper suggested that one or more of the damper blades were loose. It was decided to correct the problem during the next occasion for the fan shutdown.

[15]It was later determined that operating a walkie-talkie from the generator trailer resulted in transmissions, which triggered the low-voltage limit switch on the control panel for this particular diesel generator.

Julian Day 54: -2° to 12° C; 764 mm Hg

In spite of the fact that some borehole temperatures were higher than 200° C, and at least three active hot zones had been identified, the manifold temperature did not appear to be affected by changes in borehole openings. It was believed that the fresh air being pulled into the open boreholes, cased only to the top of the seam, might be migrating through the fractured rock strata above the coal seam rather than through the seam itself. In an attempt to correct this situation, new casings would extend to the bottom of the seam as opposed to terminating at the roof of the mine as was previously done. These new casings were perforated over the bottom several feet to better direct air to the level of the burning coal. Also, 2-in diameter casings with perforated ends were placed directly into several original 4-in boreholes (e.g., borehole 82). There was no immediate obvious effect of these new casings on station 1 output.

One of the five stainless steel tubes in a buried portion of the heated tube bundle from station 3 corroded through internally. The corrosion occurred at a low point where moisture could accumulate inside the tube.

Julian Days 55 through 60: -14° to -4° C; 759 to 767 mm Hg

Manifold temperature varied between 500° and 600° C. Borehole 86 was drilled and cased using the new length casings. To control subsidence effects around the manifold, the manifold support girders were jacked-up about 7 in at the center and held in place with timbers. The ground area in the vicinity of the manifold was then sealed with gravel and covered with a plastic sheet.

A borehole TV camera was used to observe the strata below the casing of several cold boreholes. For the most part, the strata were collapsed, the largest open void space being about 1 ft across.

The remote gas sampling system was modified to include a nitrogen backflush on the heated tube bundle lines and an air backflush on the analyzers in a continuing effort to eliminate the deleterious effects of moisture on the remote on-line gas analyses.

Boreholes 1, 2, 3, 14, 25, 27, 83, and 86 all had temperatures greater than 200° C.

Julian Days 61 through 62: -11° to 2° C; 764 mm Hg

Flow tests were carried out in which the value of vacuum measured at station 1 (PVAC1) was increased from 6.85 in H_2O to 20.62 in H_2O in steps of about 1 in H_2O with about 10 min between steps to stabilize the flow. The flow at station 1 (scfm) varied between 5,200 and

11,500 scfm, but other station 1 exhaust parameters (e.g., [CO], [O_2], and temperature) remained relatively constant, presumably because of the longer response time. The vacuum-flow data (fig. 5) were well fit by the equation (PVAC) = 4.59 × 10^{-5}(scfm)$^{1.39}$, having a variance of R^2 = 0.999. The appearance of an exponent to the flow variable (scfm) between 1 and 2 suggests a combination of darcy-flow and pipe-flow occurring underground.

Julian Days 63 through 64: -5° to 10° C; 759 to 759 mm Hg

Additional flow test data were obtained. The manifold temperature at 0400 was 532° C with little variation during the day. At 2020 h on JD063, when a severe rain storm hit the site, the manifold temperature suddenly dropped over 100° C. An inspection of the site revealed that water, draining across the surface of the fire zone areas, was apparently being drawn into the mine through the surface cracks and crevices. During the next 20 h, the manifold temperature slowly returned to its value before the rain (550° C).

Julian Days 65 through 70: -7° to 17° C; 765 to 761 mm Hg

Manifold temperatures were maintained in the 500° to 550° C range. Minor problems were continuing to plague the gas sampling system (e.g., malfunctioning of the sample pump and clogging of the permeation tube dryer).

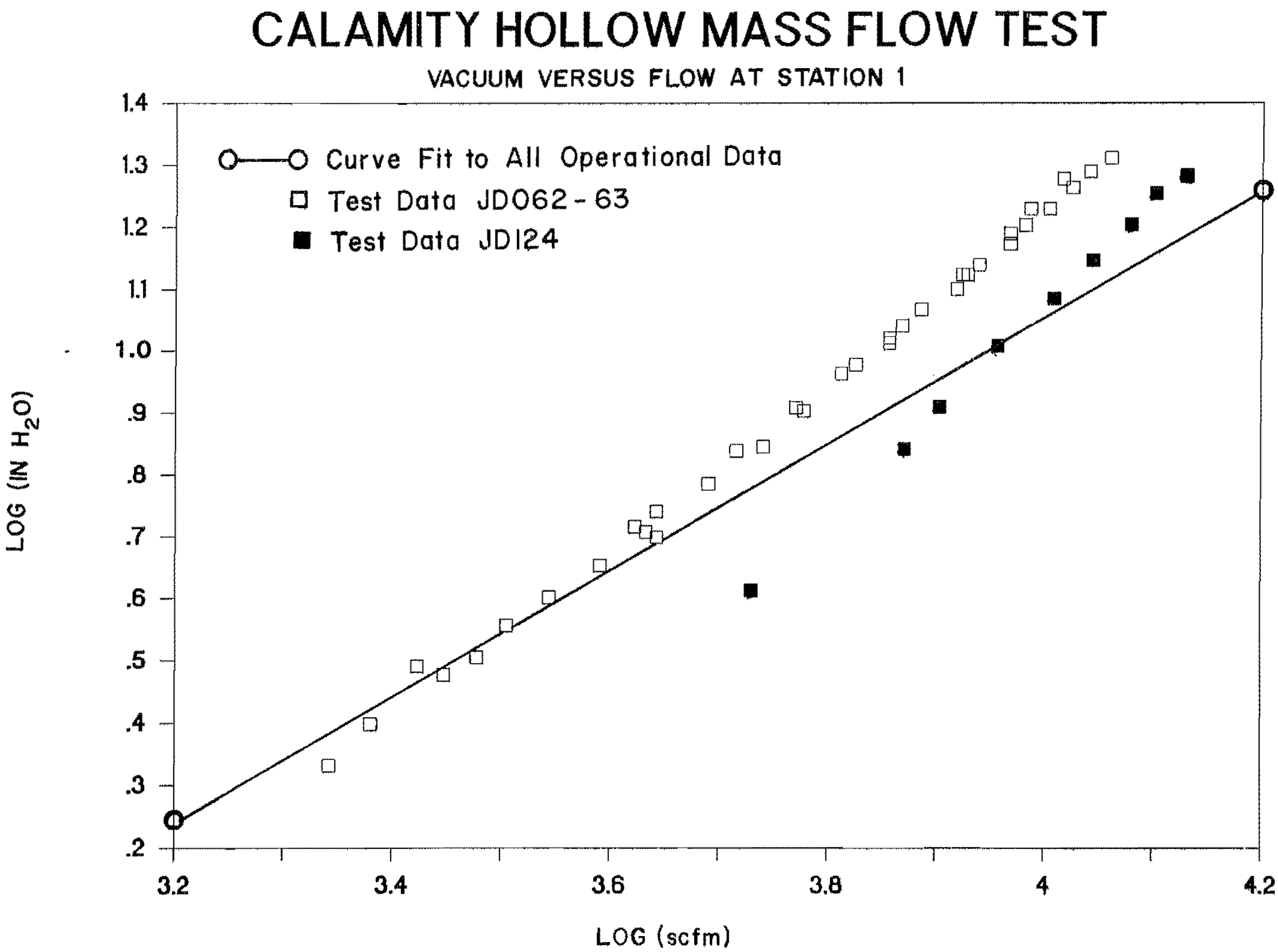

Figure 5.–Vacuum versus flow at the exhaust manifold (station 1).

These problems were readily fixed. It was also discovered that the magnetic tape recording unit had not functioned properly for about 2 weeks because of improper mounting. Data from the time period when the magnetic tape recording unit was not working was retrieved from the data logger's paper tape printout.

Julian Day 71: 5° to 16° C; 763 mm Hg

At 0730 h, the system was shutdown for required routine maintenance of the diesel generator. During the oil change, weather balloons were inserted in the duct near station 7 to protect the fan blades from corrosive vapors. During the shutdown, yellow smoke came from borehole 4. Also, popping noises were heard in the manifold, which had been sealed-off from the duct by closing the slide gate valve at station 5. These noises were presumably from explosions in the fuel-rich pyrolysis products, which were still being evolved underground. These explosions were completely contained and created no problem. The dropout tank was drained of about 2 in of condensate.

The system was started up at 1250 h without incident; the exhaust temperature at station 1 quickly rose to a relatively steady value of 520° C.

Julian Days 72 through 74: 1° to 17° C; 753 to 766 mm Hg

Manifold temperatures were in the range of 600° C and running fairly steady. Pressure distribution in the underground fire zone was measured at 48 closed boreholes, with the station 1 vacuum at 8 in H_2O. An eye-ball estimate of the isobar contours (fig. 6) describing the underground vacuum indicated that a major flow of gas was coming from the isolation trench north of the manifold, and from the outcrop south of the manifold. This could account for the difficulty of maintaining a symmetrical burn zone about the exhaust manifold.

Surface subsidence measurements indicated a 4-in drop in the exhaust manifold.

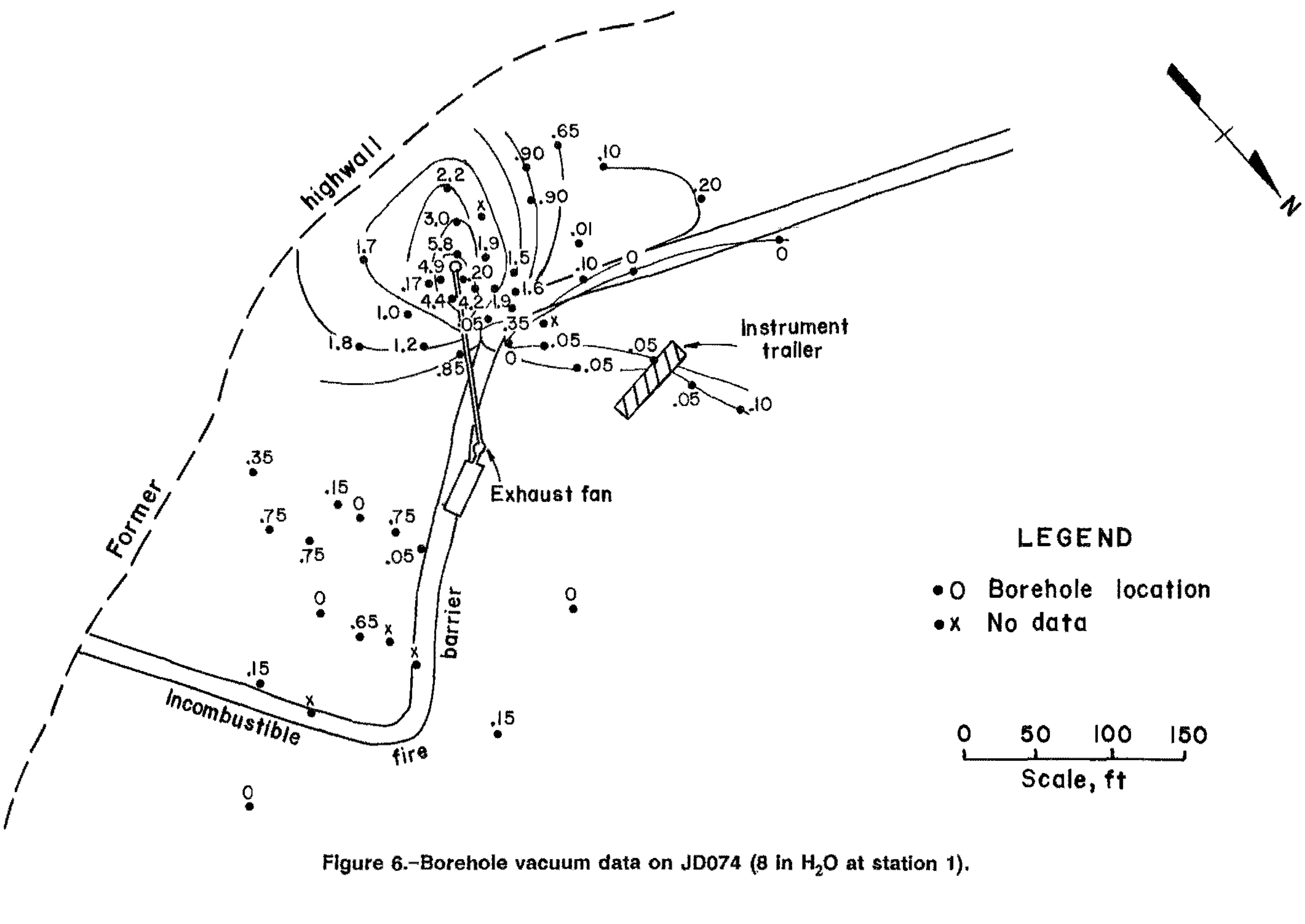

Figure 6.–Borehole vacuum data on JD074 (8 in H_2O at station 1).

Julian Days 75 through 77: 2° to 15° C; 761 to 767 mm Hg

Manifold temperature was in the range of 600° to 700° C. Two rainstorms occurred; both caused sudden drops in the exhaust temperature. The first storm occurred in the morning JD075, and the 100° C temperature drop recovered in about 3 h. The second rainfall occurred in the afternoon, and resulted in a 200° C temperature drop, which took about 7 h to recover. Again it appeared that surface water runoff, across the fire zone area and into the mine through surface cracks and fissures, was responsible for the drop in temperature. To prevent further episodes of this type, a drainage ditch was constructed around the fire zone portion of the site to divert the surface runoff. In addition, the larger surface cracks and fissures were filled in with dirt and covered with a plastic sheet.[16]

Julian Days 78 through 82: -3° to 14° C; 765 to 763 mm Hg

During most of this time period, the vacuum settings were maintained fairly steady at 6 to 8 in H_2O. Manifold temperatures drifted from 710° C to 630° C, while thermal output remained fairly constant at about 3.5 MW. On JD082, the vacuum was lowered to about 4 in H_2O, which seemed to lead to a decrease in output temperature along with decreases in flow and thermal output. Few problems were encountered except for the usual ones of maintaining the remote gas sampling system free of moisture.

Julian Days 83 through 88: -12° to 17° C; 760 to 776 mm Hg

Vacuum levels at station 1 were increased to between 14 and 19 in H_2O, which increased the thermal output to between 5 and 6 MW. Exhaust temperatures did not respond as noticeably - staying in the 550 to 610° C range. Boreholes (BH) 87, 88, and 89 were drilled and cased with BH 88, 5 ft from BH 87, apparently terminating in a pillar. Temperatures greater than 200° C were recorded for boreholes 2, 25, 27-28, and 83 through 88 with flames or orange glows observed at the bottom of several of the holes. Interestingly, some of these hot holes would heat-up and/or cool-down from day to day. Borehole 87, which was cased only to 20 ft (i.e., halfway to the coal seam), apparently became clogged at 15 ft above the seam.

[16]The drainage ditch was apparently successful in that an extensive rainfall on JD090 had no observable effect on the manifold exhaust.

Julian Days 89 through 91: 3° to 21° C; 768 to 763 mm Hg

Boreholes 90 through 93 were drilled in the area around BH 15. During drilling BH 90, material resembling red dog was logged at 18 ft, and sulfurous smoke appeared at 27 ft. Temperatures over 200° C were recorded for boreholes 1, 5, 27, 84 through 86, and 89. Subsidence and surface cracks were noticeable about the area of the manifold, which prompted filling of some of the larger cracks, and further propping of the manifold support girders.

