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REPORT OF INVESTIGATIONS/1991

Burnout Control at the Albright Coal Waste Bank Fire

By Robert F. Chaiken and Larry G. Bayles

UNITED STATES DEPARTMENT OF THE INTERIOR

MARCH 3, 1849

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

acfm	actual cubic foot per minute
atm	atmosphere, standard
atm/cm	atmosphere, standard, per centimeter
Btu	British thermal unit
Btu/h	British thermal unit per hour
Btu/lb	British thermal unit per pound
°C	degree Celsius
cm	centimeter
cm^2	square centimeter
cm^3/s	cubic centimeter per second
cP	centipoise
D	darcy
dB	decibel
dBA	decibel, A-scale
°F	degree Fahrenheit
ft	foot
ft^2	square foot
ft^3	cubic foot
gal	gallon
gal/min	gallon per minute
h	hour
hp	horsepower
Hz	hertz
in	inch
in H_2O	inch of water (pressure)
kW	kilowatt
kW·h	kilowatt hour
lb	pound
lbf	pound (force)
mol	mole
mm	millimeter
MW	megawatt
pct	percent
ppm	part per million
psi	pound (force) per square inch
rpm	revolution per minute
s	second
scfm	standard cubic foot per minute
st	short ton
st/d	short ton per day
V	volt
wt pct	weight percent

BURNOUT CONTROL AT THE ALBRIGHT COAL WASTE BANK FIRE

By Robert F. Chaiken[1] and Larry G. Bayles[2]

ABSTRACT

Burnout Control is a process developed by the U.S. Bureau of Mines for accelerating the burning of wasted coal fires in situ, while at the same time controlling the heat and fumes produced. The Albright fire project is a first field trial of Burnout Control as applied to a coal waste bank. An exhaust ventilation system was designed and constructed and then operated over a 1-year period at the site of an existing abandoned mine land fire near the town of Albright, WV. While predicted exhaust gas temperatures of 900° C and thermal power levels of 5 MW were achieved at 20- to 30-in H_2O vacuum levels, problems were encountered with engineering designs, equipment breakdown, and fuel-rich combustion that curtailed the time period of satisfactory operation. Effective afterburning of the exhaust gases (as they were drawn from the bank) corrected the problems associated with combustion stoichiometry and led to high thermal outputs. It is believed that with (1) improvements in engineering design and construction, (2) better control of the afterburning process, and (3) the use of conventional stack gas air-pollution controls, Burnout Control can be applied successfully to a coal waste bank fire.

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INTRODUCTION

Burnout Control (*1-2*)[3] is a process developed by the U.S. Bureau of Mines for accelerating the burning of wasted coal fires in situ (i.e., directly in an abandoned underground coal mine or waste bank), while at the same time controlling the heat and fumes produced. Through Burnout Control, it would be theoretically feasible to have the fire burn to completion in an environmentally acceptable manner, while at the same time converting the sensible heat of the fire to useful energy, such as steam and electricity. The first field trial of Burnout Control was carried out at an abandoned coal mine fire site near Pittsburgh, PA, where in 4 months time, 1,100 st of coal was burned in situ, producing exhaust gases at an average temperature of 600° C (1,112° F) and an average thermal power level of 3.2 MW (Calamity Hollow Mine Fire Project, 1979-82) (*3-7*). The first application of Burnout Control to a burning coal waste bank was the Albright Waste Bank Fire Project carried out during 1984-87 at an abandoned waste bank fire site in Preston County, WV. This Report of Investigations summarizes the results of that project.

For the Albright field trial, a Burnout Control system pilot plant was designed and constructed to exhaust combustion gases from the burning waste pile at temperatures as high as 900° C and at power levels up to 5 MW (thermal). While the desired thermal output was eventually obtained, engineering- and combustion-related problems were encountered that curtailed the length of time of the steady operations. However, it is believed that with improved engineering designs and constructions, Burnout Control can be applied successfully to coal waste bank fires.

ACKNOWLEDGMENTS

The authors wish to acknowledge the cooperation of R. B. Bolen, president, Patriot Coal Co., Morgantown, WV, in allowing the Burnout Control field trial to be carried out at the company's site, and the assistance of M. T. Dougherty, deputy division chief, currently with the U.S. Office of Surface Mining Reclamation and Enforcement, Greentree, PA, and of H. Moomau, president, Potomac Engineering and Surveying, Inc., Oakland, MD, in site selection and assessment. The authors are also grateful to the West Virginia Department of Energy, the West Virginia Air Pollution Control Commission, and the U.S. Office of Surface Mining, Reclamation and Enforcement for their counsel in the development of the project, particularly with regard to identifying the environmental requirements of the site. Several individuals and companies contributed significantly to the development and operation of the field trial: L. E. Dalverny, physicist, T. R. Justin, electrical engineer, and J. P. Slivon, physical science technician, Pittsburgh Research Center, all of whom contributed to the design, installation, and operation of instrumentation used at the site; W. W. Aljoe, mining engineer, Pittsburgh Research Center, who carried out noise studies at the site; RA Systems Inc., Pittsburgh, PA, which provided services for around-the-clock operations; Green Engineering Inc., Sewickley, PA, Potomac Engineering and Surveying, Inc., Oakland, MD, and Frich Construction Co., Belle Vernon, PA, who provided architectural, and engineering and construction services.

DESCRIPTION OF SITE

The coal waste pile is located along the west bank of the Cheat River, about 1 mile north of the town of Albright in Preston County, WV, and directly across the river from Ruthbelle, a village of a dozen or more homes. The pile, formed by dumping bituminous refuse from coal-cleaning plants and fly ash from a nearby powerplant, rests on a 7.5° slope of ground within 200 ft of the Cheat River. The pile is about 1,400 ft long, 200 ft wide, and 40 ft high, and contains an estimated 350,000 st of material (see figure 1). The surface of the waste pile is covered with sparse vegetation (moss, grass, brush, and scrub locust trees), with sizable barren areas of fly ash and/or coal waste. The portion of the waste bank selected for the field trial (about 0.9 acre total) has steep slopes (between 45° and 60°) and a relatively flat top, 84 by 184 ft in area (see figure 2). There are numerous erosion gullies along the steep slopes of the pile. Acidic reddish water issues from many seeps along the downslope toe of the pile, while the water observed upslope is relatively clear and alkaline (see table 1). This indicates that the pyrite content of the waste bank is forming acid mine water, which can drain directly into the Cheat River.

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

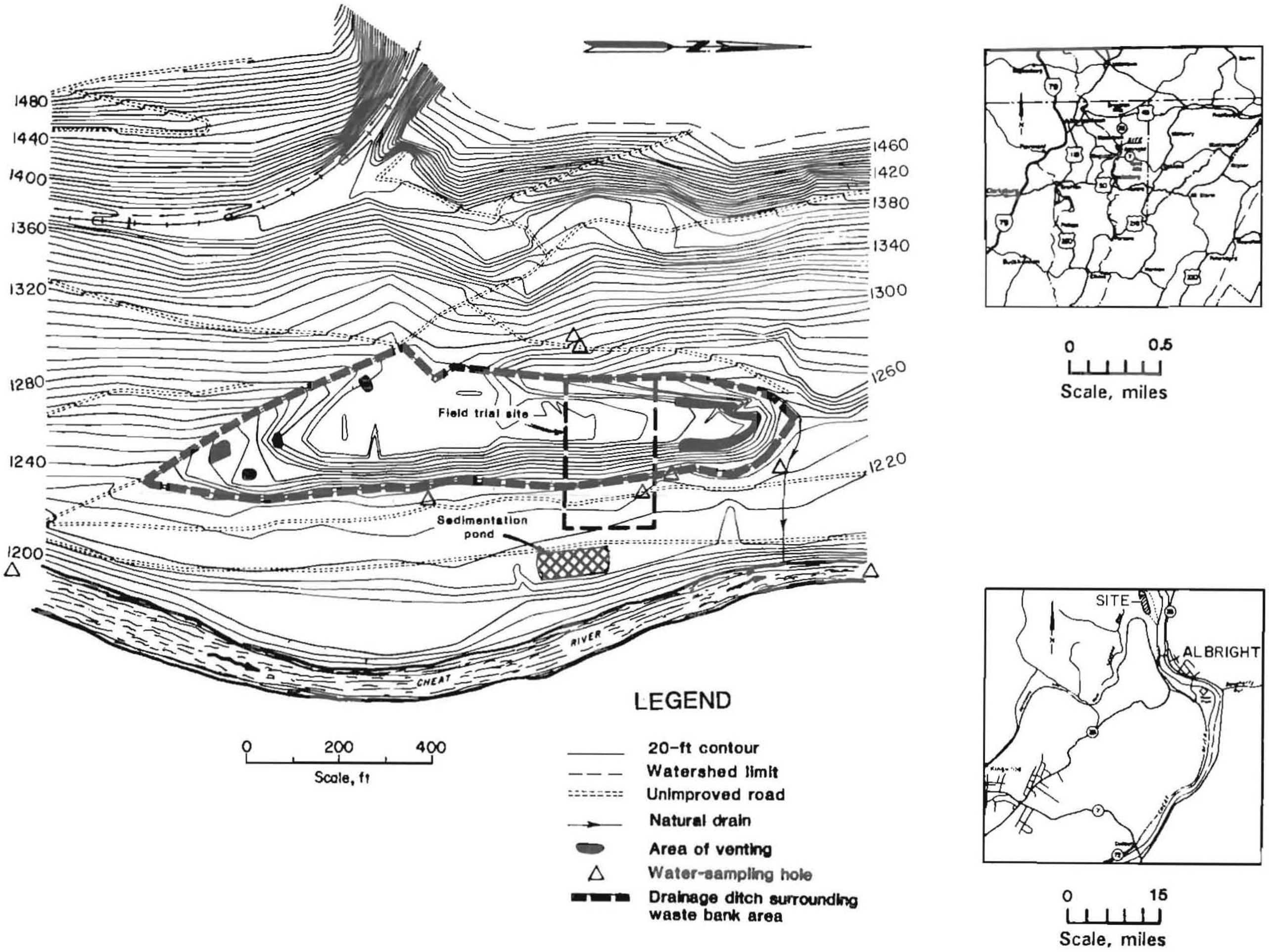

Figure 1.—Location of Albright waste bank site.

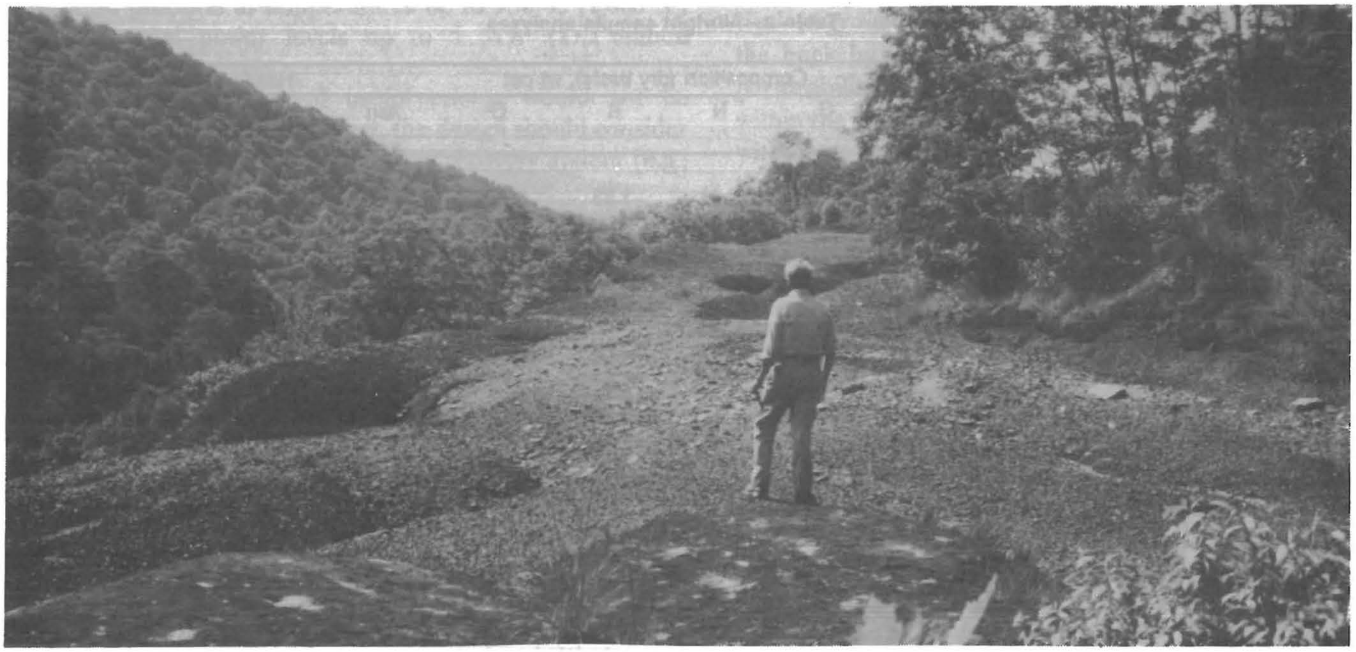

Figure 2.—Top portion of waste bank, looking south.

Table 1.—Water quality[1]

	pH	Fe, ppm	SO_4, ppm
Upslope:			
Ground water	8.5	8	115
Surface water	7.0	3	630
Downslope:			
Ground water	3.5	160	800
Surface water	2.6	3,600	6,000

[1] Average of 2 to 4 samples taken from 1 or 2 sampling points.

At the time of the first visit to the site, the entrance road, about 0.75 mile along the river south of the site, was in relatively poor condition (severely rutted with mud and holes). During the course of the project, and particularly after a severe flood of the Cheat River in November 1985, considerable application and grading of gravel was required to maintain passage for trucks and passenger vehicles between the main road (State Route 26) and the project site.

SITE ASSESSMENT

Initially, test borings were made to obtain material property data for the waste bank (seven boreholes) and its surroundings (three boreholes). The test holes were advanced through the waste from the top of the pile to the underlying soil (average depth of 44 ft) using a 6-in-OD continuous flight hollow-stem auger. In addition to material recovery from these borings through continuous split-spoon samples, six holes served for suction tests in which the permeability of the waste to airflow was determined as a function of depth. The measurements involved a somewhat novel technique and application of the Darcy equation for flow through porous media (described in detail in appendix A). The measured permeabilities, ranging from about 250 D at a 10-ft depth to 25 D at 40 ft, were useful in sizing the Burnout Control ventilation system (described in the "Design of Burnout Control System" section).

Table 2 lists material compositions found for the various borehole samples and for a 50-gal sample taken from a nearby area of the bank.[4] There are several points that can be derived from the compositional data.

The first point is the relatively large heating value of the waste (approximately 4,000 to 8,000 Btu/lb), which is in the range of 35 to 70 pct of the heat of combustion of most bituminous coals as mined. Previous theoretical considerations (*1*) indicated that coal waste, at a heating value as low as 1,500 Btu/lb, would sustain smoldering combustion in a pile; hence, no problem was anticipated in maintaining a fire in that portion of the Albright pile selected for burnout.

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[4] The five boreholes that supplied material for analysis were distributed over the 84- by 184-ft flat top area of the bank selected for the field trial. Different numbered samples from the same borehole refer to material at different depth ranges from just below any fly ash layer to the bottom of the bank. The 50-gal sample (included in the average) was accumulated bank material from several near-surface locations.

Table 2.—Albright sample analyses

Sample	Water, wt pct	Composition (dry basis), wt pct						Heating value (as received), Btu/lb	Mass mean particle size, mm
		H	C	N	S	O	Ash		
Borehole:									
1-1	5.6	3.25	31.86	0.41	1.33	12.03	56.29	5,272	12.2
1-2	2.9	2.60	29.40	.37	2.83	9.66	57.96	5,188	7.6
2-1	4.8	2.64	29.95	.44	3.16	11.25	56.85	5,206	5.2
2-2	3.7	2.45	27.84	.38	1.40	10.92	60.51	4,563	7.2
5-1	5.0	3.34	35.16	.54	2.21	8.67	54.52	5,934	4.8
6-1	4.4	2.75	31.52	.52	2.15	8.43	58.93	5,330	3.0
6-2	2.9	3.00	36.50	.57	2.88	7.82	51.73	6,308	4.6
7-1	3.2	3.79	41.70	.83	1.98	5.15	49.25	7,296	3.8
7-2	2.2	3.48	46.66	.77	2.54	5.61	43.08	8,111	4.8
7-3	2.8	2.49	30.93	.56	1.47	9.48	57.65	4,416	3.2
7-4	3.0	1.81	25.79	.44	1.52	9.04	64.48	3,867	3.2
50 gal[1]	9.0	3.87	41.09	.62	1.22	15.78	46.47	6,719	7.0
Average[2]	3.7	2.87	33.39	.53	2.13	8.91	55.57	5,684	5.6
Std dev	1.1	.56	6.21	.15	.66	2.16	5.82	1,188	2.5
Fly ash	19.5	.64	8.77	.10	.73	1.23	89.19	937	.15

[1] Accumulated bank material.

[2] The average elemental formula is $CH_{1.033}\,O_{0.200}\,N_{0.013}\,S_{0.024}\,(ASH)_{0.333}$, calculated on dry basis with ASH taken as SiO_2. The calculated heat of combustion is 5,805 Btu/lb.

The second point is the sulfur level (average of 2.1 pct) in the waste. With stoichiometric burning, 0.024 mol of SO_2 would be present in 5.94 mol of gaseous combustion products, which could result in SO_2 concentrations in the exhaust as high as 4,000 ppm, or 7.1 lb SO_2 per million British thermal units, when normalized to the average heating value. However, absorption of sulfur gases by the coal ash and dilution of the exhaust gases with excess air could significantly decrease the SO_2 concentrations in the stack emissions, perhaps to levels where air-pollution controls would not be required. This initial assessment was based on complete oxidation of the coal waste and did not consider the potential formation of reduced gaseous products (e.g., H_2S, COS, and mercaptans), which could occur when combustion is far less than stoichiometric (i.e., fuel-rich burning). As will be described later in the "Burnout Control Operations" section, odoriferous exhaust gases related to fuel-rich combustion led to an emissions problem shortly after startup of the Burnout Control operations.