An intense rainstorm accompanied with high winds occurred on JD090. Minimal damage occurred despite a temporary power failure and considerable surface water runoff. The drainage ditch, previously constructed around the fire area, diverted the water runoff sufficiently so that no effect on the manifold temperature (580° C) was observed.

Julian Days 92 through 96: -7° to 19° C; 763 to 743 mm Hg

During this time period, the cracked and corroded portion of the horizontal duct near the cooling water sprays was repaired by welding a suitably curved plate over the affected area. At the same time maintenance was carried out on instrumentation and the remote sampling system. Vacuum levels of 1 to 3 in H_2O, which did not interfere with the welder's arc, maintained the power output at a reasonable operational level (580° C and 2.5 MW).

Borehole 94 was drilled into a pillar. Temperatures over 200° C were recorded for boreholes 5, 15, 25, 27-28, and 84 through 89.

Julian Day 97: -8° to 0° C; 765 mm Hg

At 1000 h, the manifold temperature was 581° C with the vacuum maintained at the relatively low level, 4 in H_2O. Boreholes 95 and 96 were drilled and cased to 27 and 39.5 ft, respectively. A simple borehole intercommunication test was carried out by injecting air under pressure (from an air compressor) into one borehole and observing the surrounding boreholes. Air injected into BH 5 resulted in steam or smoke being emitted from BH's 86, 88, and 89. Air injected into BH 94 (presumed to be drilled into a pillar) led to emissions from BH's 86 and 89. Air injected into BH 96 was emitted from BH 94.

Julian Days 98 through 100: -10° to 6° C; 767 to 764 mm Hg

At 1300 h of JD098, the vacuum level at station 1 was increased from 4 in H_2O to 8 in H_2O resulting in the manifold exhaust flow rate quickly increasing from 6,500 to 8,800 scfm. The exhaust temperature as usual did not respond, but remained at its previous value of 570° C, yielding a thermal power output of 3.7 MW.

Borehole 97 was drilled and cased. A borehole vacuum survey was carried out on holes within 50 ft of the exhaust manifold.

A momentary system power failure occurred at 0826 h on JD099. The system was quickly restarted without incident and the vacuum again set to 8 in H_2O.

The SOX and NOX analyzers, after being out of service for some time, were brought on-line. SOX and NOX concentrations of 150 and 36 ppm, were recorded respectively. Combustion efficiency was not 100 pct as evidenced by a relatively high [CO] level of >1,000 ppm; the [O_2] and [CO_2] were at 14 and 4 pct, respectively.

Julian Days 101 through 104: -6° to 20° C; 761 to 763 mm Hg

A planned shutdown of the generator for oil change was made mandatory by the occurrence of excessive fan vibration and noise as if something solid hit the fan (possibly a balancing weight or some part loosened from the exit damper). After the fan was balanced and restarted during JD103, the vacuum was set to about 13 in H_2O. The power level quickly climbed to 4.5 MW as the exhaust temperature, initially at 490° C, slowly climbed to 550° C.

Boreholes 98 through 104 were completed; good suction being observed at all except BH 100. Temperatures over 200° C were noted at boreholes 5, 15, 25, 84 through 86, 89, 93, 94, 96, and 98.

Julian Days 105 through 108: -1° to 26° C; 764 to 765 mm Hg

Boreholes 105 through 112 were drilled and cased in the lower field near boreholes 93 and 98. Except for boreholes 8 and 9, all exhibited slight to good downdrafts. The manifold support beams were jacked-up 3 in and additional timber support set in place.

The Burnout Control system was run at elevated vacuum levels (about 16 in H_2O) for several days to establish a high level of thermal output (about 5 MW). The exhaust temperatures varied between 570° and 600° C over the time period, while the [CO] and [O_2] remained fairly constant at 400 ppm and 14 pct, respectively. During this high level output it was found necessary to increase the water spray flows to as much as 16 gpm.

Julian Day 109: 3° to 23° C; 765 mm Hg

Between 0 and 0200 h, station 7, which monitored the gases going into the fan, exhibited a significant drop in temperature from 146° to 54° C. Visual inspection of the dropout tank showed it to contain a substantial quantity of water that was subsequently drained through an existing drainage pipe (taking about 25 min). During draining, the temperature at station 7 quickly returned to a normal value of about 150° C. The water sprays were then decreased to 14 gpm. The 3-in drainage valve was left open for continuous removal of water from the dropout tank; the water being piped directly to BH 10.

With all the boreholes open and the vacuum at 15.4 in H_20, the temperature at station 1 was 560° C with a flow of 11,900 scfm yielding a thermal output of 5 MW.

Julian Days 110 through 111: 3° to 19° C; 765 to 761 mm Hg

The I-beams supporting the manifold were jacked-up about 6 in to accommodate additional timber supports. The expansion joint continued to expand; over 4 months the total expansion amounted to about 5 in, probably to compensate for downhill ground slippage at the manifold. The surface around the manifold still had numerous cracks forming, some of which demonstrated considerable suction. However, these cracks did not appear to affect the exhaust output. In any case, they were readily sealed with dirt and/or a plastic cover.

Boreholes 113, 114, and 115 were drilled and cased with plastic pipe to a depth of 5 ft. Temperature measurements indicated that 16 boreholes had temperatures higher than 200° C (1, 5, 15-16, 25, 84, 86-87, 89, 90, 93 through 96, 113, and 115).

The station 1 output remained fairly steady at 580° C and 5 MW. Problems with the on-line gas sampling of SOX and NOX in the exhaust prevented continuous reliable monitoring of air pollution parameters.

A camera crew from the Bureau arrived to record on film and video tape the Calamity Hollow Burnout Control operations.

Julian Days 112 through 115: -2° to 24° C; 769 to 766 mm Hg

The Burnout Control system was operated at a station 1 vacuum slightly over 16 in H_2O. The manifold exhaust gave about 5 MW thermal output at 570° C. Combustion efficiency was fairly good at [CO], [CO_2] and [O_2] levels of approximately 450 ppm, 5.5 and 14.5 pct, respectively. At station 4, the exhaust to the atmosphere had a SOX level of 120 ppm and a NOX level of 11 ppm. The fan motor was very steady at 340 A and 480 V indicating an electrical power usage of 0.24 MW. The cooling water sprays were set at a steady 18.5 gpm.

Julian Days 116 through 117: 4° to 16° C; 761 mm Hg

The steady operations continued, however, the exhaust temperature started a slow downward drift, losing about 50° C over the 2 days, despite raising the vacuum at station 1 to 18 in H_2O for about 24 h.

To see if the airflow through those boreholes, which were assumed to terminate in pillars could be increased, explosive charges of Torvex (up to 4 lb per shot) were set-off in BH's 102, 104, and 109. In each case there was a noticeable increase in air suction at the borehole (up to 200 scfm), but there was no observable change in the manifold exhaust.[17]

Work was initiated on installing the water quenching system preparatory to cooling and excavating the site (*4*).

At 0750 h of JD117, the fan was shutoff when a backhoe inadvertently severed a buried 110 V powerline to the fan control switch. Power to the fan was restored within one hour; within two hours the manifold temperature was at 535° C, and the CO, CO_2, and O_2 were 540 ppm, 3.5 and 16.0 pct, respectively.

Julian Day 118: 1° to 15° C; 768 mm Hg

Manifold temperature continued to decline, approaching 510° C. The vacuum level was reduced to about 13.5 in H_2O (or 11,000 scfm) to observe its effect on the temperature decline. The temperature did seem to stabilize over the next 36 h between 490° to 500° C with a thermal output of about 4 MW.

In a communication test, BH's 95 through 97 were interconnected with a manifold pipe, which in turn was connected to a small blower. When air was blown into these boreholes, smoke was emitted from boreholes 3, 16, 87, 94, and 113 through 115. This test also had the effect of increasing the temperature of three other distant boreholes (98 through 100) to over 200° C from the previous days' values of about 25° C. It would appear that the injected air might have enhanced the combustion of coal in the vicinity of these other holes, which were about 160 ft away from where the air was injected.

[17]During excavation of the site, there was no discernible effect of these explosive charges on the strata at mine level; however, the effects could have been masked by the excavation operation.

Julian Days 119 through 120: 0° to 20° C; 771 to 770 mm Hg

Excessive vibration of the fan was observed along with damage to various signal wires and electrical line conduits that had pulled apart. These were repaired and the fan balanced. At 1800 h of JD120, when the fan was restarted, the manifold temperature was 750° C. With the vacuum level maintained at 10 in H_2O, over the next 6 h the manifold temperature slowly decreased to about 500° C.

Julian Days 121 through 123: 4° to 21° C; 766 to 765 mm Hg

In essence, these were the last days of operating the Burnout Control system. The operation was maintained steady at relatively low-thermal output, about 3 MW, while efforts were directed at getting the water injection system ready for quenching the fire zones (*4*). With the vacuum level at about 10 in H_2O, the manifold temperature continued to decline from 500° to 446° C on JD123 at 1000 h. The corresponding concentrations of CO, CO_2, and O_2 were 650 ppm, 3.4 and 16.3 pct, respectively.

Prior to shutdown of the fan, a vacuum communication study of all the boreholes was initiated with the station 1 vacuum maintained at 8.28 in H_2O. The manifold temperature climbed to 600° C during the 3-h test.

The fan was shutoff at 1420 h for the night. Smoke vented from numerous areas around the borehole casings and surface cracks. However, the amount of smoke escaping was readily controlled by using dirt to seal the venting areas.

Julian Day 124: 3° to 22° C; 768 mm Hg

At 0750 h, the fan was started in order to complete the vacuum communication study initiated yesterday. Borehole vacuum measurements on 10 holes completed the study at the station 1 vacuum of about 8 in H_2O. In addition, the vacuum-flow relationship at station 1 was determined over the range of 4 to 19 in H_2O (5,400 to 13,500 scfm). The fan was shutdown at 1410 h for the night. Quenching operations began the following day (May 5, 1982).

RESULTS AND DISCUSSION

OUTPUT DATA

General Comments

During the course of 120 days of operating the Burnout Control system, 35 channels of data from remote sensors and instruments that monitored temperature, vacuum level, dynamic pressure (i.e., flow), and gas composition were recorded automatically every 60 min by a data logger. In addition, much of this same information was also recorded hourly by hand (written) along with observations of other data of interest (such as fan or motor voltage and amperage, coolant water flow rate, etc.), which were not included in the automatic data recording system. A detailed discussion of the instrumentation and its use for process control and diagnostics can be found in reference 3.

The storage, processing, and presentation of these data (over 100,000 pieces) for interpretive and reporting purposes presented a formidable problem, even with the use of computerized calculations to convert the recorded voltage signals into engineering units (e.g., temperature, flow rate, oxygen concentration, etc.). A simple computer-drawn plot of output, such as the temperature versus time (*3*), constructed on a size scale appropriate for a Report of Investigations (figs. 7-8) is probably as confusing as it is illuminating. Here, the observed numerous spikes

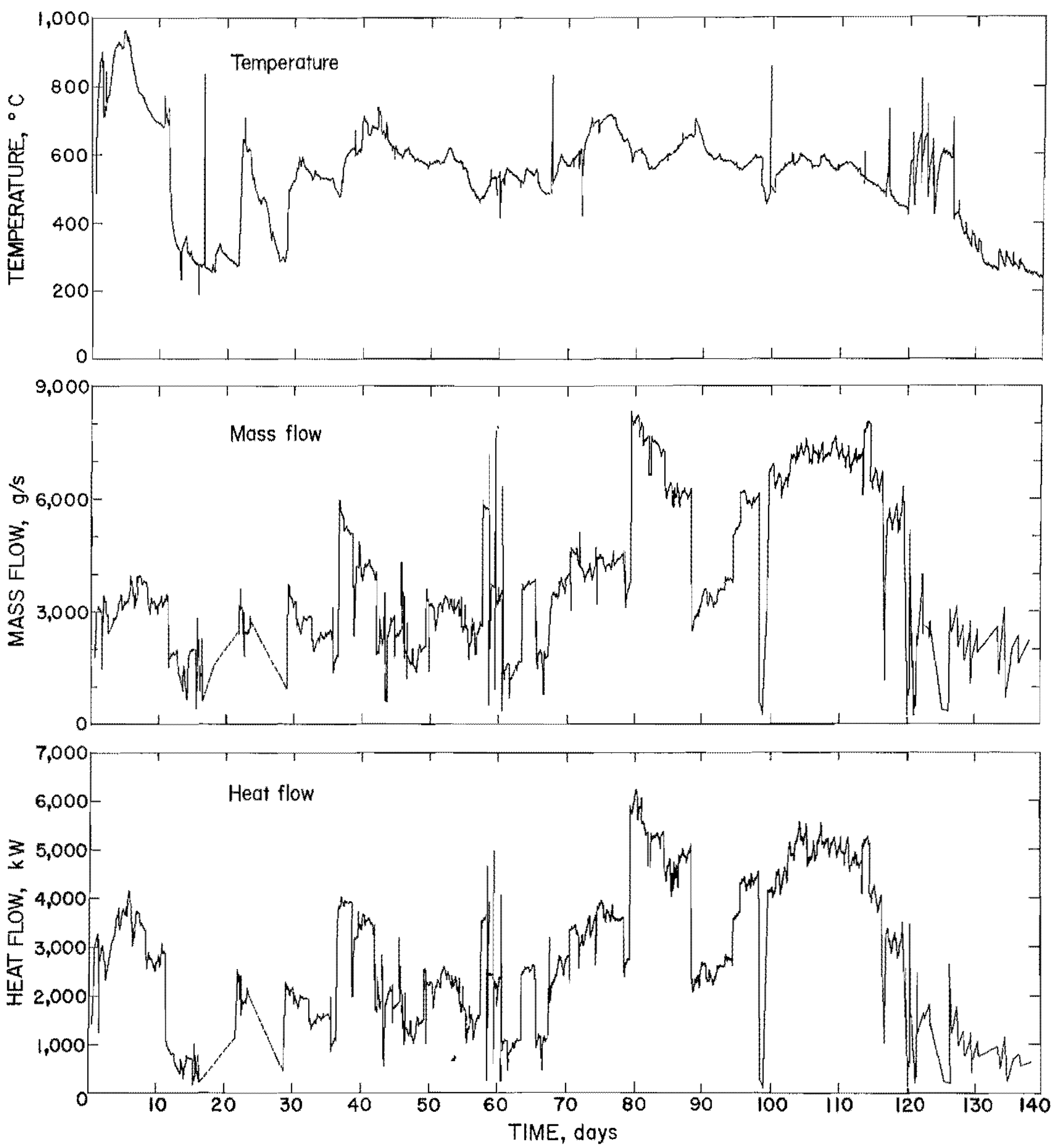

Figure 7.–Temperature, mass flow, and thermal power at station 1.