The third point is the nature of the fly ash sample, which was taken from a surface layer at another area of the pile and is probably representative of the fly ash on the waste bank.[5] This fly ash material had only a small heating value (less than 1,000 Btu/lb) and would not be expected to burn.

The average ash content of the coal waste is about 55 pct, which suggests that complete burnout might result in a sizable reduction in volume of material in the burn zone. Significant subsidence could be expected during the field trial, which, while desirable from the viewpoint of testing the effects of such subsidence on the Burnout Control process (one of the objectives of the field trial), would be undesirable from the viewpoint of hazards to personnel working on top of the pile. Handling the potential safety problems of surface subsidence became a consideration for the project designs and operations.

DESIGN OF BURNOUT CONTROL SYSTEM

The Bureau's objective at Albright was to demonstrate the technical feasibility of applying Burnout Control to a fire in a coal waste bank. The information gathered during site assessment suggested nothing to indicate that the process could not be applied to the Albright site.[6] Several criteria were set up for consideration by the architect-engineering firm contracted to design and oversee construction of the system:

1. The Burnout Control system is to generate exhaust flows of potentially oxidizing and corrosive gaseous combustion products at temperatures up to 982° C (1,800° F) and thermal power levels up to 5 MW (17.1 million Btu/h).
2. While recovery of useful energy would not be required in the present project, the design should consider the possible inclusion of an energy recovery system (e.g., a boiler-steam turbine) at a later time.
3. While air-pollution control systems for sulfur and other emissions would not be required initially, the design should consider the possible addition of scrubbers, if and when operational data dictate their need.
4. While previous work by the Bureau on Burnout Control would serve as a technical base, the designs for Albright should not necessarily be the same as those used previously—e.g., horizontal emplacement of the combustion manifold in the pile versus vertical emplacement and air cooling of ducts versus water cooling.
5. Total construction costs, excluding instrumentation, should not exceed $500,000 (1984 dollars).

The final design is depicted in the artist's drawing shown in figure 3. An induced draft fan applies vacuum on a combustion manifold (pipe with a perforated end section in the combustion zone), which is inserted into the bank at ground level. Fresh air is drawn into and through the bank by virtue of the induced vacuum and inherent permeability of the waste. The air and coal waste react within the bank, and hot gaseous combustion products are withdrawn from the bank through the perforated end section of the combustion manifold, which is connected externally, in series, to a hot exhaust pipe, a dropout tank, the induced draft fan, and finally to an exhaust stack. Ambient air for cooling the underground section of the manifold and/or for afterburning purposes is introduced directly into the underground portion of the manifold through a borehole cased from the surface of the bank to a point near the end of the manifold. To cool the exhaust pipe outside the bank, ambient dilution air is mixed with the exhaust gases at a point shortly after the hot exhaust exits the bank. Through probes and valves located in the ducts carrying the flowing gas streams, the burning rate and thermal output are measured and controlled (see figure 4).

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[5] According to verbal accounts, the pile was used primarily for disposal of reject coal, but fly ash from a nearby utility powerplant was also periodically disposed on the bank. It was also reported that several attempts were made to control the fire by surface sealing with fly ash.

[6] Acceptability of the site included obtaining suitable agreements with several property owners concerning the use of the waste bank, roadways, and rights-of-way, and with several State officials regarding applicable permits.

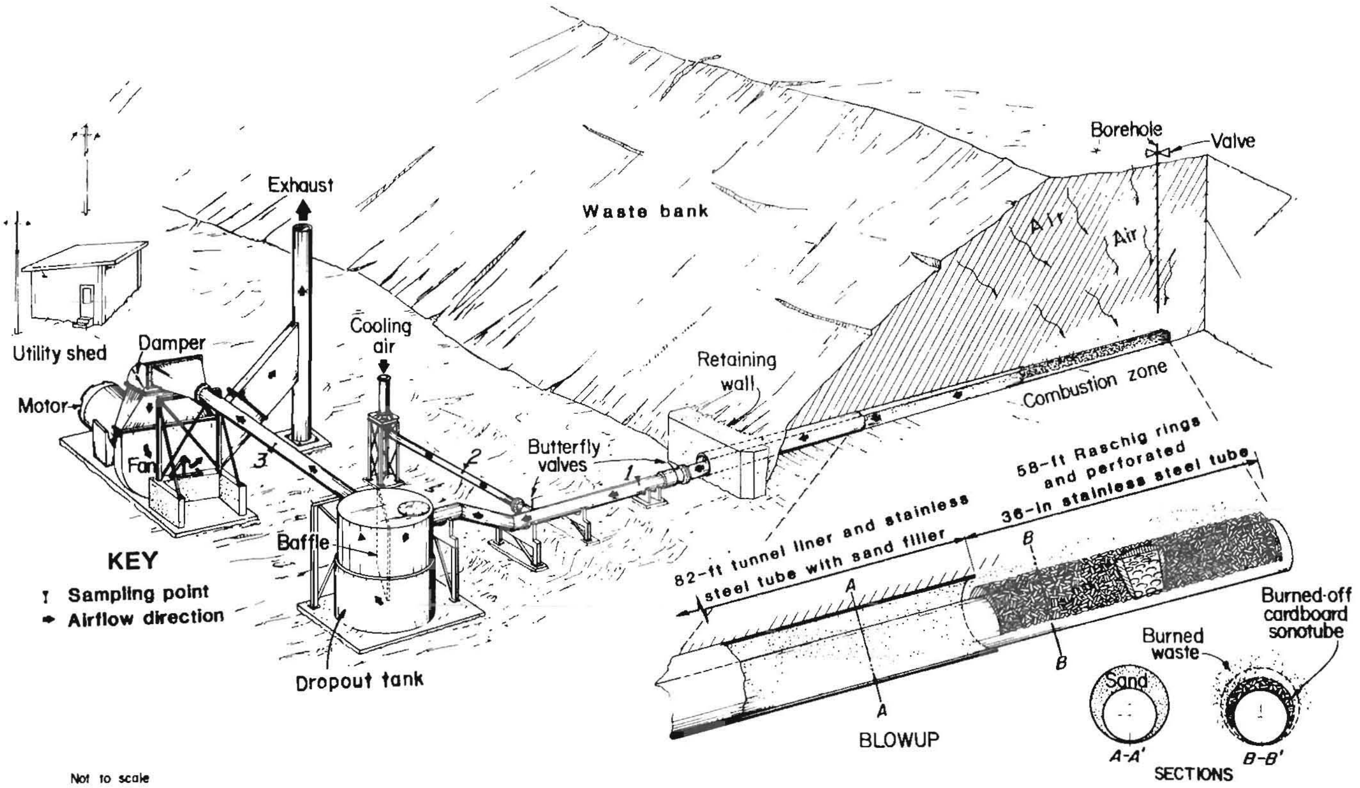

Figure 3.—Artist rendition of Burnout Control system (induced draft fan shown to left of dropout tank).

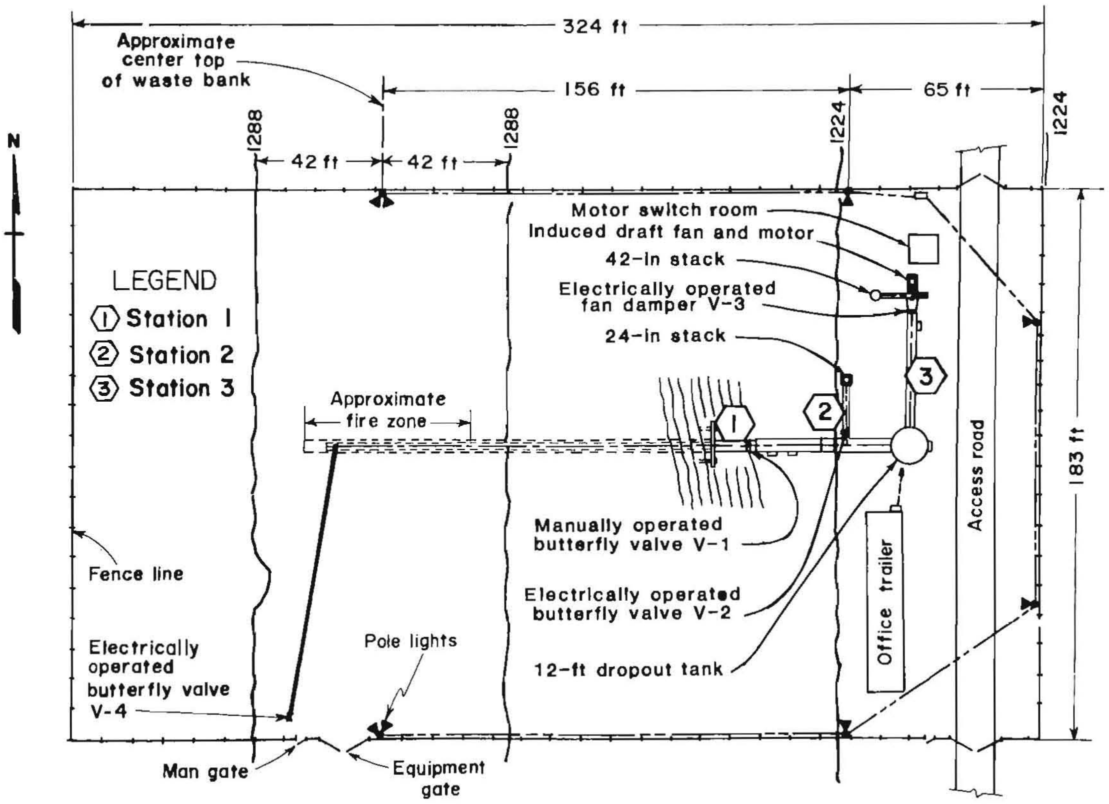

Figure 4.—Location of measuring and control stations.

The following is a brief description of the major parts of the Burnout Control ventilation system as initially designed and constructed (see figure 5):

Combustion Manifold

The combustion manifold consisted of a 36-in ID stainless steel duct, AISI Type 309, 3/16-in wall thickness. The duct is 137 ft long, including a 40-ft end section perforated by 300 2.5-in-diameter holes and a 10-ft half-round igniter section filled with charcoal and ceramic Raschig rings. The stainless steel was chosen to support up to a 35-psi vertical load at oxidizing atmosphere temperatures up to 980° C (1,800° F). The perforated end section was surrounded by up to a 1-ft-thick layer of 3-in ceramic Raschig rings (i.e., pieces of ceramic tubes). The layer of Raschig rings, having a 70 pct porosity, was to prevent direct contact between the duct and the burning waste without impeding the flow of hot gases into the duct.

Hot Exhaust Pipe

These exhaust pipes, 36-in-ID and 42-in-ID refractory lined ducts, were fabricated by casting 4-in-thick refractory in carbon steel pipes. The refractory is acid resistant and suitable for 1,800° F (980° C) service. The smaller diameter duct (24 ft in length) is connected to the combustion manifold through a butterfly valve and a slip joint (Type 309 stainless steel), which accommodates up to 4 ft of linear expansion of the manifold. Refractory lined couplings connect the 24-ft duct section to the 42-in-diameter duct, which in turn is connected to the dropout tank. A refractory lined "T" section at the juncture of the two duct sections connects the hot exhaust pipe to a 24-in-ID standard steel pipe through which ambient dilution air can be introduced into the hot gas stream.

Dropout Tank

The dropout tank has a 12-ft-diameter base, 18-ft-high cylindrical tank constructed of carbon steel with internal structural supports and a baffle plate. The tank is suitable for withstanding a vacuum of 70-in H_2O and a temperature of 316° C (600° F). The tank is equipped with a number of flanged openings of various sizes for (1) connecting with inlet and outlet gas flow ducts, (2) manhole entry, (3) explosive venting relief, (4) water drainage, and (5) instrument probes.

Induced Draft Fan

The fan is rated at 41,000 acfm when handling 316° C (600° F) combustion gases at 50-in H_2O draft. A 400-hp, 2,300-V electric motor powers the fan's corrosion resistant rotor at 1,780 rpm. The fan housing is equipped with an actuator-controlled inlet damper.

Stack

The stack is constructed of carbon steel pipe, 42-in OD 30 ft high.

Valves

Hot gas valve, V-1: 36-in manually operated butterfly valve of AISI Type 309 and Type 310 stainless steel, for service up to 980° C (1,800° F).

Cold air valve, V-2: 24-in actuator-controlled butterfly valve of mild steel construction.

Fan inlet valve, V-3: a louvered damper on the induced draft fan housing, actuator controlled, mild steel construction.

Figure 5.—View of Burnout Control system from top of waste pile (30,000-ft^3 sedimentation pond shown in upper right).

Top-of-bank air valve, V-4: 6-in actuator-controlled valve on pipe connected to the 8-in ID Type 304 stainless steel borehole casing that supplies cold air to the combustion manifold underground.

Instrumentation

Station 1 is located in the combustion manifold upstream of valve V-1. This station consists of thermocouple, pressure, flow, and gas sampling probes to allow on-line measurements.[7] Sensed electrical signals from the thermocouple and from nearby mounted pressure transducers are transmitted about 100 ft through an underground conduit to a 60-ft trailer, which served as combined office, workshop, instrumentation and control rooms. Gas samples are conditioned through a nearby mounted permeation tube dryer and then transported by tube bundle to analyzers in the trailer.[8]

Station 2 is located in the 24-in dilution air duct. Same arrangement as for station 1 except for absence of gas sampling.

Station 3 is located in the "cold" exhaust duct between the dropout tank and the fan. Same instrumentation arrangement as station 1.

CONSTRUCTION

Construction of the Burnout Control system began in September 1985 and was essentially completed (as initially designed) 9 months later. Much of the construction proceeded normally, but was delayed significantly by a record-high flood on the Cheat River, which destroyed portions of the access road, necessitating its reconstruction. However, there were several special occurrences that did have (in retrospect) a significant effect on the outcome of the Burnout Control trial.

Combustion Manifold

Installation of the stainless steel duct or combustion manifold was carried out with the aid of a 5-ft-diameter, 138-ft-long horizontal steel tunnel liner that was inserted by augering into the pile along its base. The stainless steel manifold pipe (in 40-ft sections welded in place) was slid into the tunnel, pushing ahead a 10-ft-long pallet containing about 2,000 lb of charcoal briquets to serve as an igniter (see figure 6). Upon completion of the manifold, the tunnel liner was withdrawn 50 ft to expose the perforated section of the manifold and the surrounding layer of ceramic Raschig rings to the coal waste. Prior to this installation, the contractor drilled three inspection boreholes from the surface of the bank into the path that the horizontal auger would take. This was to ensure that very high temperature material would not be intercepted by the auger. Unfortunately, air-rotary drilling rather than augering, used for this task loosened the surrounding waste material. This apparently resulted in flow (movement) of waste in the region of the boreholes as the 5-ft-diameter horizontal auger drove past these locations. At two of the three inspection hole locations (east and west), surface subsidence occurred during augering, which required filling and compaction with added coal waste. It is almost certain that the permeability of the coal waste was altered in these regions, leading to somewhat uneven (i.e., faster) localized burning during the burnout operation.

The disturbed waste probably contributed to the difficulties experienced by the contractor in withdrawing 50 ft of the steel tunnel liner from the waste bank. The flow of waste around and in direct contact with the tunnel liner apparently increased friction between the waste and the liner, such that the original force estimate (140 tons)[9] to withdraw the liner had to be greatly exceeded. This required fabrication of a new concrete bulwark (see figure 7) and the use of two large hydraulic jacks (1,500-ton capacity each), adding about 6 weeks to the task. During this time, sufficient air was introduced into the interior of the bank to cause self-heating and ignition of the waste around the manifold. The temperature readings at the west inspection borehole rose from an initial 90° to 700° C (194° to 1,290° F). Withdrawal of the liner was finally accomplished after applying 580 tons of force to break the bond that had formed between the waste and the liner.

8-in Cased Vertical Borehole

Subsequent to installation of the combustion manifold, an 8-in-diameter cased (stainless steel, AISI Type 304) borehole was installed from the top surface of the waste

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[7] In accordance with accepted practice, it was attempted to locate sampling stations so that there would be a length of at least 4 duct-diameters upstream and 8 duct-diameters downstream of perturbations in the gas flow. This proved impractical at station 1, which was about 2 duct-diameters upstream of the expansion slip joint, and at station 2, which was about 6 duct-diameters downstream of an elbow and 3 duct-diameters upstream of valve V-2.

[8] Nondispersive infrared CO and CO_2 analyzers, a paramagnetic O_2 analyzer, chemiluminescent NOX (NO_2 and NO) analyzer, and pulsed fluorescent SOX (SO_3 and SO_2) and H_2S analyzer. See reference 5 for a detailed description of the types of instrumentation used at Albright.

[9] In this report, "ton" indicates 2,000 lbf.