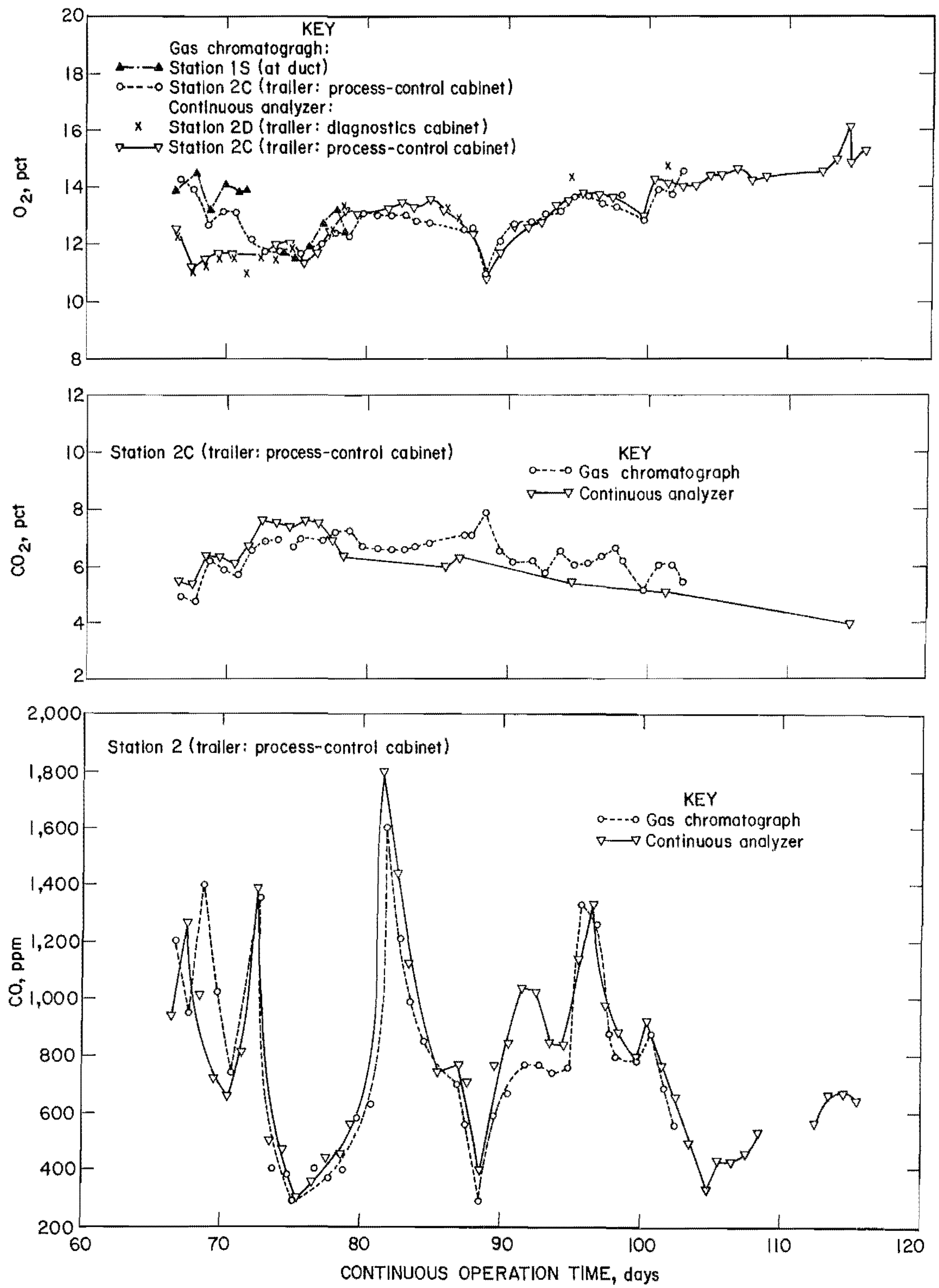

Figure 8.–Continuous and chromatographic analyses of O_2, CO_2, and CO concentrations.

and short-term trends are due primarily to changes in the process control settings. To relate each change in output to a specific alteration of some control setting would be extremely difficult, due in part to the fact that not all control setting changes were recorded. Also, relating a change in control setting to a specific change in output was complicated by the fact that response times for a change in output with a change in process control parameter varied widely for different outputs. For example, exhaust temperature appeared to take days to respond to a change in vacuum, while exhaust flow rates responded within minutes.

In scanning the tables of data constructed in spreadsheet form,[18] it seemed that a useful data display could be obtained by averaging the output of each day, and then representing the averaged data on a daily time line. This significantly reduced the number of spikes and number of points that would appear on the data-time plots. Also, by comparing the results of time weighted averaging versus numerical averaging for several days chosen at random, it was determined that simple numerical averaging would adequately represent the complete data field provided that those days when the fan was continuously off for a major portion of the time (>12 h) were excluded. Therefore, in the discussions to be presented, averaged results refer primarily to numerical averaging.

[18]An RS/1 software package (BBN Research Systems, Cambridge, MA) on the Bureau's VAX computer (Digital Equipment Corporation) was employed.

Vacuum Data

Figure 9 depicts a time plot in bargraph form of the daily averaged manifold vacuum levels at station 1, which

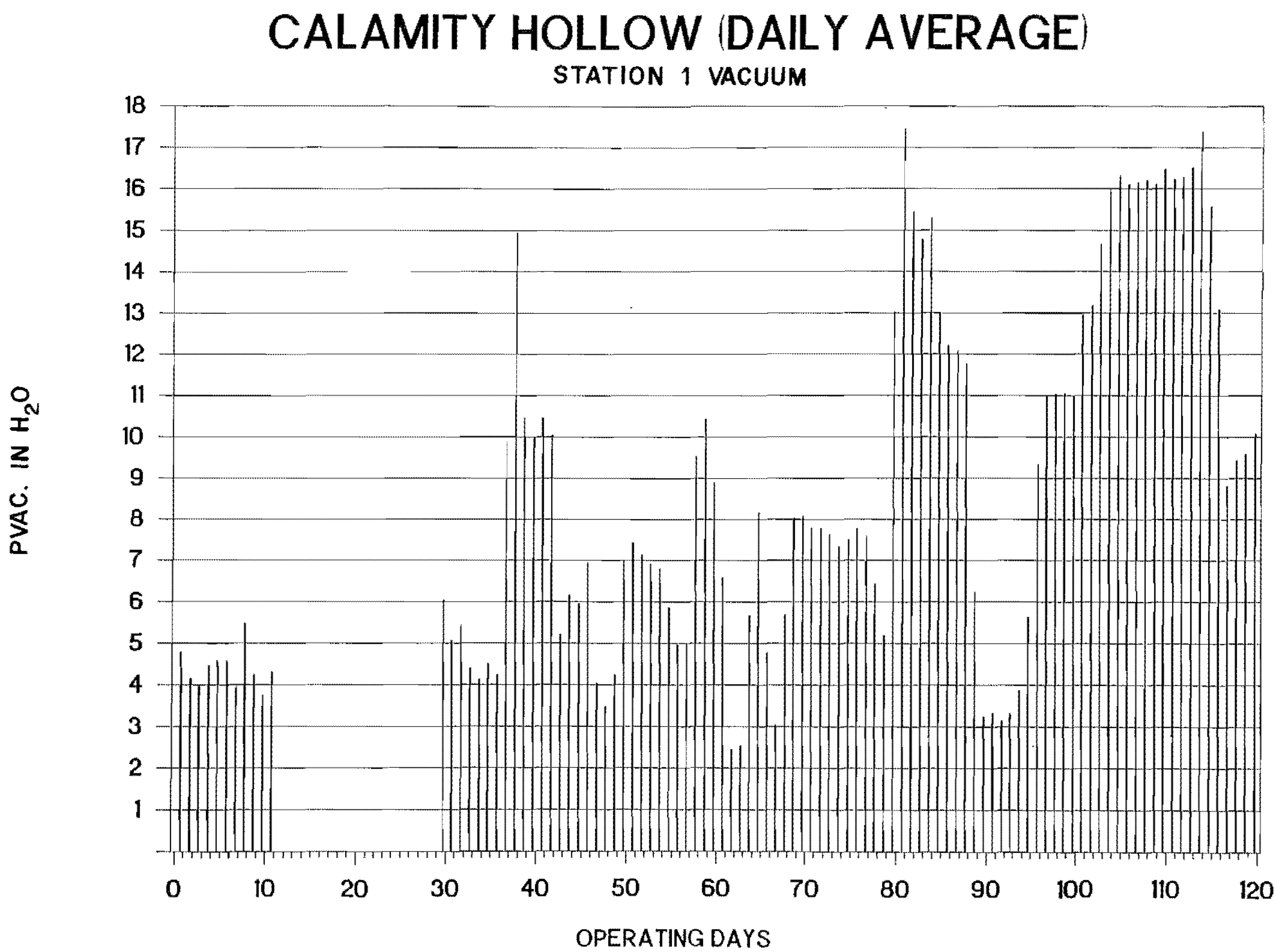

Figure 9.–Station 1 vacuum levels during operations.

is the first measuring point for the hot combusted gases as they exit the underground (fig. 4). The vacuum applied at the manifold is expected to be the principle process control parameter for establishing exhaust flow rate. Power output and combustion efficiency, as discussed later, are likewise controlled by the station 1 vacuum level. The vacuum at this station was altered by changes in (1) the damper (valve) settings for the fan near station 4, (2) the damper settings at the cold air inlets near stations 6 and 7, and (3) by changes in the amount of water spray cooling of the hot gases. In general, when a specific vacuum level was desired, the valve setting at station 6 was altered. However, this was sometimes accompanied by undesirable changes in exhaust gas cooling (by water spray and/or dilution air), so that several process controls would have to be altered at one time in order to obtain the desired operating level.

The vacuum at the exhaust manifold was communicated through the underground mine workings for up to several hundred feet and even beyond the isolation trench. Figures 10 and 11 depict isobar contours evaluated from vacuum measurements made at individual boreholes while maintaining vacuum levels of 8 in H_2O at station 1. Considering a borehole vacuum of 0.1 in H_2O or greater to indicate direct communication with the manifold, it is seen from figures 3 and 10 that boreholes as far away as 300 ft (e.g., BH 8 and BH 59) were communicating with the fan. If the flow were radially uniform about the exhaust manifold, this would mean that control of an underground fire zone as large as 7 acres could be achieved from the single exhaust point when maintained at an 8 in H_2O vacuum level. However, the contours in figures 10 and 11 indicate a nonuniform underground gas flow, and a communication area of about 2 acres.

The contours of figures 10 and 11 represent two different time periods, JD074 and JD124, respectively. They are sufficiently similar to suggest that burning had little effect on the underground communication, at least in the time between these periods. This was somewhat surprising since ground subsidence that did occur might be expected to alter the underground resistance to gas flow. It is possible that the major portion of subsidence (as discussed in "General Observations") actually occurred before JD074, and hence, its effect on the gas flows would not be apparent from vacuum measurements taken subsequently. Unfortunately, similar borehole vacuum data are not available for earlier time periods.

From the spatial distribution of pressure gradient as represented by the contours of figures 10 and 11, the dropoff in vacuum appears to be strongly influenced by the isolation trench. This suggests that the trench, being more porous and permeable than normal overburden, was acting as a short-circuit channel for airflow into the mine fire area. This in turn could lead to more rapid burnout of coal in regions directly between the trench and the exhaust manifold. It could also provide excess air in this region beyond that needed for combustion, and hence dilute the exhaust gas. The dilution effect was quite apparent from the observed exhaust temperatures and gas compositions.

Temperature Data

The bargraph in figure 12 shows the daily average exhaust temperature at station 1, with the vacuum data superimposed for comparison. The daily averaged temperatures ranged from about 400° C to over 900° C over the 120-day period with the highest values (700° to 900° C) occurring prior to breakdown of the diesel generator on JD015 (OD012).[19] The overall average temperature for 102 days of fan operation, excluding the time period OD012 to OD029 when the replacement generator was being brought on line, is 603°±104° C. The reason for the decline in exhaust temperature after OD029 is not known with certainty; however, the large amounts of oxygen in the exhaust (see "Gas Compositions" below) indicate that the combustion products were diluted with mine air, which had by-passed the major burn zones. This fresh air could have reached the exhaust by flowing through the strata above the coal, and/or through previously burned out or nonburning coal areas. In any case, the exhaust temperature stayed between 500° and 700° C for the remainder of the operational period after OD030.

Comparing the time trend of exhaust temperature with the vacuum at station 1 reveals no obvious correlation between the two parameters. A correlation might have been expected on the basis that increased mine air-flow should lead to more rapid coal burning, and hence, higher temperature. However, the very large thermal inertia of the burning mine (*4*) apparently precluded observing this effect. Perfunctory observations of the change of exhaust temperature with a change in vacuum suggest that at least several days were required before the exhaust temperature would respond to a new flow rate condition. Such a long time period implies that the exhaust temperature will not be a very useful process control parameter, even though it is significant in determining power level and combustion efficiency.

Several times during the operational burn, downhole temperatures were recorded for boreholes communicating with the manifold. These data have been discussed in part 5 of this report series relative to the probable directions of fire propagation. For this report, the

[19]"OD" referes to operating day. OD01 occurred on JD04, or the 4th of January.

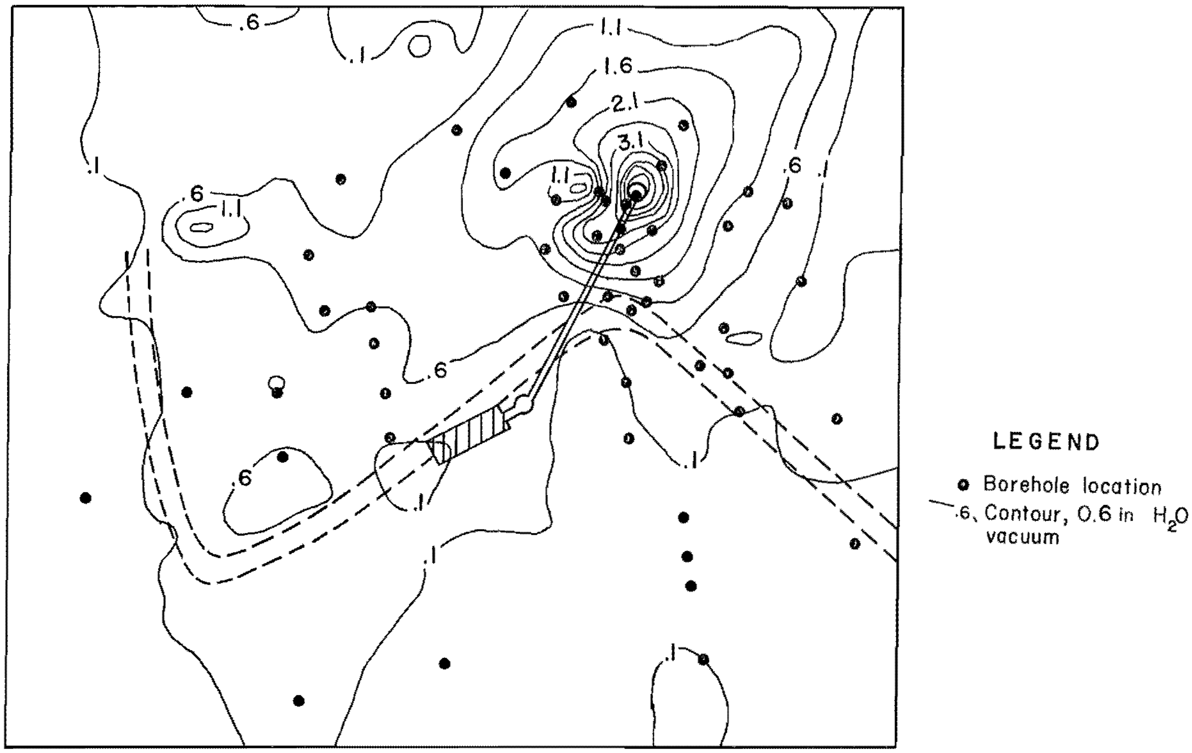

Figure 10.–Borehole vacuum distribution on JD074. Calculated contours range from 0.1 to 8.0 in H_2O at intervals of 0.5 in H_2O (5.6 to 8.0 in H_2O contours not shown).

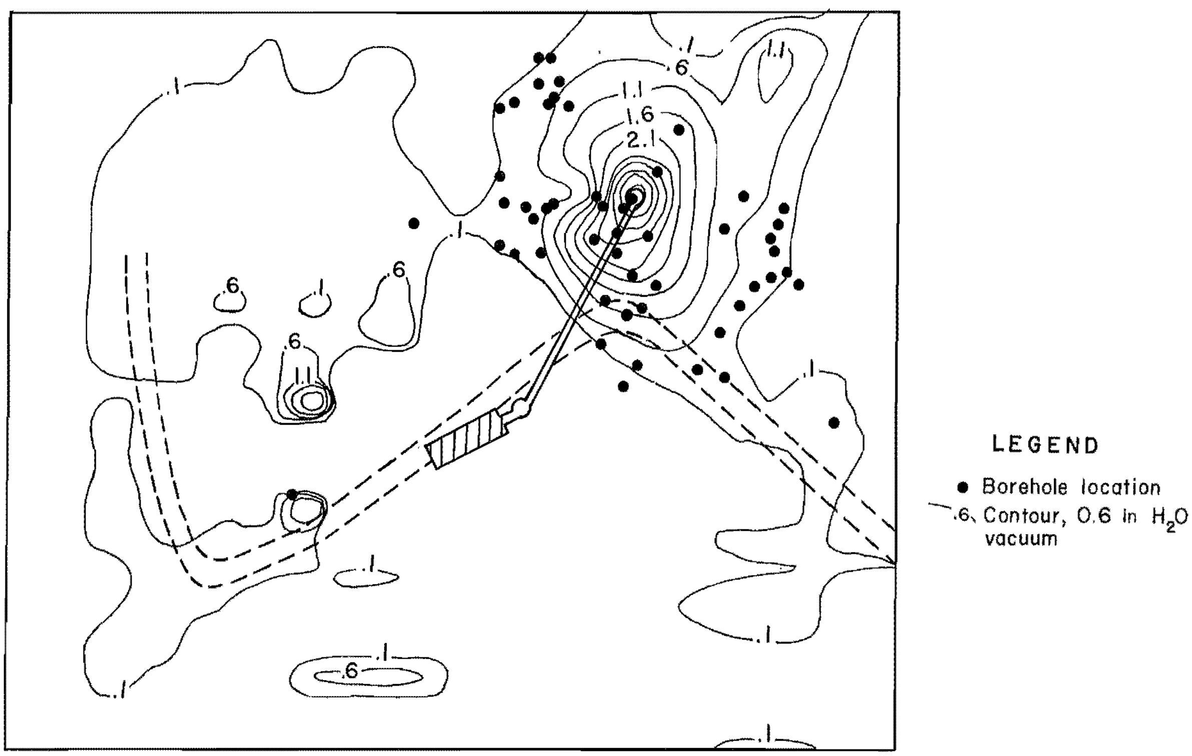

Figure 11.–Borehole vacuum distribution on JD124. Calculated contours range from 0.1 to 8.0 in H_2O at intervals of 0.5 in H_2O (5.6 to 8.0 in H_2O contours not shown).

borehole temperature data have been analyzed further using the same isopac contouring program as for the borehole vacuum data.

Figures 13 through 15 depict three isotherm plots that span the operational period. The contours range from 100° to 600° C in increments of 100° C. Their significance should be viewed with some caution; particularly when the contours enclose an area that contains no measured data points. Such contours probably represent an artifact of the isopac program algorithm. However, even with this caution, it is apparent that the initial fire zone (on JD008) was located primarily in a relatively narrow region about 100 ft to the southwest of the manifold towards boreholes 21 (105° C) and 14 (201° C). By JD047, this initial fire zone decreased in intensity, while the fire spread to areas about 100 ft south and 100 ft east of the manifold (fig. 14).

By the end of the burnout trial (fig. 15), the borehole temperatures indicate that the fire advanced about 75 ft further east of the manifold along the isolation trench. These isotherms are consistent with the findings of the excavation phase of the project when the entire 1 acre fire zone was excavated and quenched (5). The physical evidence at that time indicated the Burnout Control fire zone to be 120 to 140 ft from the manifold along specific paths of combustion.

Mass Flow Data

Figure 16 depicts a bargraph time plot of the daily averaged exhaust mass flow, expressed as standard cubic feet per minute (scfm) at station 1. For comparison, the vacuum data are superimposed on the bargraph. With

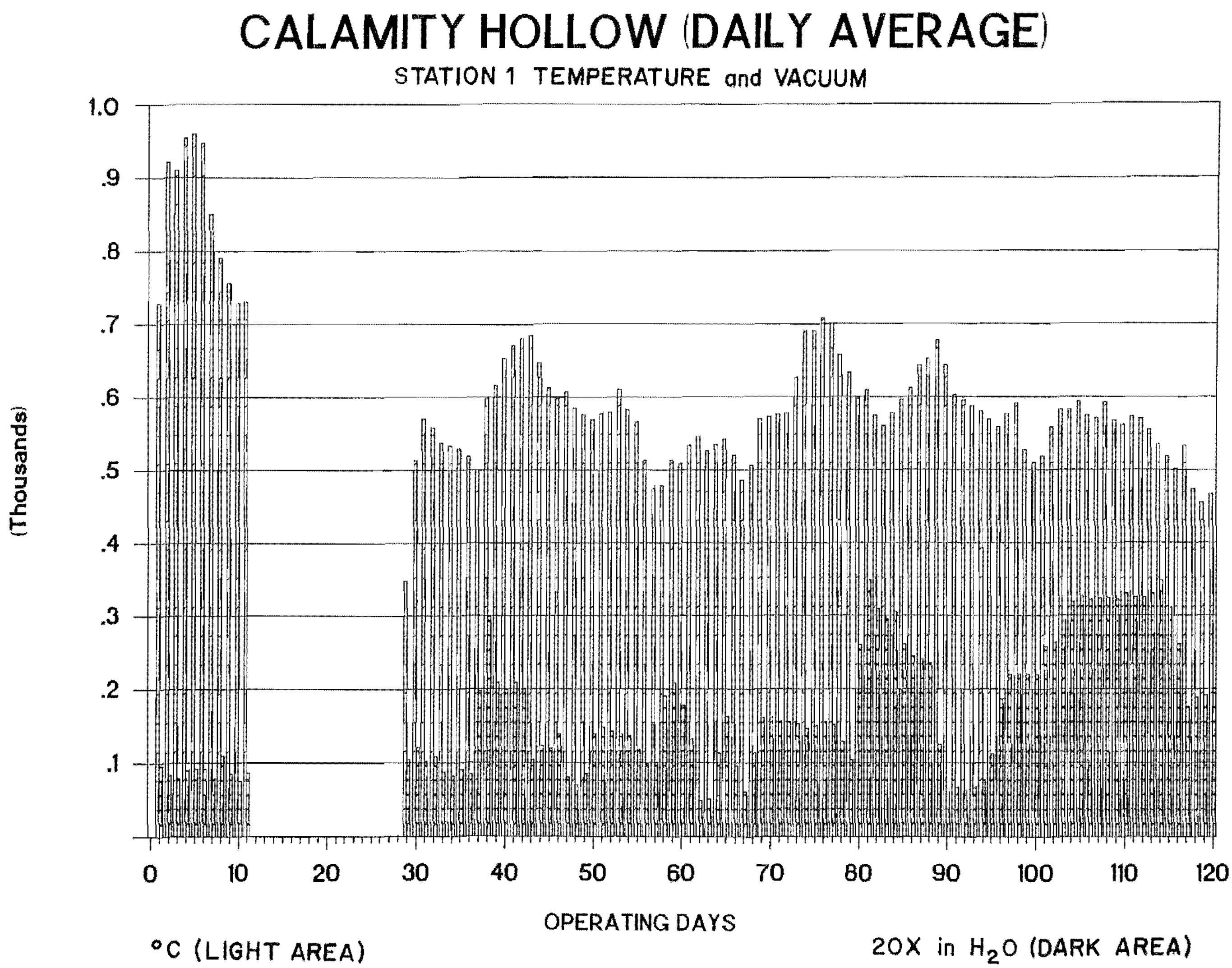

Figure 12.–Exhaust gas temperature and vacuum at station 1.

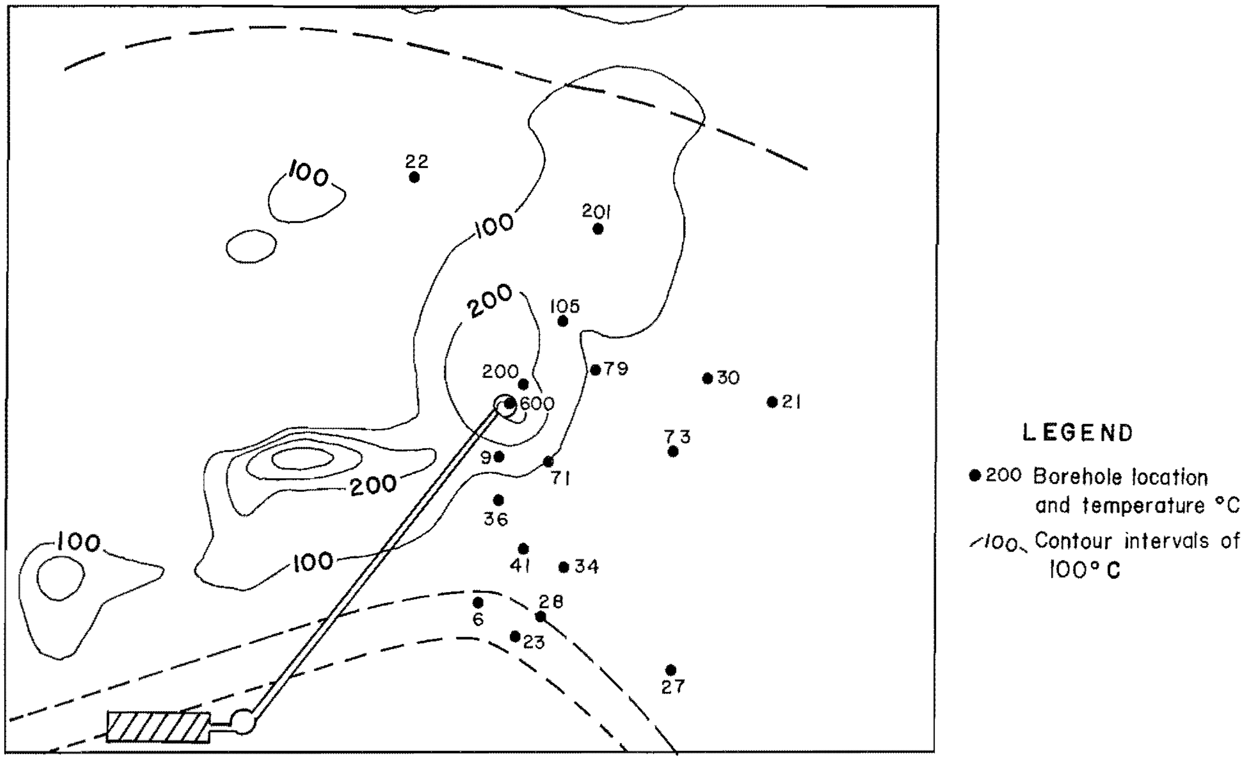

Figure 13.–Borehole temperature distribution on JD008. Calculated contours range from 100° to 600° C in intervals of 100° C (300° to 500° C contours not shown).

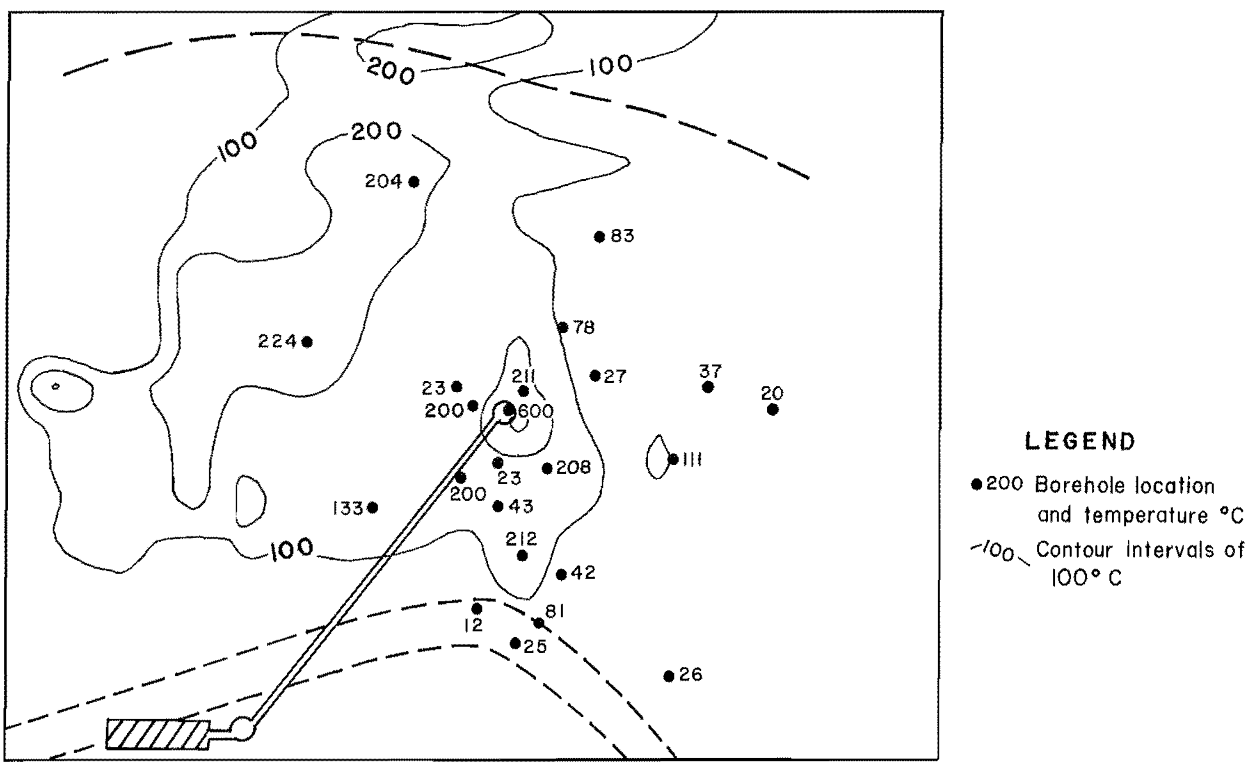

Figure 14.–Borehole temperature distribution on JD047. Calculated contours range from 100° to 600° C in intervals of 100° C (300° to 500° C contours not shown).

vacuum levels varying from 4.5 to 17.3 in H_2O, the exhaust flow varied between 4,000 and 13,000 scfm. It is readily seen that the mass flow and vacuum correlate very well. In general, it was found that the response time for a change in manifold flow with a change in vacuum was on the order of 5 to 10 min.