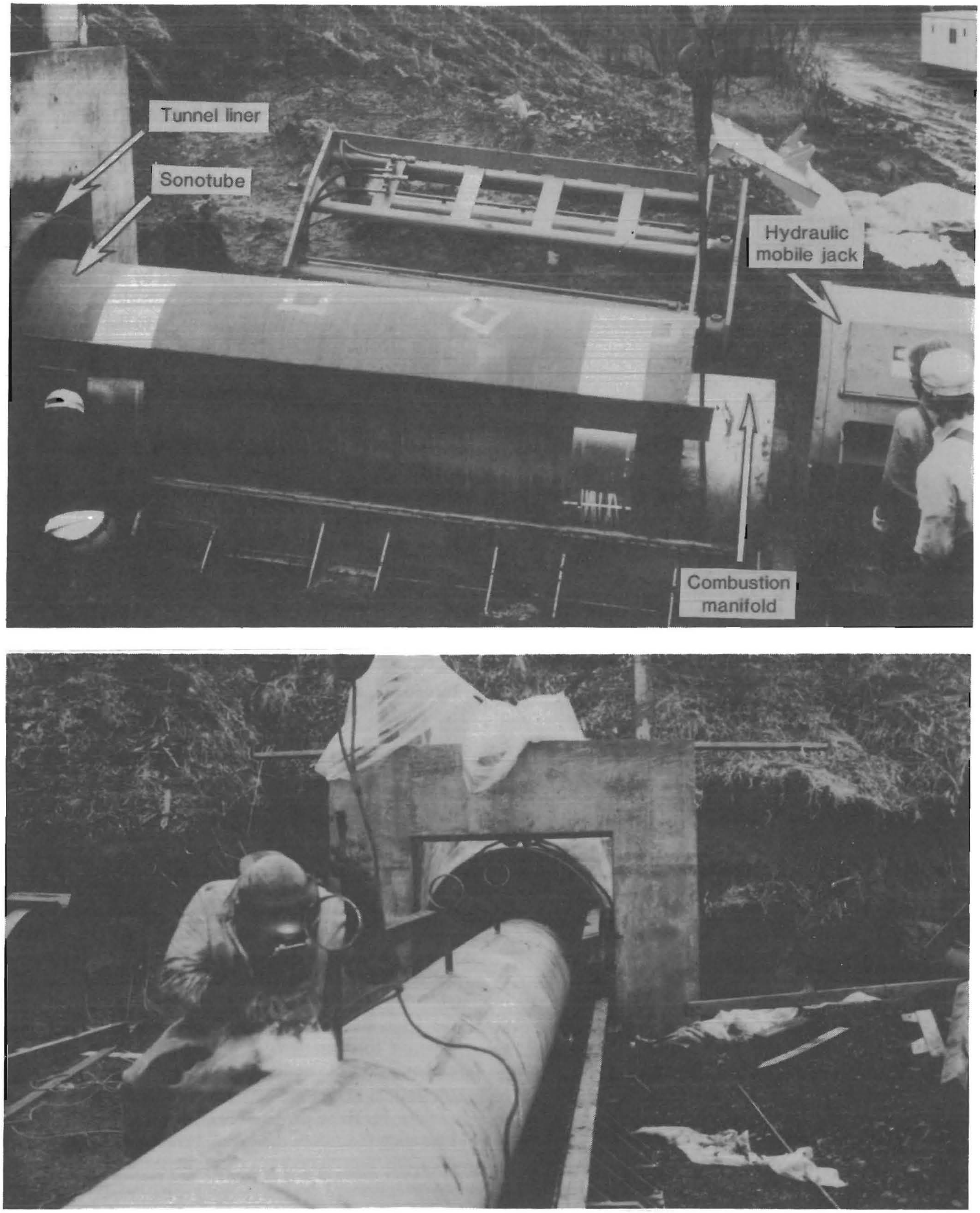

Figure 6.—Combustion manifold being inserted into tunnel liner. Top, perforated section (cardboard sonotube around manifold containing ceramic Raschig rings); bottom, adding lengths of stainless steel sections onto manifold.

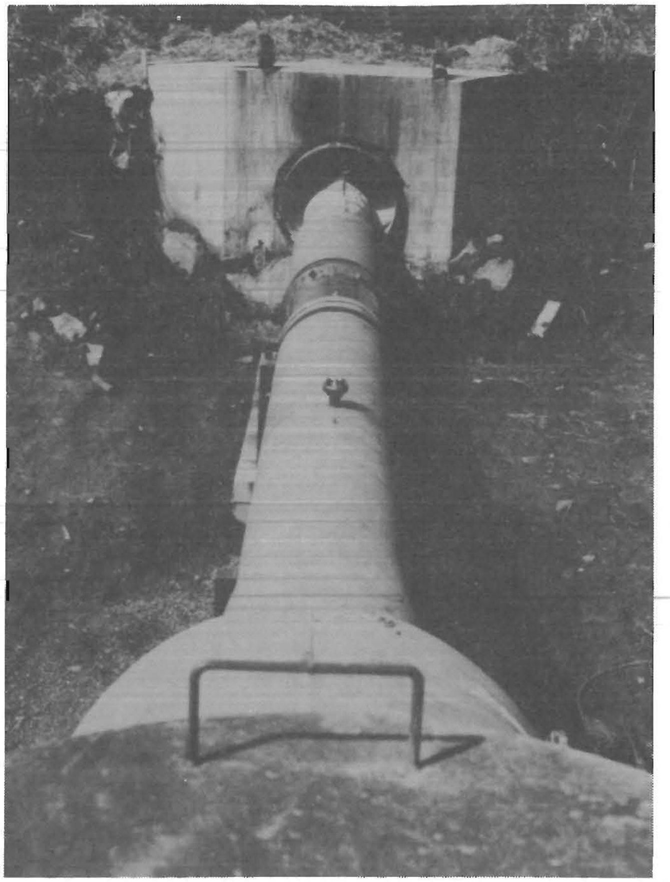

Figure 7.—View of 54-ft concrete bulwark from top of dropout tank (combustion manifold emerging from steel tunnel liner; sand seal between manifold and liner).

pile (near the location of the west inspection borehole) to terminate in the igniter zone of charcoal and Raschig rings at the end of the combustion manifold (see figures 3 and 4). This cased hole (with actuator-controlled valve) was to (1) supply air to ignite the charcoal and quickly establish a uniform cylindrical combustion zone within the pile, (2) supply afterburner air, if needed, to complete the burning of the hot exhaust as it moves through the combustion manifold, and (3) supply cold air directly to the combustion manifold, if needed, to reduce the temperature of the manifold below its maximum operational temperature (i.e., 982° C or 1,800° F). This borehole was augered to minimize disturbance of the waste; however, its location in a region already disturbed by air-rotary drilling for the inspection boreholes and subsidence still led to difficulties in installation of the casing to the required 41-ft depth. Due to continual collapse of the uncased hole, the contractors actually pushed and hammered the casing into the waste pile. This resulted in waste buildup within the casing, which the contractor then tried to remove with a smaller diameter auger bit. The borehole was apparently opened to its full depth (41.5 ft), but with an estimated 1-in thickness of waste still remaining attached to the inside casing wall, i.e., the annular space between the 8-in casing and the cleanout auger. Although positive evidence was obtained from the removed debris that the hole terminated in the zone of Raschig rings, the borehole never functioned as planned. It is surmised (in retrospect) that the debris attached to the inside wall of the casing fell inward to plug the bottom of the casing, and this plug hardened considerably as the burnout progressed. As it turned out, air from the 8-in borehole was not required for igniting the waste; however, it was vitally needed during burnout for afterburning and/or cooling of the hot exhaust. The problems this caused will be discussed in more detail in the "Burnout Control Operations" section.

BURNOUT CONTROL OPERATIONS

QUALITY ASSURANCE TESTING (DAYS 1 TO 55)

Initial Phase (days 1 to 14)

Startup of fan operations began on JD6126 (May 9, 1986) to test the various components of the Burnout Control system and to evaluate what modifications would be required. The plan was to achieve continuous around-the-clock operations at elevated temperatures as quickly as possible; however, numerous problems arose within the first 2 weeks, which led to interruptions in the operation. This can be seen from figure 8, which depicts time-line bar graphs of the daily average vacuum, temperature, flow, O_2 and CO at station 1 and the daily average SOX emissions at station 3.[10] During the first 14 days, the fan was on only 61 pct of the available time, and for 2 of those days, the fan was completely off (shown in figure 8 as days when the vacuum is zero).

The gas-sampling system apparently could not handle the large amount of water vapor present in the exhaust. This led to operational problems with the gas analyzers and questionable on-line results for CO, O_2, and SOX concentrations in the exhaust. This is reflected by the absence of data for these parameters in figure 8 when the fan was operating (i.e., when the vacuum was nonzero at station 1).

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[10] Daily averaged data in figure 8 and subsequent figures of this report refer to time-weighted averaging of the recorded data (generally every hour) during a 24-h operating day (midnight to midnight).