The quantitative relationship between vacuum and flow was examined in two ways. First, specific field tests lasting several hours were carried out in which the vacuum at station 1 was increased every 10 min. Flow rates were determined with an arrangement of boreholes either opened or closed. These data, corresponding to the two different time periods, JD062-63 and JD124, are shown in figure 5. The data on JD062-63 include results for various combinations of boreholes being opened and closed, which had little apparent effect on the manifold flow. Also shown in figure 5 is the best fit of the flow equation

$$(PVAC) = R * (scfm)^N \qquad (1)$$

where PVAC = vacuum in mine at the exhaust manifold; approximated by the vacuum measured at station #1,

R = overall effective resistance of the mine to gas flow,

* = symbol for arithmetic multiplication,

scfm = standard cubic foot per minute flow measured at station #1,

and N = numerical exponent

to all 3,000 data points taken during the operational phase. For darcy flow, the exponent N would have a value of 1, while for pipe flow, N would have the value of 2. The best fit values and their standard deviations for all three sets of data are listed in table 1.

It is clear that the test data are curve-fit exceedingly well by the flow equation with the value of N indicating an underground flow somewhere between pipe- and darcy-type. The test data also suggest that as the burnout operations proceeded, the flow became more pipelike. On the other hand, the curve-fit to all the operational data

Table 1.—Best fit values for $(PVAC) = R * (scfm)^N$

	R, 10^{-5} (in H_2O) * $(scfm)^{-N}$	N
TEST: JD062-63	6.09 (±) 0.23	1.36 (±) 0.01
TEST: JD124	.183 (±) .003	1.70 (±) .02
JD004-124	98.3 (±) 11.0	1.02 (±) .01

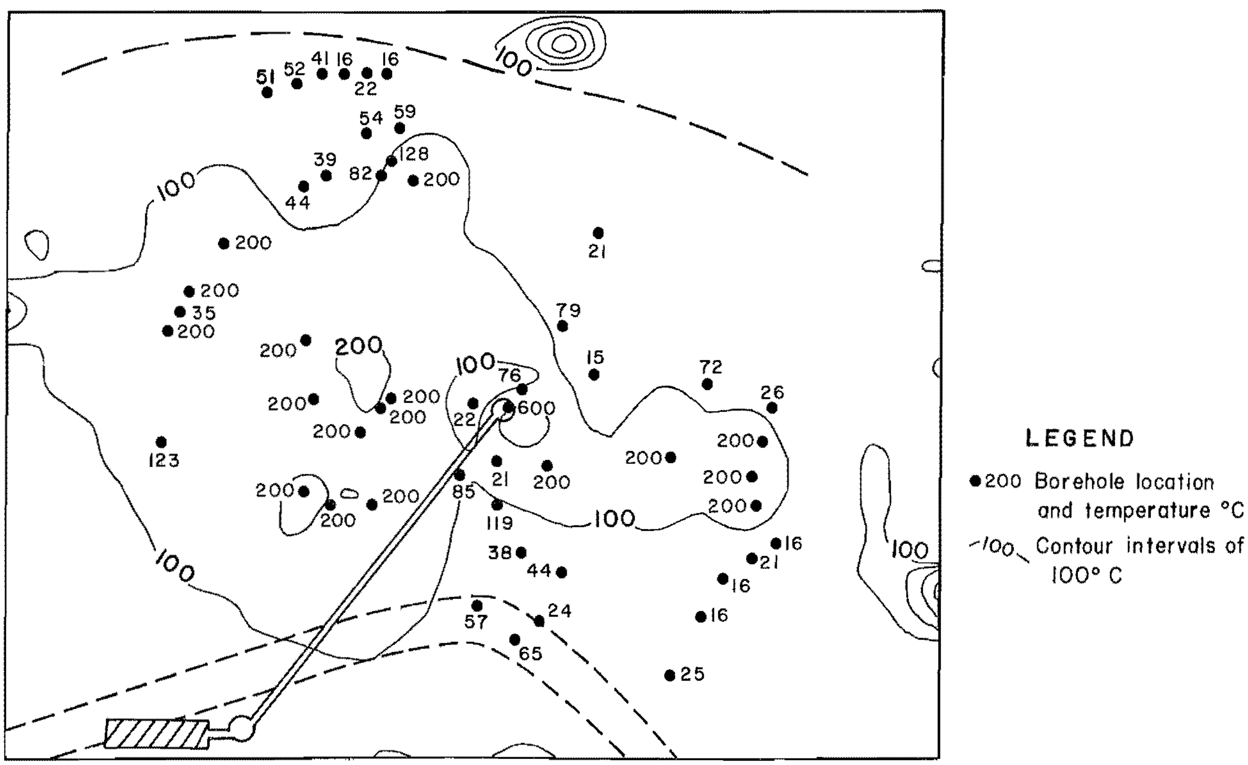

Figure 15.–Borehole temperature distribution on JD119. Calculated contours range from 100° to 600° C in intervals of 100° C (300° to 500° C contours not shown).

(JD004-JD124) yields a value of N indicative of essentially 100 pct darcy-type flow.

At the time of the actual flow tests, a mass flow that behaved between pipe- and darcy-type seemed quite reasonable. The mine with its open passageways would behave like a pipe, and the surrounding highly fractured strata would behave like a porous bed. However, the heated sections of the ground uncovered during site excavation after the burn (*5*) indicated that both the coal seam and surrounding strata were generally highly fractured and collapsed, which supports the darcy-type flow postulated from the operational data. The reasons for the apparent discrepancy between the test and operational mass flow data of table 1 are not clear. However, it is not unreasonable to conclude that darcy flow is the dominant underground flow process.

It is now useful to apply the porous flow model developed in reference 1 to the above findings. Assuming the underground gas flow to be steady-state, and radially symmetric in a pancake-like cylindrical volume about the manifold, Darcy's law of porous flow takes the form (*1*):

$$q(x) = [(2) * (pi) * (k) * (L) * (x/mu)] (dP/dx) \quad (2)$$

where q(x) = volumetric flow rate across a cylindrical surface of height, L, and radial distance, x, along the flow direction from the manifold,

k = effective permeability of strata,

mu = viscosity of gas,

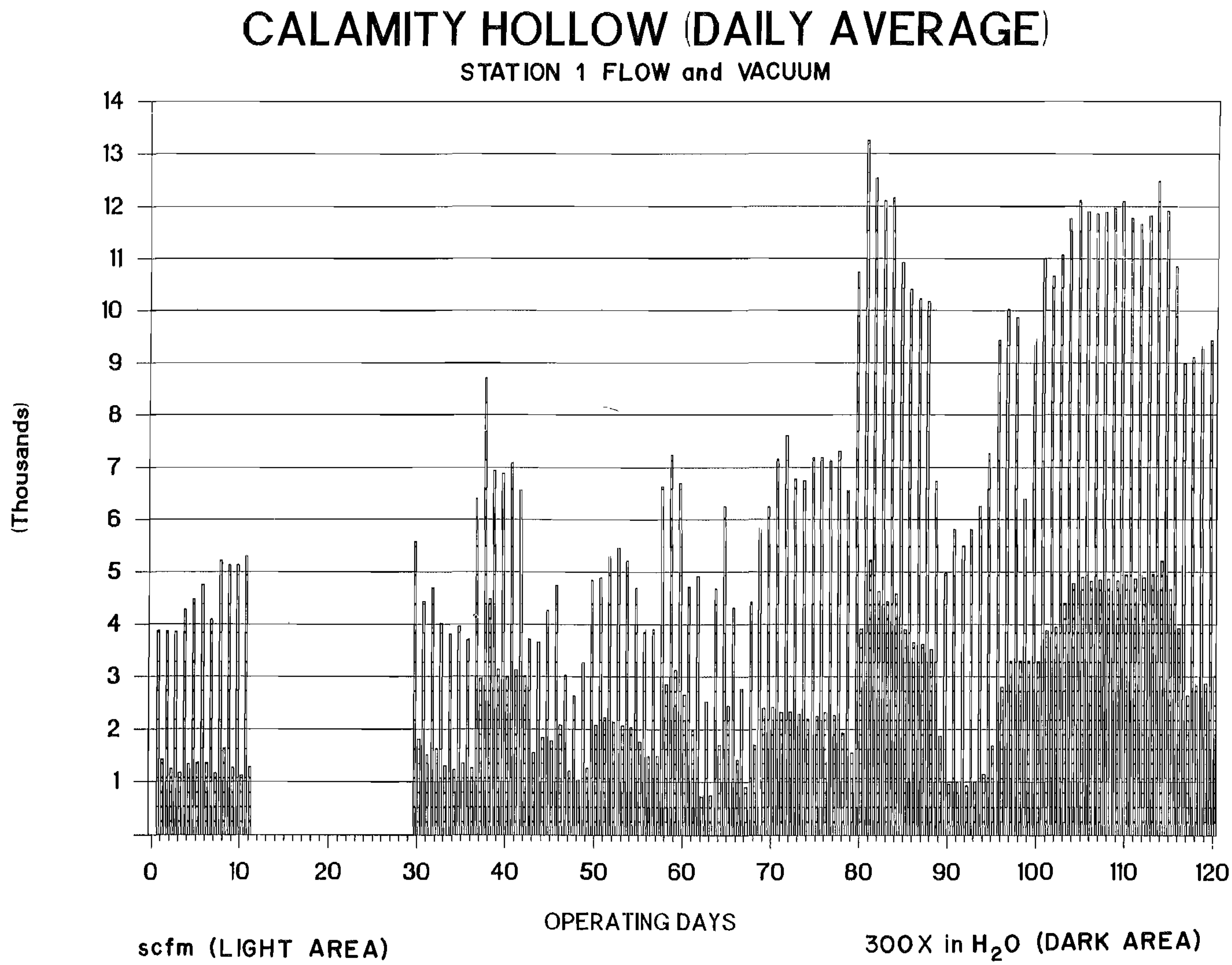

Figure 16.–Exhaust flow and vacuum at station 1.

and (dP/dx) = pressure gradient along flow direction.

Integrating equation 2 yields the following Darcy-flow expression:

$$\ln(x_2/x_1) = [(R) * (DP)]/q(x) \quad (3)$$

where DP is the pressure drop between radial distances, x_2 and x_1, from the manifold, and R is the effective constant flow resistance. Assuming x_1 to be some nonzero distance at the manifold location, it is readily seen that the logarithm of the area under effective control of the applied vacuum (i.e., the area of the pancake) varies directly with the vacuum.

It was estimated in section "Vacuum Data" above that at 8 in H_2O vacuum the underground communication area could be as large as 7 acres. Equation 3 then implies that control of a 35-acre burn zone would require a vacuum level of only 13 in H_2O. A 30-acre burn zone was considered in reference 6 to be commercially viable for producing electricity by the Burnout Control method.

The observed value of the flow resistance to darcy flow, as shown in table 1 (98.3×10^{-5}), can now be used in conjunction with equations 2 and 3 to determine the effective gas permeability of the underground strata. For reasonable parameter values: (x_2/x_1) = (300 ft/2 ft); mu = 0.02 cP; L = 450 cm (15 ft), the permeability is calculated to be about 7,000 darcys or some 100 times that of a pile of sand (porosity fraction of 0.31 to 0.50). Seven thousand darcys is also equivalent to the permeability of a packed bed of crimped wire having a porosity fraction of 0.68 to 0.76 (*7*). The suggested 70 pct porosity for the flow medium at the collapsed Calamity Hollow mine seems somewhat high; however there are no similar flow data available with which to compare this result.

Thermal Power Data

Figure 17 shows the daily average thermal power output of the hot exhaust as determined from the temperature and mass flow data points at station 1 by the relationship,

$$TP = scfm1 * RHO * CP * (T1-T6) \quad (4)$$

where TP = thermal power, W,

scfm1 = volumetric flow rate at standard-state conditions,

RHO = density of gas flow at standard state (taken as 0.075 lb/ft^3),

CP = gas specific heat (taken as 5.63 W•min/lb/•°F)[20],

T1 = temperature of exhaust at station 1, °F,

and T6 = temperature of dilution air at station 6, °F (taken to be the initial condition).

Output thermal power levels ranged from 1 to 5 MW, in keeping with the original design requirements. Comparing the thermal output with the imposed vacuum (superimposed on figure 17), it is apparent that the two parameters follow each other quite closely, as expected from the mass flow-vacuum relationship described above (fig. 16), and the observed immediate insensitivity of temperature to changes in vacuum.

The average thermal output over the entire 102 days of effective full-time fan operation is 3.2 MW, which for the Calamity Hollow coal and other carbonaceous materials at an average heating value of 12,000 BTU/lb (*2*), corresponds to a total of 1,100 st of combustibles consumed. Thermal power levels calculated from the totally independent temperature and mass flow measurements at station 2 were about 9 pct higher than at station 1, due primarily to the slightly higher flow rates that were always observed at station 2. This relatively good agreement between the station 1 and 2 results lends credibility to the overall method of measurement and treatment of data.

To obtain insight into the commercial viability of the Burnout Control process, it is useful to examine the energy gain, i.e., how much energy is produced relative to how much energy is consumed. The energy gain at Calamity Hollow can be looked at in several ways. First, is the gross thermal gain, GTE, which is defined as

$$GTE = (\text{Station 1 power})/(\text{fan motor power}) \quad (5)$$

This is the ratio of the thermal energy produced to the energy consumed by the fan motor, the largest and only major consumer of power in operating the Burnout Control system. However, at Calamity Hollow, a significant amount of the fan power was used to mix cold air into the hot combustion products, in order to lower the temperature of the gases passing through the fan. This fan power for artificial cooling would not be required if the energy of the hot exhaust gas was extracted in a heat exchanger, such as a steam boiler.

[20]Equivalent to 0.32 BTU/(lb/°F), a value that is weighted somewhat higher than the specific heat of nitrogen to account for the presence of significant amounts of water vapor in the gaseous combustion products.

A second energy gain can then be defined by accounting for the additional fan power used in cooling the hot exhaust. Since the motor power is directly proportional to the fan power, which in turn is directly proportional to the product of the pressure drop and mass flow across the fan, a net thermal energy gain, NTE, can be obtained from

$$NTE = (GTE) * (scfm3)/(scfm1) \quad (6)$$

where scfm3 is the total standard flow rate through the fan[21] and scfm1 is the standard flow at station 1.

[21]For calculation purposes, the total flow rate through the fan is taken as the sum of flows at stations 2 and 6. The measured flow rate at station 3, which originally was to be taken as the total flow into the fan, was sometimes incorrect - apparently due to the cooling water spray which occasionally impinged directly onto the Annubar flow probe at station 3.

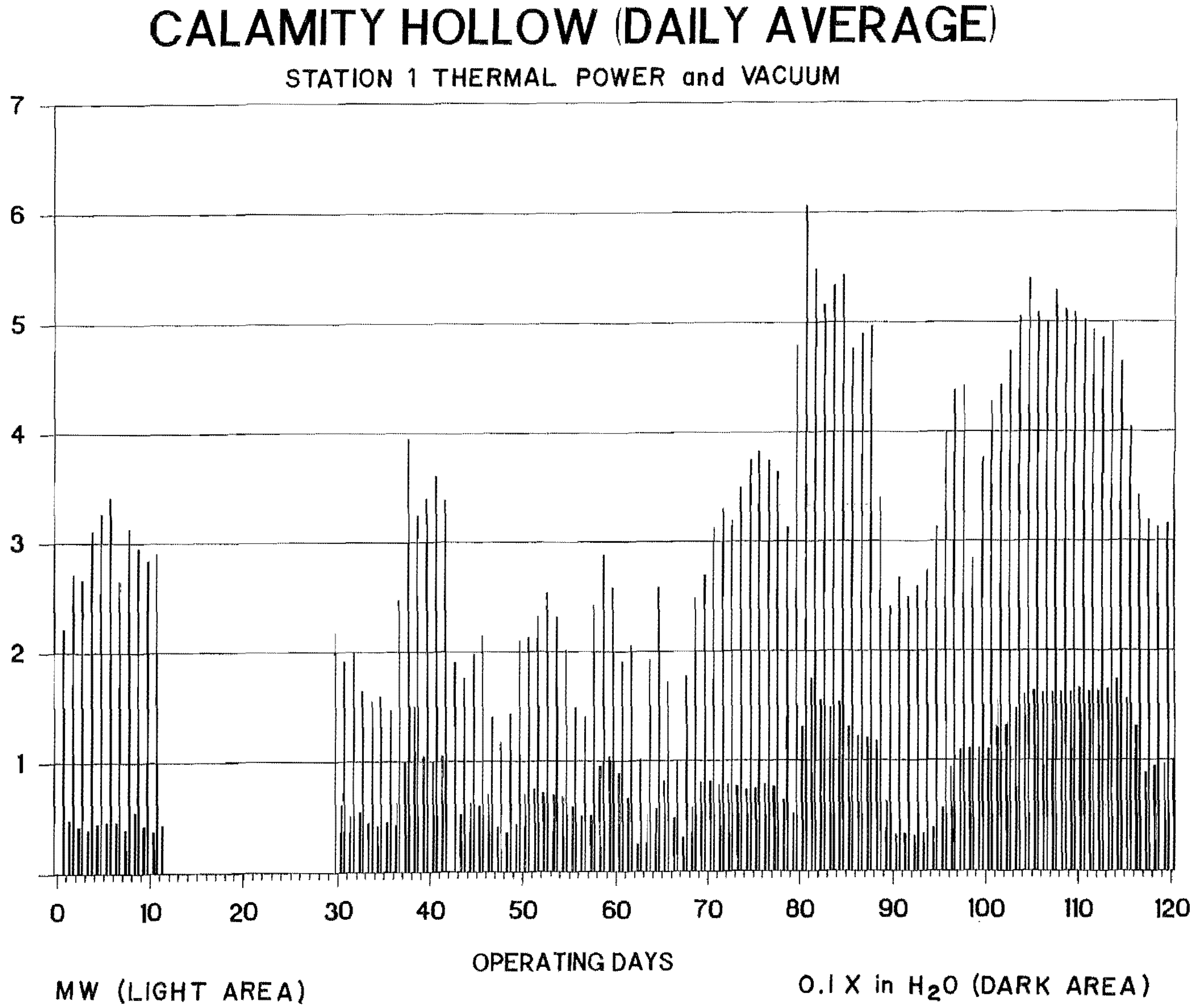

Figure 17.–Thermal power level and vacuum at station 1.

Another correction to the energy gain that should be considered accounts for the fact that the energy consumed in operating the site is electrical - a higher form of energy than the thermal energy being produced. Hence, a net electrical energy gain, NEE, can be defined from the product of NTE and an appropriate efficiency factor for converting thermal to electrical energy, assuming the Burnout Control system to be powering a small electrical generation plant. A reasonable conversion efficiency for a small boiler-steam turbine system might be 25 pct, so that

$$NEE = 0.25 * (NTE). \quad (7)$$

Figures 18 through 20 depict the three energy gain factors as defined by equations 5 through 7, and the

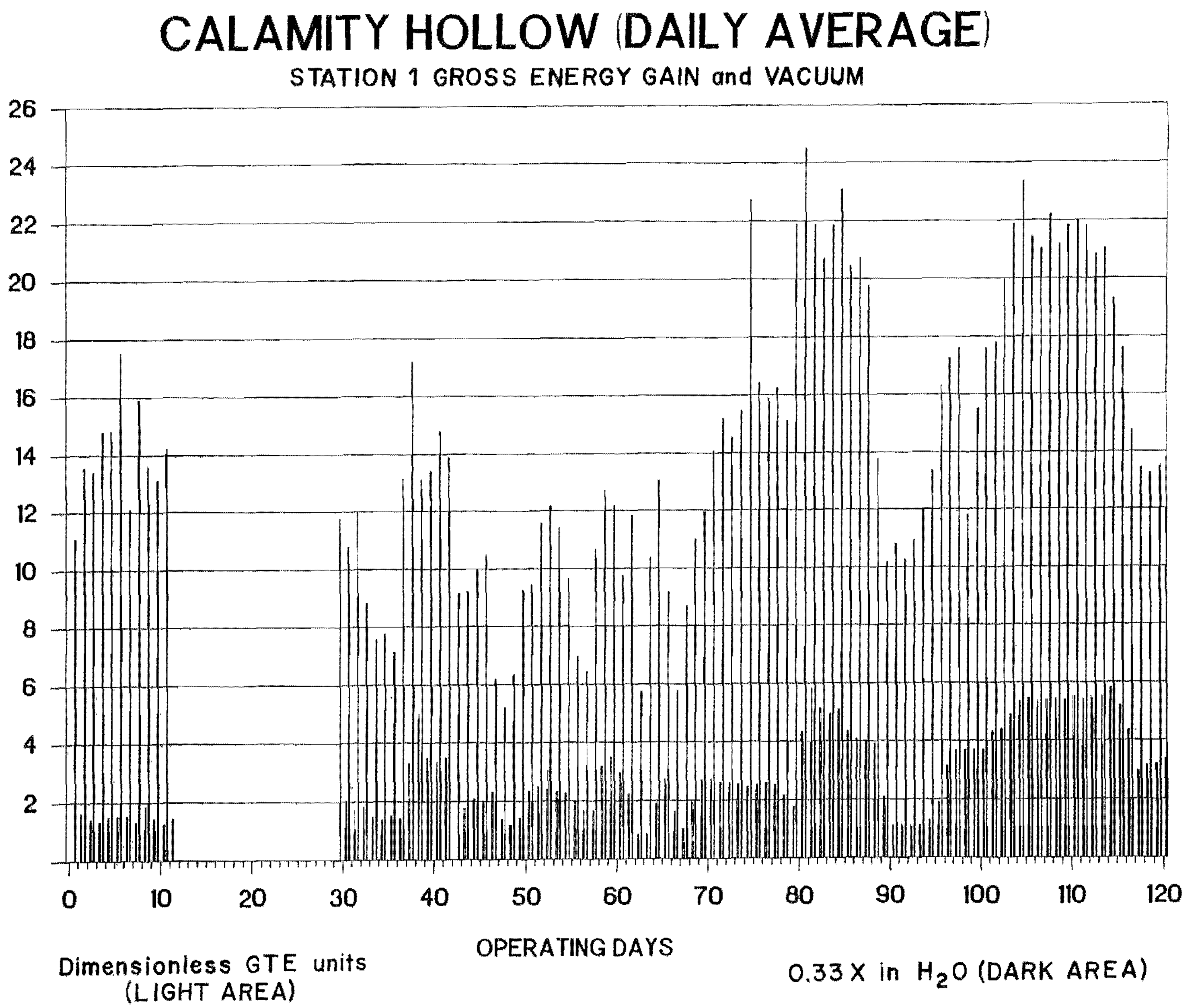

Figure 18.–Gross thermal energy gain and vacuum (station 1 data).

operational output data. While the gain factors tend to follow the station 1 vacuum, there are apparently numerous variances to this correlation. Since mass flow correlates quite well with vacuum (fig. 16), it is suggested that the variances are due to a nonconstant fan-motor efficiency (ratio of air to motor power). This could have been expected on the basis of the variable fan efficiency reported in Part 1 of this report series.

The average, minimum, and maximum values observed for all three energy gain factors are listed in table 2 along with a predicted energy gain that was calculated in reference 1. The observed values of the energy gain, and in particular the maximum values, are quite comparable to those expected from theoretical considerations. The fact that 20 W•h of *electricity* might be produced for every watt-hour of *electricity expended*, suggests that a small

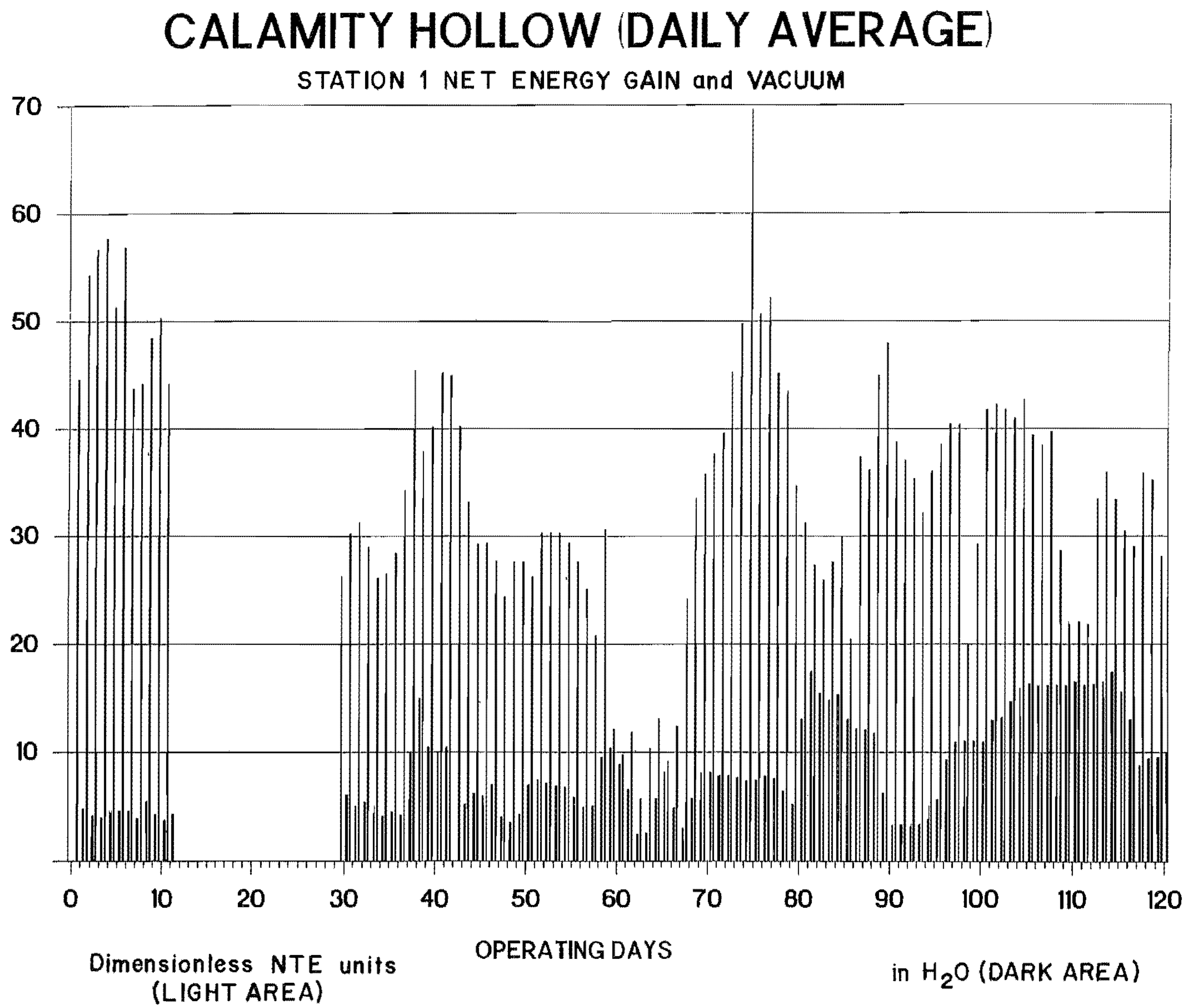

Figure 19.–Net thermal energy gain and vacuum (station 1 data).

Table 2.—Observed energy gain factors

	GTE	NTE	NEE
Average	14	39	9
Minimum	5	11	3
Maximum	24	76	19
Prev. Calc. (*1*) ...	—	61	20

electrical generation plant powered by Burnout Control would operate as efficiently as that of a large public utility.

Gas Compositions

Details of the arrangement, operation, and performance of the gas analyzers used during the field trial have been discussed in Part 3 of this report series. There were two exhaust gas sampling locations on the duct (stations 1 and 2), which were connected by heated tube bundle to instruments located in the control room. This allowed for remote on-line measurement of O_2, CO_2, CO, nitrogen

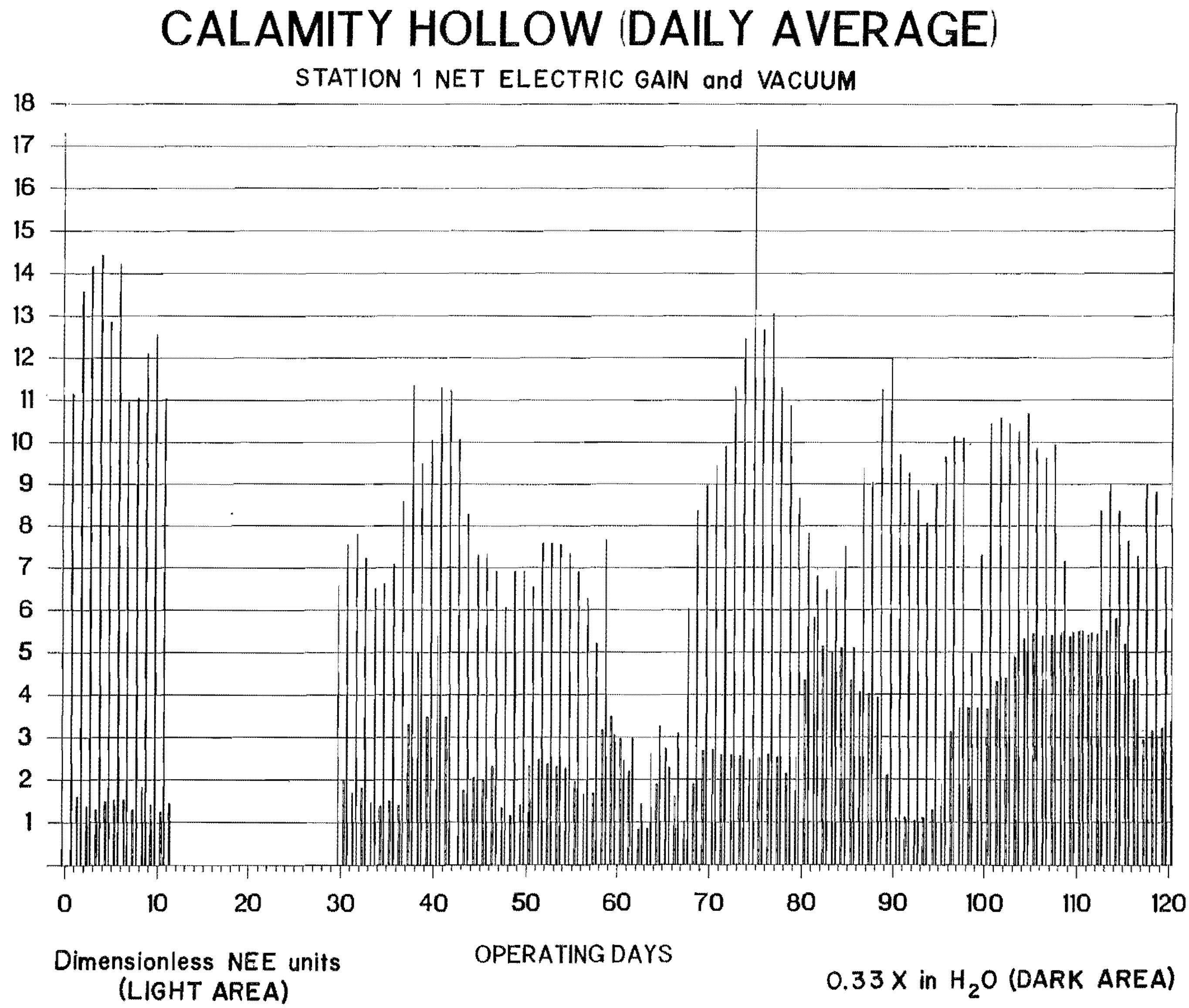

Figure 20.–Net electrical energy gain and vacuum (station 1 data).