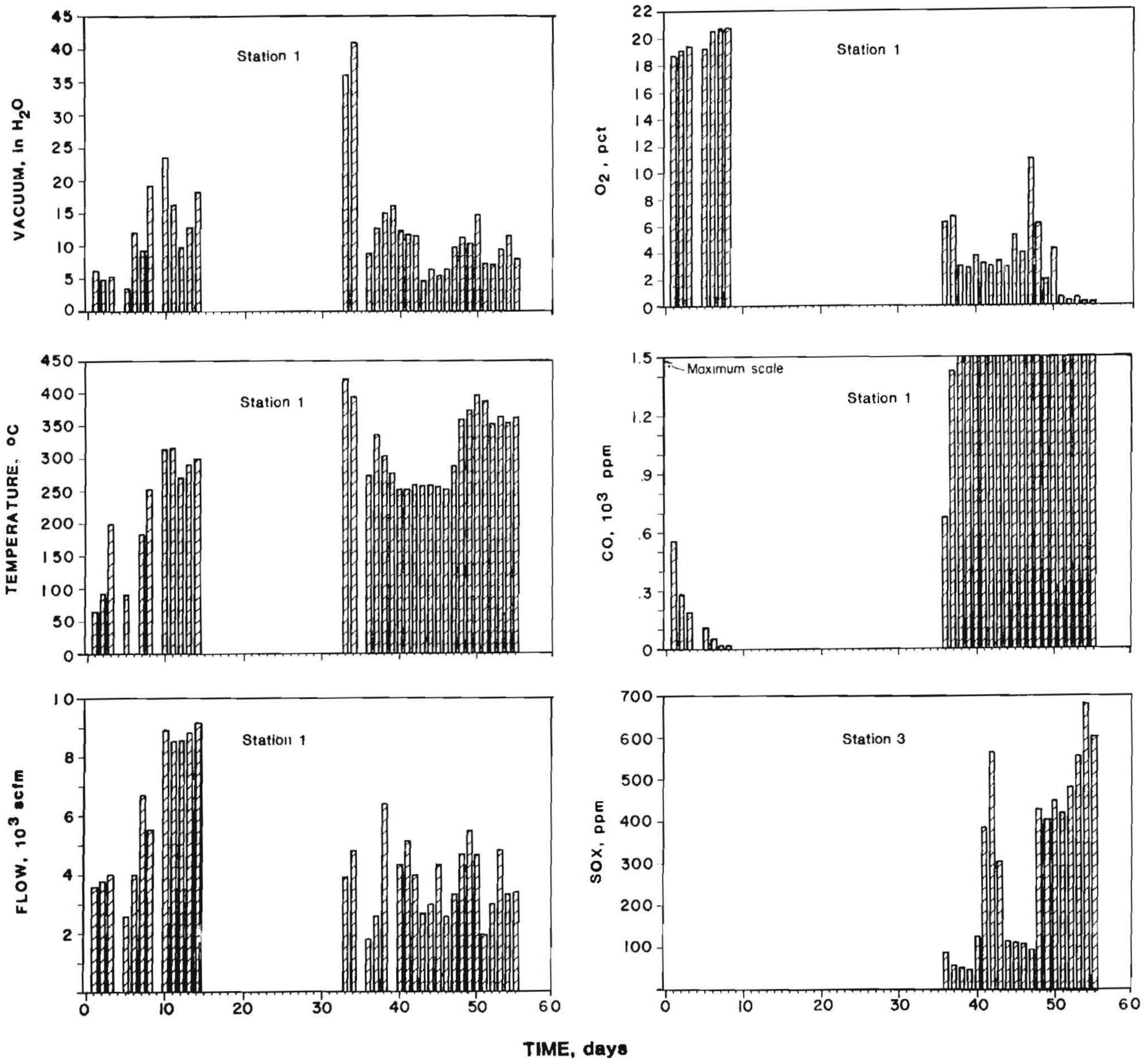

Figure 8.—Albright daily averages for JD6129 to JD6183.

A major design problem was the failure of a sand seal formed by blowing sand into the annular space between the tunnel liner and the nonperforated length of stainless steel combustion manifold (see figure 7). The seal was to prevent vacuum leakage along the exterior wall of the manifold, i.e., between the tunnel liner and the combustion manifold. Under the vacuum imposed in the interior of the pile, sand was sucked inward along the annular space into the perforated end section manifold and then outward along with the exhaust. This meant that the induced airflow was partially short circuited through the tunnel liner rather than flowing through the burning waste. This resulted in less suction on the bank, excessive dilution and cooling of the exhaust, tar-coated sand in the exhaust, and fouling of the fan damper, which in turn contributed to breakdown of the fan damper actuator mechanism. The low-temperature exhaust 100° to 300° C (212° to 572° F) and inadequate aeration of the burning waste resulted in the production of odoriferous reduced combustion products (such as H_2S and COS), which in turn led to complaints from nearby residents about the exhaust odor and the fan noise.

The system was shut down from May 22 to June 7, 1986 (days 15 to 32), to make necessary repairs to the damper and its actuator and to install a brick stopping between the tunnel liner and the combustion manifold to serve as the sand seal. In addition, coiled tubing condensation traps were added to the gas-sampling system upstream of the permeation tube driers to aid in moisture removal from the on-line sampled gas.

Second Phase (days 33 to 55)

Intermittent problems with flow and gas composition measurements at station 1 persisted. The problems were eventually traced to (1) electrical instabilities in the on-line strain gage pressure sensors, and (2) continued moisture and solids buildup in the remote gas-sampling system, which would periodically foul the on-line permeation drier tube and/or analyzers.

The objective for this period of testing was dominated by the desire to achieve high exhaust temperatures (greater than 600° C or 1,112° F) with moderate O_2 levels (about 5 pct) that would enhance complete combustion of gases in the exhaust manifold and hopefully alleviate the odoriferous exhaust, which results from fuel-rich burning conditions. As can be seen from figure 8, low temperatures (300° to 400° C or 572° to 752° F), low O_2 concentrations (less than 5 pct), and high CO concentrations (greater than 1,500 ppm[11]) dominated the exhaust condition at station 1. The West Virginia Air Pollution Control Board was receiving numerous complaints from nearby residents that foul odors and fan noise were emanating from the site. Seasonal weather conditions apparently played a significant role in this connection with the onset of temperature inversions that formed in the river valley almost every night. Elevated river temperatures from a power station's cooling water discharge 1 mile upstream contributed to the fog conditions.

Achieving high temperatures through suction of more air into and through the pile was believed to be the key to solving the odor problem. With higher vacuum, more air could be drawn into the pile, but higher vacuum also meant greater exhaust flow rates, which would lead to higher levels of pollution and noise, all while attempting to achieve the higher temperatures. In an attempt to resolve this dichotomy, Burnout Control was cycled through periods of low and high exhaust levels. Low vacuum levels (about 5 in H_2O) were applied at night or whenever the weather conditions were unfavorable for dispersing the stack exhaust, and higher vacuum levels (20 to 50 in H_2O), at all other times. It was hoped that in this manner, favorable operating conditions could be achieved, albeit slowly, but without undue disturbance of the local residents. The temperature at station 1, which initially decreased, eventually increased from a level of 300° C (572° F) to a level of 400° C (752° F) after day 47 (see figure 8). However, the temperature rise apparently leveled off and was accompanied by a decrease in O_2 concentration to below 1 pct, and an increase in SOX level to about 700 ppm at the exhaust stack (see figure 8). The inability to draw air directly into the combustion manifold through the clogged 8-in ventilation pipe undoubtedly contributed to the overall fuel-rich burning condition.

At the end of this second phase of equipment testing, it was decided to incorporate a wet alkali scrubber into the exhaust system (dropout tank). This would allow the Burnout Control system to operate continuously at high vacuum, which was perceived to be necessary to achieve the desired O_2 and temperature levels in the exhaust.

Design, fabrication, and installation of the scrubber system was carried out at the field site over an 11-week period, after which testing of the entire system was resumed. Figure 9 shows in schematic form how the scrubber was incorporated into the original ventilation exhaust ductwork. (A written description of the scrubber and its operation is given in appendix B.) A photograph of the modified Burnout Control system is shown in figure 10. As shown, the system has been winterized through the use of sheet metal structures to house the heat exchanger and spray pump assembly.

Also shown in figure 10 is a muffler that was installed on the exhaust stack in an effort to decrease fan noise, which had caused complaints from residents across the river. Unfortunately, the muffler did not function to a satisfactory extent.[12]

TEST PERIOD WITH SCRUBBER SYSTEM (DAYS 134 TO 196)

Upon completion of the installation of the wet alkali exhaust scrubber, Burnout Control operations continued with the main objective still to overcome the fuel-rich burning conditions that were experienced earlier. Unfortunately, numerous problems were encountered in maintaining the scrubber, which in turn seriously affected the burnout operations, namely, the ability to sustain high vacuum fan operations and to achieve O_2 rich burning conditions and the elimination of odors. The percentage

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[11] Maximum scale on the on-line CO analyzer was 1,500 ppm.

[12] The fan noise was due primarily to the fan-blade rotation (328 Hz), yielding a peak level of 69 dBA as measured at the open campground directly across the river (800 ft distant). This level of sound is within a range deemed acceptable for industrial areas, but outside the 50 to 60 dBA maximum suggested for residential areas (*8*). The installed muffler was specified by its manufacturer to reduce stack noise by about 30 dB, which would have brought the A-scale decibel level at the campground to well within desired range; however, in actual operation, the level was reduced only 5 dBA, and the complaints, not at all.