oxides, and sulfur oxides. In addition, grab samples of exhaust for later gas chromatographic analyses (O_2, CO_2, CO, H_2, and C_1 to C_5 hydrocarbons) were obtained at points located in the control room and on the duct. In general, the on-line instruments, particularly the chemiluminescence NOX and the pulsed-fluorescence SOX analyzers, were plagued by inadequate moisture removal from the sampled gas stream. This resulted in water plugged lines and/or interference with the operation of the analyzers. It was not until late in the trial, with the installation of an on-line permeation tube dryer system and the implementation of an appropriate schedule of gas sampling and back-flushing, that adequate continuous monitoring of the exhaust gas composition was achieved. The 560 Vacutainer samples, which were collected for GC analyses during the entire operational period, provide data on O_2, N_2, CO_2, CO, and hydrocarbons, and form the basis of most of the discussions presented in this section. However, the concentration data for SOX and NOX are limited since they were available only from the on-line instruments. As pointed out in Part 3 of this report series and also shown in figure 8, the GC and on-line gas compositions, when they could be compared (O_2, CO_2, and CO only), are in good agreement.

It was obvious throughout the burnout operation, that considerable air dilution of the combustion products was occurring underground. Figure 21 depicts the average daily O_2 concentration at station 1 along with the corresponding vacuum level. The two parameters do not appear to correlate, which suggests that the excess O_2 (or air) was not being drawn into the system directly from around the outside of the manifold pipe. The outer casing of the manifold was not grout-sealed to the augerhole along its entire length, but for only a short depth (perhaps 3 ft) near the ground surface. Ambient airflow along the annular space between the walls of the augerhole and manifold, if significant, would undoubtedly have yielded O_2 levels in the exhaust, which would correlate with the station 1 vacuum (i.e., in the same manner as the total mass flow). On the other hand, significant amounts of air flowing through nonburning regions of the collapsed coal mine would also account for the highly diluted exhaust. It was this thought early in the trial that prompted the decision to: (1) inject burning charcoal underground so as to spread the fire more uniformly about the exhaust manifold; and (2) lengthen the air inlet borehole casings so as to enhance the introduction of O_2 directly into the coal seam instead of into the overlying rock strata.

Although a more uniform burn region was established, and a number of additional inlet air holes were cased to the bottom of the coal, the high O_2 levels in the exhaust persisted. It is now believed that one or more short-circuits for airflow existed underground, probably in the horizontal fracture system in the shales above the rider-seam coals. The isolation trench, which exerted noticeable influence on the underground pressure gradients (figs. 6, 10, and 11) may have contributed to this short-circuit.

Diluting the combustion products with underground airflows primarily lowered the exhaust temperature at station 1, which in itself, did not result in a decreased thermal power output. As can be seen from equation 4, a decrease in exhaust temperature by dilution with air is offset almost exactly by a proportionate increase in mass flow. However, the decrease in temperature apparently can have a noticeable effect on the extent of afterburning in the exhaust. This is seen from figures 22 through 24 where the air-free concentrations[22] of CO_2, CO, and total hydrocarbons (THC), are plotted against the exhaust (station 1) temperature. The observed 15 to 17 pct CO_2 levels and maximum combustible gas concentrations on the order of 0.1 pct (1,000 ppm) indicate that the underground combustion process is rather complete. However, figures 23 and 24 also indicate that exhaust gas cleanup through afterburning of residual CO and THC was not achieved when the exhaust temperature, as the result of underground air dilution, fell below 600° to 650° C. While not required from the view point of power output, temperatures in excess of 600° C would apparently promote cleaner stack emissions by assuring complete combustion.

[22]The air-free concentration, [AFX], is obtained by correcting the measured concentration, [X], for the presence of air as determined from the measured excess oxygen, i.e., $[AFX] = [X]/(1 - 4.773[O_2])$, where the excess oxygen $[O_2]$ is given in mole fraction.

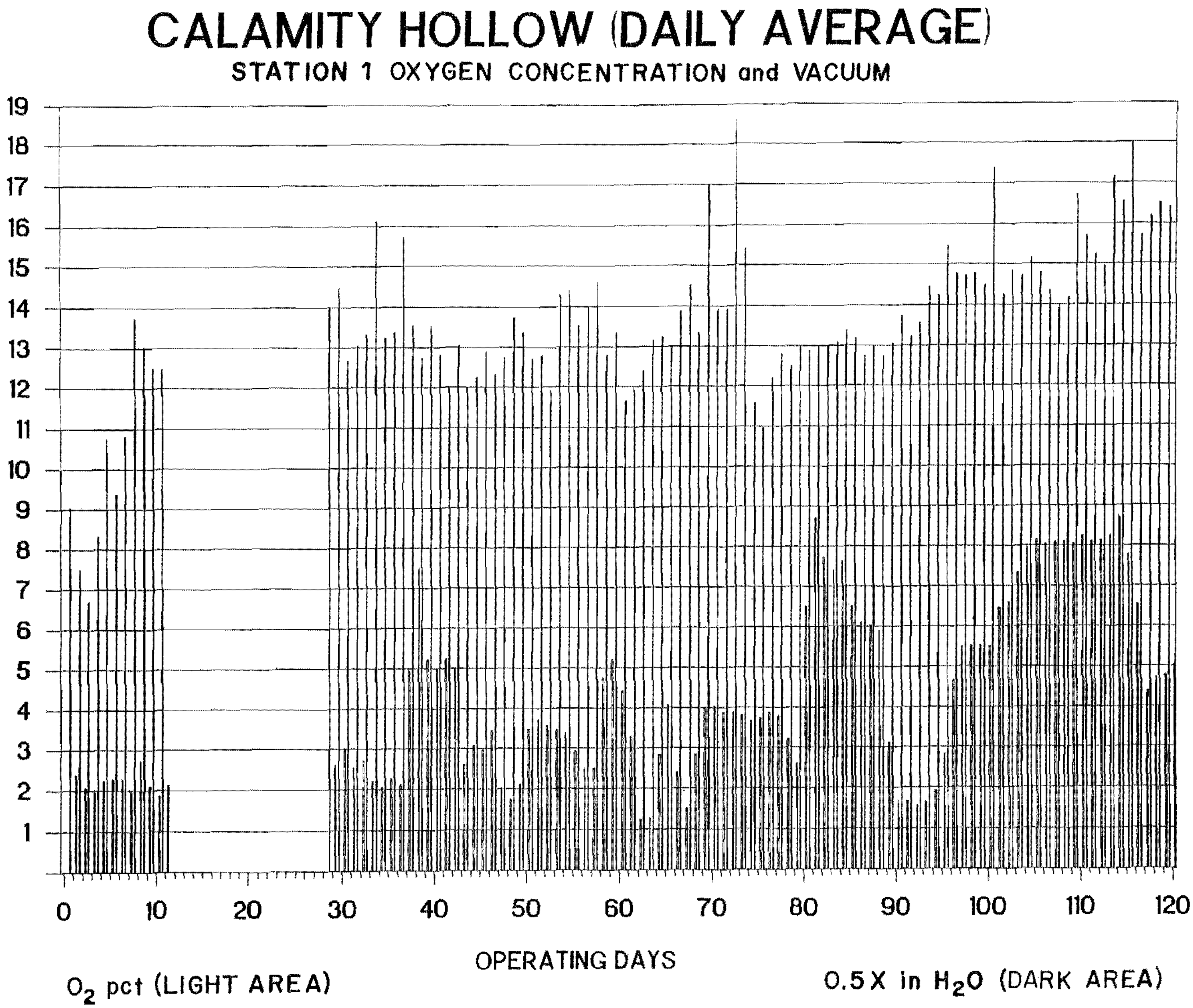

Figure 21.–Oxygen concentration and vacuum at station 1.

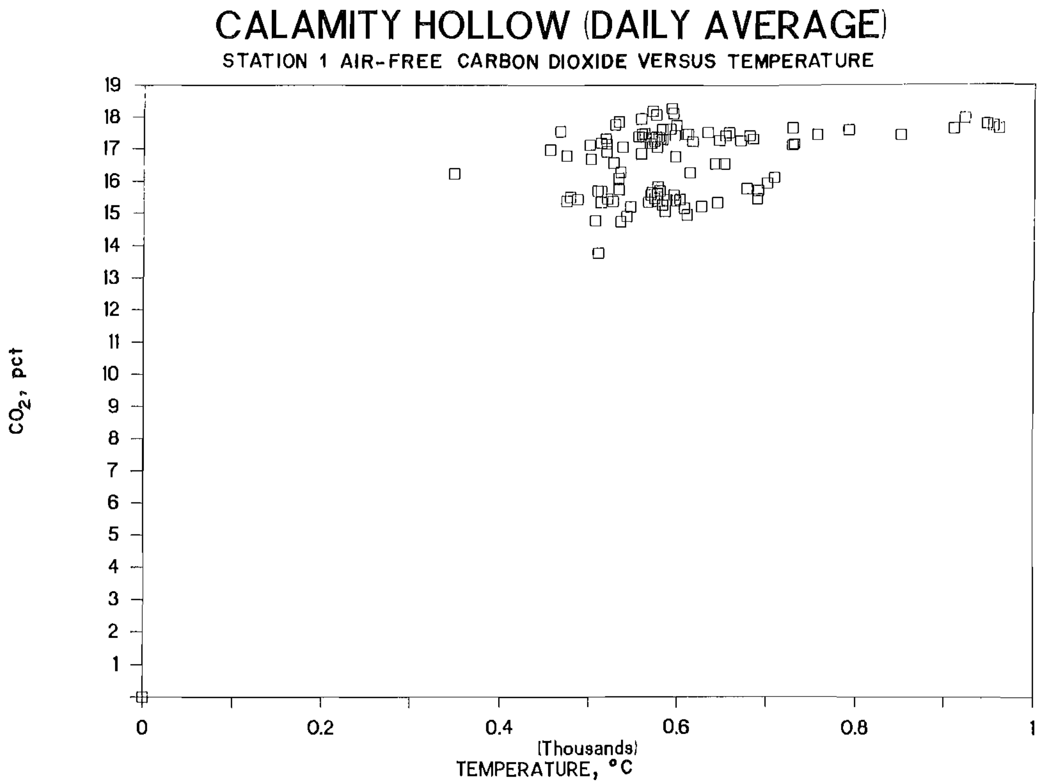

Figure 22.–Air-free carbon dioxide versus temperature (station 1 data).

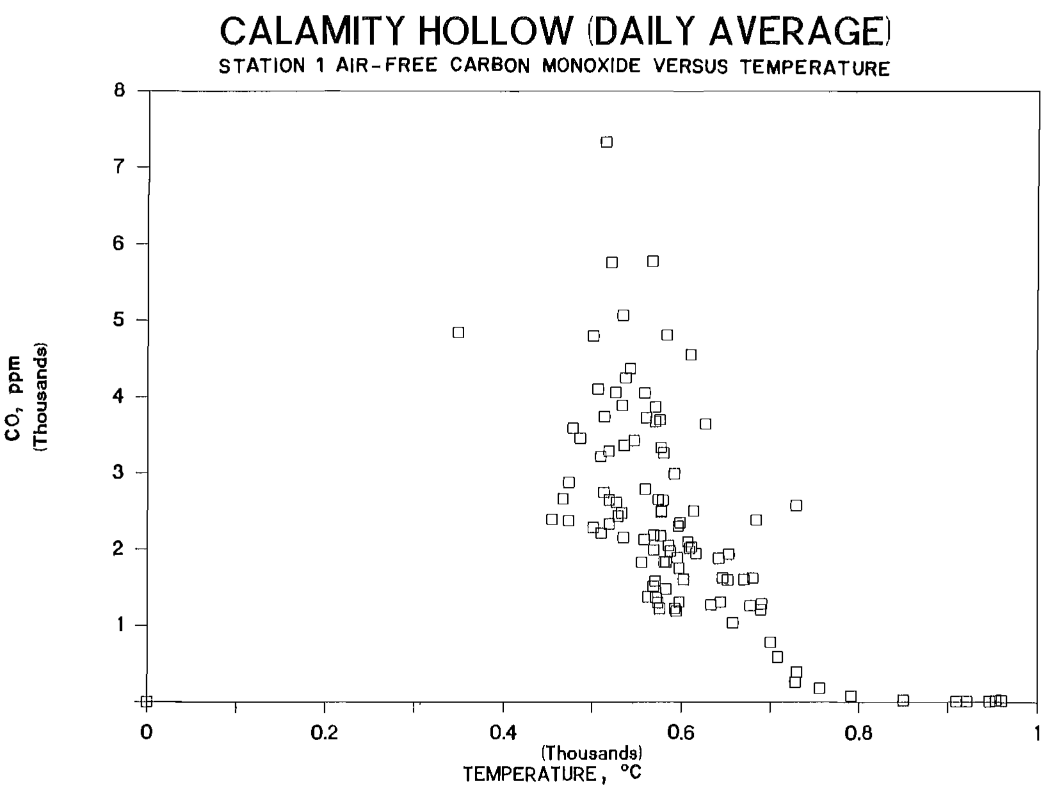

Figure 23.–Air-free carbon monoxide versus temperature (station 1 data).