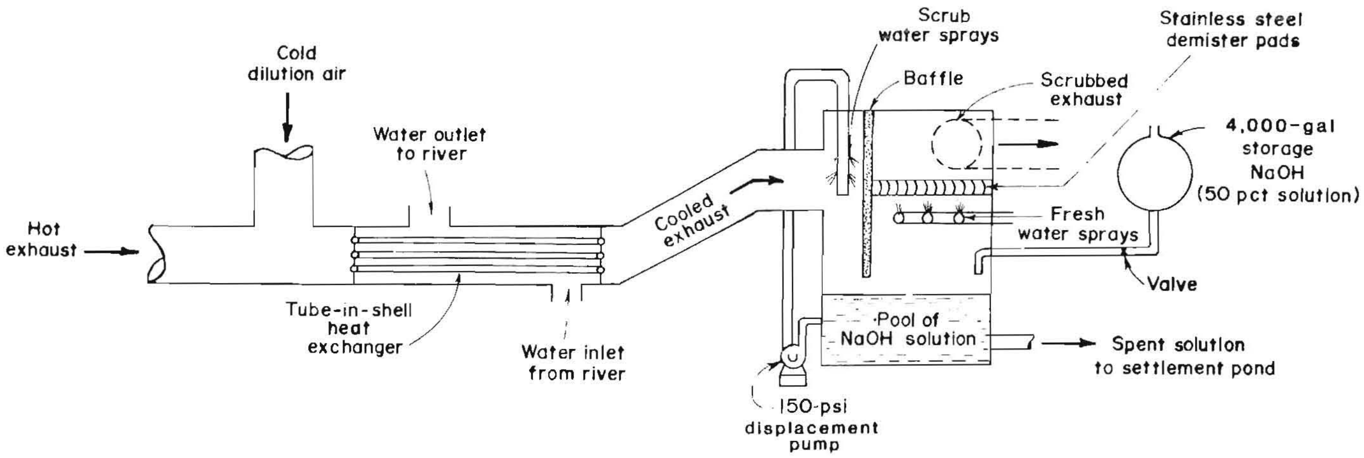

Figure 9.—Diagram of added wet alkaline scrubber system.

Figure 10.—Burnout Control system after installation of scrubber and stack muffler and after winterizing (metal shed in foreground encloses tube-in-shell heat exchanger).

of time the fan was off during this time period was 37 pct, due mostly to breakdown of subassemblies related to the scrubber system. These breakdowns included (1) corrosion and leakage of tubes in the tube-in-shell heat exchanger, (2) leakage in the piston pump that fed alkali to the sprays, (3) plugging of the submerged river foot-valve through which cooling water for the heat exchanger was obtained, (4) corrosion and loss of spray heads, and (5) excessive breakthrough of scrubber solution through the demister pad with the resultant buildup of cementitious coatings on the fan blades and the fan inlet damper (causing fan imbalance, sticking, louvers, and malfunction of the damper actuator).

During this time period, the vacuum was varied between 2 and 38 in H_2O (see figure 11). The exhaust temperature rose to as high as 700° C (1,292° F), with an average temperature of 500° C or 932° F, but the O_2 concentrations remained mostly at less than 2 pct, indicating fuel-rich burning conditions. This was confirmed by the CO levels observed at station 1; these levels were continuously greater than 1,500 ppm, i.e., exceeding the maximum scale of the on-line analyzer. Gas chromatograph (GC) analyses of batch samples from station 1 yielded very high levels of CO, ranging from 0.7 to 4.0 pct. All efforts to increase airflow through V-4 directly to affect more efficient afterburning in the exhaust manifold did not succeed. These efforts included dropping four separate explosive charges (1 lb each) down the 8-in vertical borehole to break up whatever was apparently clogging the ventilation pipe. The explosives did lead to a temporary increase in flow through V-4 (from zero to 1,000 acfm at 20-in H_2O vacuum), but the increase was apparently insufficient for achieving complete afterburning. Shortly after the use of the explosives, the recorded station 1 exhaust temperature rose to over 700° C (1,292° F), but the O_2 level remained at only 0.5 pct (see day 175 in figure 11).

On average, the scrubber system was successful in removing about 60 pct of the SOX passing station 1 as

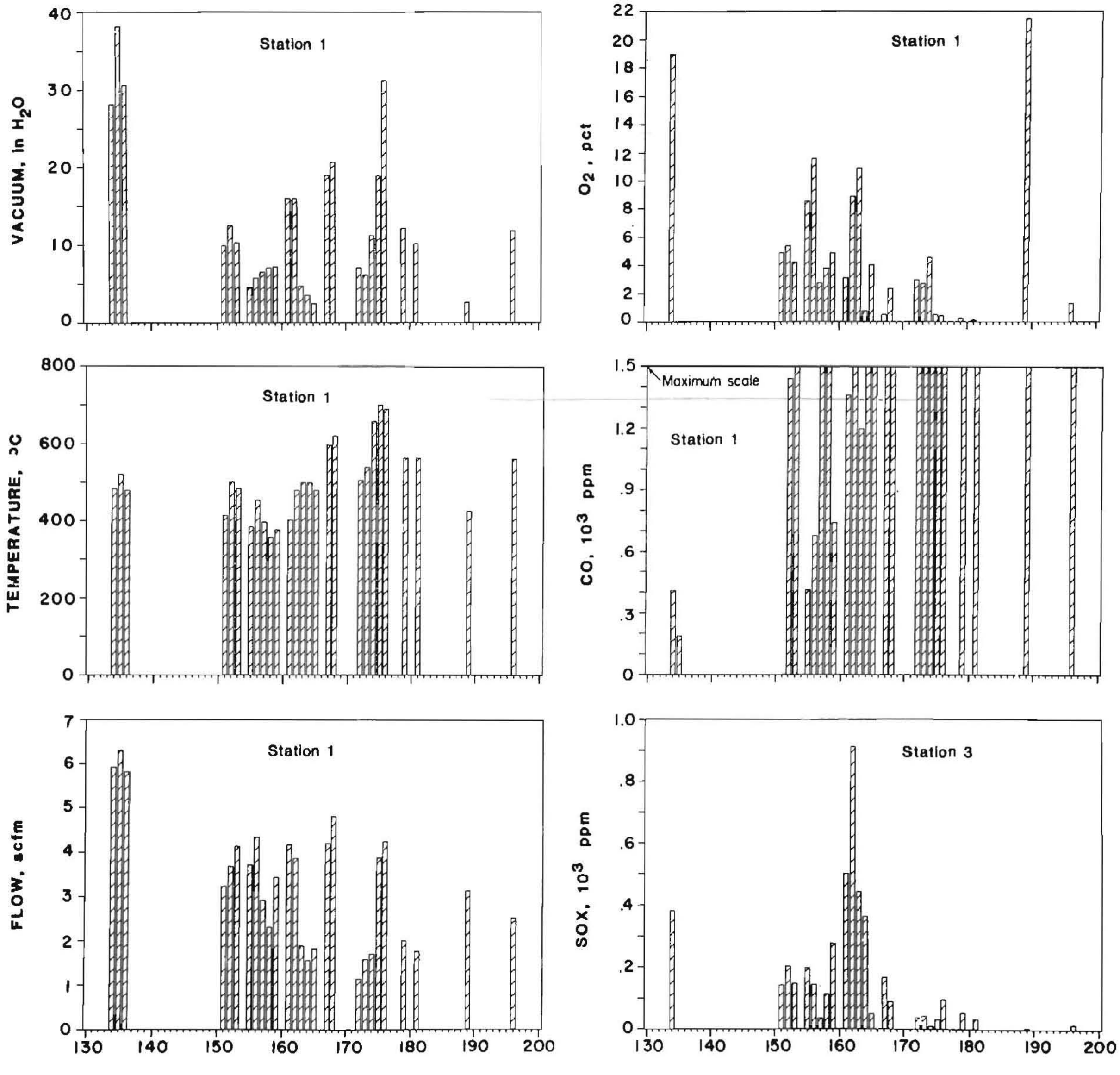

Figure 11.—Albright daily averages for JD6258 to JD6328.

long as the pH level of the scrub solution was maintained at 8 or above.[13] However, the small amount of odoriferous constituents released to the atmosphere (primarily reduced sulfur gases such as H_2S produced during fuel-rich burning) was still sufficient to cause complaints from nearby residents. This in turn led to a decision to impose operational constraints on the Burnout Control system, namely, when weather conditions were not favorable for dispersing the stack emissions away from residents across the river, the station 1 vacuum was lowered to reduce the amount of combustion products exhausted. This decision was probably not optimal since the general trend of the data suggested that higher vacuums would lead to higher exhaust temperatures. A plot of vacuum versus temperature for the time period (see figure 12) shows considerable scatter; however, the data do suggest a possible correlation between higher exhaust temperatures and higher vacuums. Also, it was known that temperatures greater than 650° C (1,202° F) were needed to ensure afterburning with O_2 (*4*). However, at operating days 175 and 176, when both high temperature and high vacuum were achieved, the O_2 level at station 1 still remained quite low (0.4 to 0.5 pct). It was finally concluded that the waste pile fire was probably behaving like a deep packed bed gasifier (perhaps as much as 40 ft deep), which would consume all the O_2 drawn into it, even at high vacuum. Hence, complete combustion of the fuel-rich gases generated in the pile would have to be achieved by afterburning in the exhaust manifold. This would only occur when sufficient additional air could be drawn directly into the manifold, e.g., as through V-4 as versus through the surface of the waste pile.