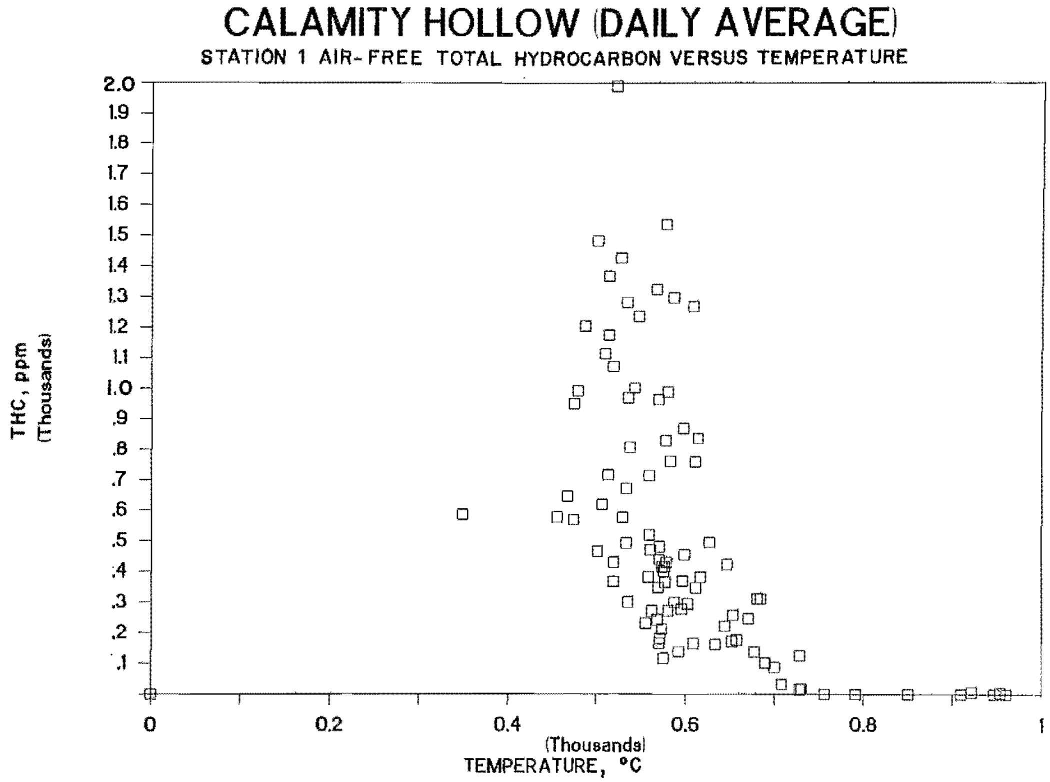

Figure 24.–Air-free total hydrocarbons versus temperature (station 1 data).

It is interesting to note that the observed Jones-Trickett Ratio (JTR) (*8-9*),

$$JTR = ([CO_2] + 0.75[CO] - 0.25[H_2])/(20.94 - [O_2]) \quad (7)$$

which is well approximated by the ratio,

$$[CO_2]/(20.94 - [O_2]) = [AFCO_2]/20.94 \quad (8)$$

varied almost exclusively around the two values, 0.746(±)0.024 and 0.836(±)0.016. These values of JTR would be expected from oxygen-rich burning of two different hydrocarbon fuels (gas, liquid, or solid); viz., one having a carbon to hydrogen ratio of 0.73 and the other having a ratio of 1.27 (*9*). The carbon to hydrogen ratios for the overlying carbonaceous shale and for the Pittsburgh Coalbed at Calamity Hollow are 0.66 and 1.17, respectively,[23] both of which are reasonably consistent with the values inferred from the burnout data. These results likewise suggest that both the coal and shales were being completely burned during Burnout Control.

Figure 25 depicts the available station 1 data for SOX and NOX, which owing to the previously mentioned gas sampling problems, are limited to the last 25 days of the

[23]The ultimate analysis of core samples obtained at Calamity Hollow as reported in table 1 of reference 2, indicates the following effective elemental formulae for the coal and overlying carbonaceous shales: Black Shale - $CH_{1.516}O_{0.198}N_{0.018}S_{0.026}(ASH)_{0.756}$; Coal - $CH_{0.855}O_{0.079}N_{0.017}S_{0.01}(ASH)_{0.053}$. In calculating the elemental formulae from the ultimate analyses, ASH was assumed to be silicon dioxide having a gram molecular weight of 60. The formula given for coal is an average of that determined for the Pittsburgh Coalbed and its two rider coal seams.

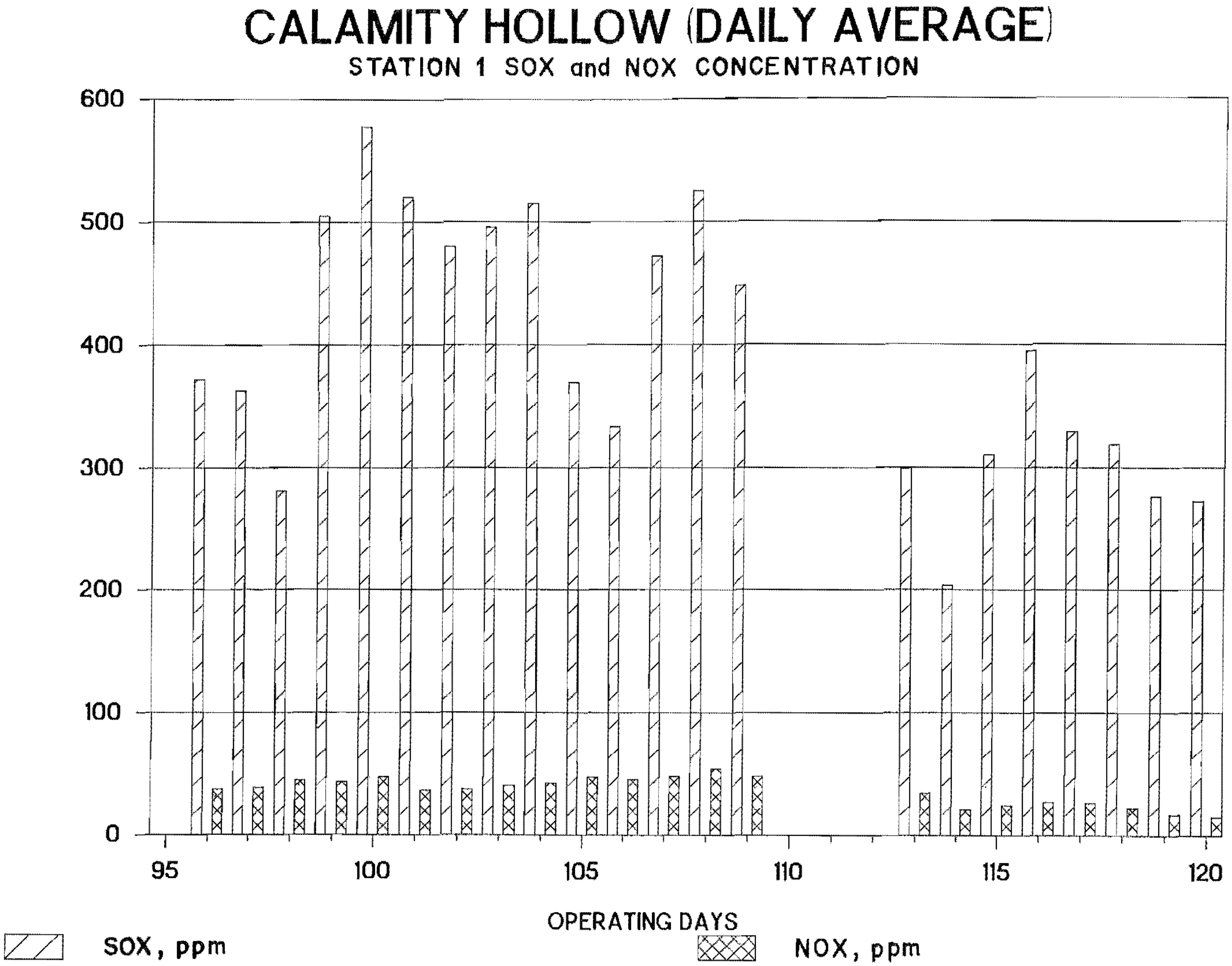

Figure 25.–Concentration of sulfur oxides and nitrogen oxides at station 1.

Burnout Control operations. The average of the *air-free* concentrations over this time period are 140(±)30 ppm and 1,660(±)580 ppm for the NOX and SOX, respectively. These values should then be compared with the theoretical air-free NOX and SOX concentrations of 2,600 ppm and 1,540 ppm, respectively, that would be expected from complete burning of the coal seams (see footnote 23). It would appear that during burnout, SOX was produced almost stoichiometrically from the 1.73 pct fuel-sulfur, but far less NOX was produced than what might be expected from the fuel-nitrogen (average of 1.37 pct). This result for NOX is similar to that obtained previously in simulated in situ coal burning experiments (*9-10*).

If only the overlying carbonaceous shales (1.3 pct fuel-sulfur) were burned, the air-free SOX concentration would be about 3,700 ppm - a level considerably higher than that observed. It would then appear that the coal and rider seams were the main sources of fuel for burning - although other physical evidence during excavation of the burn zone (*5*) suggested that up to 10 ft of the carbonaceous shales overlying the main coal seam also burned.

GENERAL OBSERVATIONS

Subsidence

There was no serious attempt to accurately determine the extent of subsidence at the site, although it was certainly expected and it did occur, but not so as to seriously interfere with the Burnout Control operations. The initial design for the system hardware required only "floating" supports for the ductwork located over the potential burnout zones. The support for the vertical exhaust manifold consisted of a cradle formed from two 36-in I-beams lying on the ground, which could traverse a subsidence zone up to 36 ft in length. However, it was apparent by JD012 that the actual subsidence zone around the manifold, accompanied by ground fractures up to 40 ft away, greatly exceeded this span dimension. This support problem was resolved by extending the length of the I-beams an additional 80 ft (40 ft on each end of the original beams). This resulted in an 120-ft long span for the beams, which was sure to encompass sufficient ground support to avoid any chance that catastrophic ground subsidence, if it did occur, would cause the exhaust manifold to collapse. It was relatively simple to maintain the proper elevation of the manifold by jacking-up and supporting the I-beams whenever and wherever necessary. Over the operational period, the ground under the central portion of the I-beams subsided a total of about 36 in.

While numerous ground fractures (some as large as 25 ft in length and 10 ft in depth) occurred during the operational period, they did not appear to seriously affect the burnout process except for allowing surface runoff of rain water to infiltrate the underground burn zones (on JD064 and JD076). Early in the field trial, these cracks were sealed with cement grouting. However, as it was discovered that the cracks had little influence on the burnout, they were subsequently covered with dirt and/or plastic sheet. The larger ones were also staked out for safety reasons.

System Hardware

Breakdown of the main diesel generator 11 days into the burn was the only catastrophic failure encountered with the system hardware (as contrasted with the system instrumentation). Although not a necessary and integral part of a Burnout Control system, the use of a trailer-mounted diesel generator-motor-fan assembly at Calamity Hollow was to demonstrate the potential mobility of the system for use in the field. As described in the chronology, it took 2-1/2 weeks to obtain, install, and make operational a government-owned replacement diesel generator, which did perform satisfactorily for the remainder of the trial. There were also numerous smaller, but troublesome problems encountered with the system hardware, almost all of which could be traced to corrosion. For example, excessive fan vibration caused the failure of numerous metal welds, the separation of mounted electrical conduits, breakdown of the stations 6 and 7 valve actuator controls, and periodic shutdown of the entire system in order to balance the fan. Corrosion of the fan blades, from SOX saturated moisture in the cooled exhaust, was the most probable cause for the fan vibration. Almost all the equipment and hardware used in fabricating the Burnout Control system at Calamity Hollow was acquired from government or private surplus (including the fan and diesel generator), and in some cases, such as the fan, the equipment was really not suitable for operation in corrosive environments.

The corrosive nature of the cooled moist exhaust was most clearly demonstrated by the occurrence of significant erosion of the unlined steel duct near the cooling water sprays, as well as the spray heads themselves. On the other hand, instrumentation probes for gas sampling, and for temperature and flow measurements, which were located in high temperature regions of the duct (e.g., at stations 1 and 2), suffered little if any erosion (*5*). It is quite apparent that these difficulties with corrosion can be avoided by maintaining the temperature of the exhaust gas at above the dew point of the SOX and NOX, or by using materials resistant to such corrosion.

Operation of the Burnout Control system was not seriously impeded by severe ambient weather conditions, which included snow, sleet, ice, and freezing temperatures that dipped as low as -28° C (-18° F). For 83 days out of the 4 months of the Burnout Control operations temperatures dipped below freezing. In this regard, the Calamity Hollow field trial was indeed a *trial* of personnel and equipment.

CONCLUSIONS

A number of things can be said about this first field trial of the Burnout Control process:

First and foremost, it was demonstrated that it is possible to accelerate an abandoned mine fire while maintaining complete control over the heat and fumes produced. When the exhaust fan was operating, there was no evidence of fumes venting from the approximate 1 acre of ground surface over the fire zone. Even during those time intervals (up to 17 days) when the fan was turned off, closing all the boreholes and sealing major surface cracks led to rapid dampening of the fire and minimal escape of fumes to the atmosphere.

A second significant finding was that surface subsidence during burnout, which was very noticeable in terms of ground displacement and fissure formation, did not appear to alter the underground burning process, at least not as it affects overall coal combustion efficiency and thermal output. However, it is probable that ground subsidence contributed to the excess air being drawn into the mine, leading to diminished exhaust temperatures and diminished afterburning in the exhaust.

A third point is that the Burnout Control system as designed and built for Calamity Hollow did achieve its goals of 5 MW thermal output (corresponding to 17 st of coal burned per day), and 900° C exhaust temperature, albeit not at the same time. The average output over the trial period, i.e., 3.2 MW and 603° C, was less than these peak values, but still significant in terms of burnout of the fire and production of energy for heat, steam, and/or electricity.

Relative to the system design, a fourth point that can be made concerns the demonstrated need for using corrosion resistant materials at locations where moisture might condense as acidic solutions of SOX and NOX. This is particularly significant for the fan blades, inlet and outlet dampers, instrumentation probes, and gas sample plumbing. Likewise, it would be beneficial not to use direct water sprays for cooling the hot exhaust, but rather to utilize an external heat exchanger (boiler, or air-to-air). An external heat exchanger would also eliminate the need for dilution air cooling of the hot exhaust, with its attendant inlet duct connected in parallel with the exhaust manifold. By decoupling the control of exhaust manifold vacuum from that of the exhaust cooling, it would then be possible to apply all of the fans' suction capability directly to the exhaust manifold.

The last point to be made relates to the efficiency of the underground combustion process and atmospheric emissions. It is clear from the observed exhaust gas compositions (as well as the physical evidence reported in part 5 of the report series), that the underground coal and carbonaceous shales that did burn were essentially completely combusted even though there were very small residual quantities of CO and hydrocarbon gas left in the exhaust, and a considerable quantity of char and unburnt coal left underground. The fact that solid fuel was left underground after the 4-month trial is certainly not surprising since even at a steady 5 MW thermal output, it would have taken over 1.6 years to completely burnout the 10,000 st of coal (updated estimate from part 5 of this report series) located at the 1.8-acre site.

The 0.1 pct levels of residual CO and hydrocarbons in the exhaust did not represent a significant combustion inefficiency or air pollution problem at Calamity Hollow, and they apparently disappeared altogether by afterburning when the exhaust temperatures were higher than 600° to 650° C.

The observed SOX in the exhaust directly out of the mine (about 400 ppm), which corresponds closely to complete burning of the fuel-sulfur, might present a problem in obtaining a permit for commercial practice. On the other hand, the observed concentrations of NOX (less than 50 ppm) are well below those observed with most other coal burning devices, and should not be a problem.

In conclusion, it is believed that the Calamity Hollow Mine Fire Project was a successful demonstration of Burnout Control as applied to controlling an abandoned mined-land coal mine fire. While further engineering development is needed, the results of this first field trial warrant the continued development of the energy producing potential of Burnout Control.

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