The test period ended with the decision to install additional ventilation ducts that would supply air directly into the high-temperature exhaust manifold. This was not a simple task in view of the large high-temperature zone of burning waste above the combustion manifold and the accompanying surface subsidence. These potential hazards were avoided by auger tunnelling from beneath the waste pile directly into the "ignition" zone at the end of the combustion manifold. During December 1986, two 12-in-diameter, 100-ft-long steel-lined ventilation tunnels were installed with manually controlled gate valves, V-5 and V-6 (see figure 13). Also during the November-December period, subsidence zones around the vertical observation boreholes were filled in and heavy fencing wire was rolled out flat over the surface of the pile as an additional safety precaution.[14]

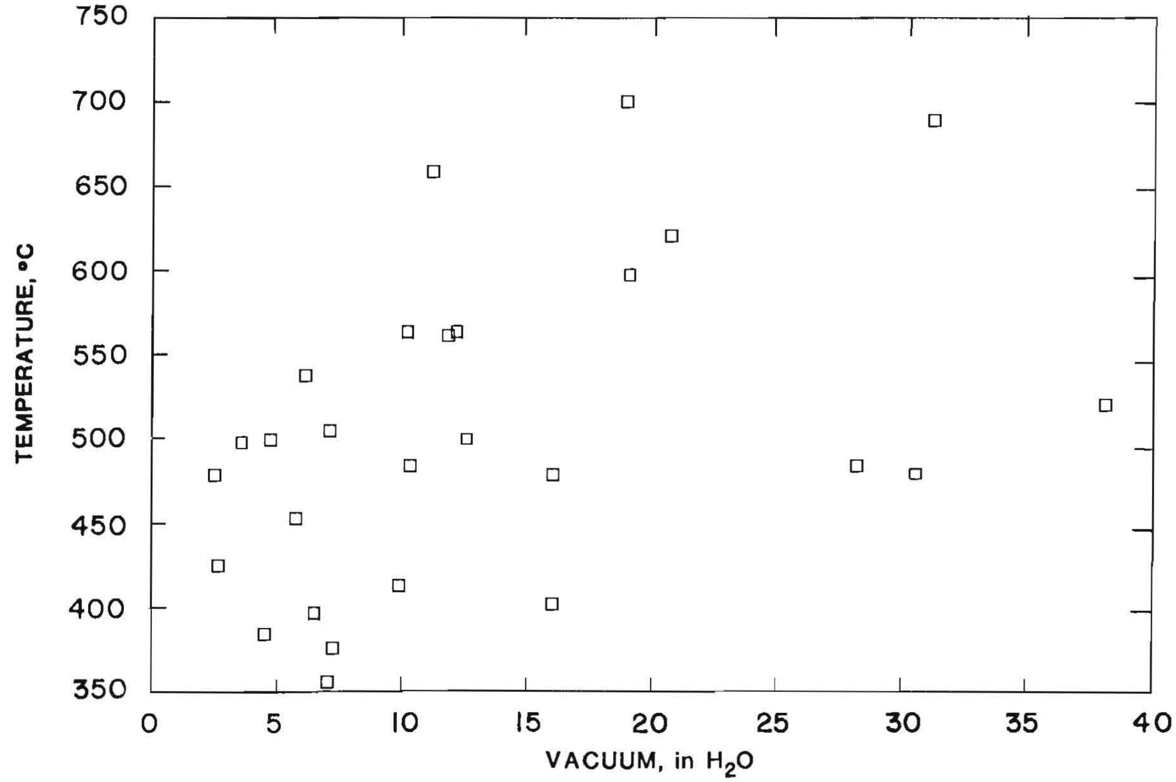

Figure 12.—Albright daily averages for JD6258 to JD6328: temperature versus vacuum.

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[13] Suflur removal efficiency is calculated from the sulfur mass balance based on measurements of SOX (parts per million) and flow (standard cubic feet per minute) at stations 1 and 3. Removal efficiency, pct = [1-(SOX3·SCFM3)/SOX1·SCFM1)]·100.

[14] The fencing wire was placed for emergency access only. Operating personnel were normally prohibited from walking over a 40- by 80-ft-wide section of the pile surface centered over the combusiton manifold.

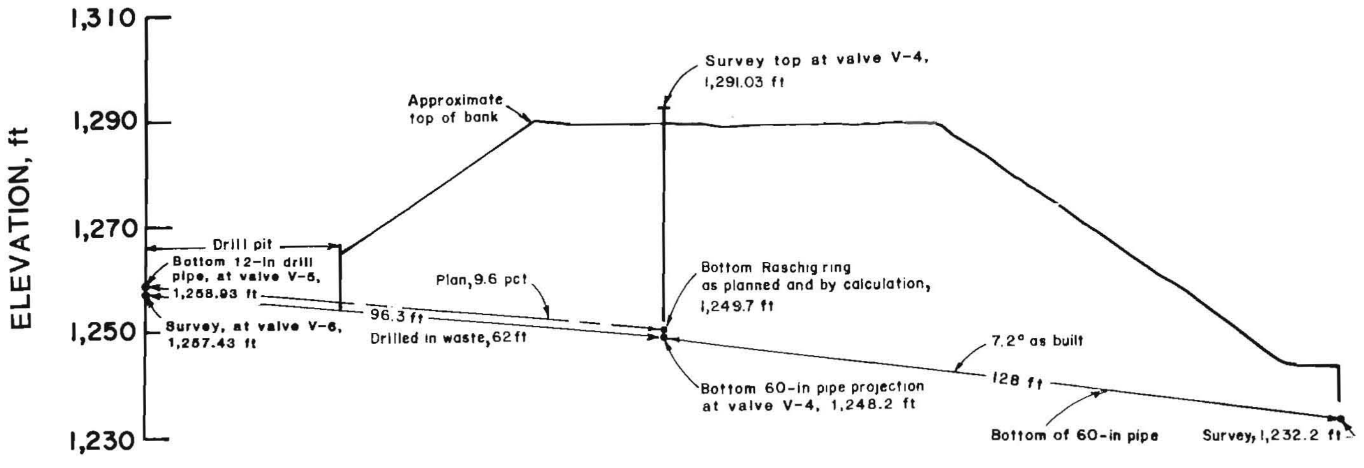

Figure 13.—Horizontal drilling setup for 60-in tunnel liner and two 12-in afterburning air ducts (V-5 and V-6).

OPERATIONAL PERIOD WITH AFTERBURNING AND SCRUBBING (DAYS 236 TO 316)

Shortly after the resumption of fan operations, the effect of the additional afterburner air (1,200 to 1,400 scfm) was apparent. During the first 11 days (days 236 to 247), the exhaust temperatures at station 1 rose to greater than 700° C (1,292° F), with O_2 levels generally exceeding 3 pct and CO levels dropping to less than 250 ppm by on-line analyses (see figure 14). This exhaust output at station 1, achieved at vacuum levels of 10 to 20 in H_2O and flows of 1,000 to 4,200 scfm, was accompanied by a SOX concentration at station 1 (not shown in figure 14) of about 500 ppm, which is only about 10 pct of the theoretical maximum based on fuel-sulfur. The alkaline scrubber performed at an average SOX removal efficiency of 40 pct, but even at this relatively poor removal efficiency, total sulfur emissions at the stack were generally less than 200 ppm with little noticeable odor (H_2S concentrations averaged about 8 ppm at station 1 and 3 ppm at station 3).[15]

During day 247, fan operations had to be turned off (days 248 to 271) while needed repairs were carried out on the alkaline scrubber and fan damper systems; e.g.: (1) The corroded cylinders and valves in the high-pressure spray pump were refurbished, (2) the demister pad area was increased to improve the efficiency of capture of alkali droplets at the higher exhaust velocities, (3) the river pump foot valve was repaired and a submergible wire-screen enclosure was constructed to prevent clogging of the coolant water inlet, and (4) the louvered fan damper, which had suffered considerable corrosion because of alkali droplets passing through the demister, was refurbished.

Burnout operations were restarted on day 272, initially at higher vacuums (20 to 35 in H_2O). As can be seen from figure 14, exhaust temperature and composition at station 1 quickly returned to the previous complete combustion values. At elevated vacuum (e.g., 35 in H_2O), the flows increased to over 7,000 scfm, leading to some of the highest thermal outputs produced during the field trial. (Based on the recorded hourly data, the output at times exceeded 5.5 MW.) However, it was observed that attempting to maintain the high-vacuum operation led to what appeared to be a cycling of the combustion stoichiometry. The temperature at station 1 would drop rather quickly to about 500° C (932° F) accompanied by an increase in O_2 level to about 8 pct, and then after awhile, it would return almost as suddenly to a high value along with low levels of O_2. This is shown in figure 15, which is a plot of the hourly data recorded for operating days 274 through 277. These sudden changes are believed to involve the quenching and reignition of gaseous combustion processes in the afterburner section of the exhaust manifold. Apparently, the cold air (1,000 to 1,400 scfm), added to the manifold through V-5 and V-6, can cause quenching of afterburning as well as promoting it. When afterburning occurs efficiently, O_2 from added air is consumed in the manifold during the completion of burning

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[15] H_2S levels measured at less than 10 ppm are highly questionable. This is due to the method of determination that involves subtracting two experimental quantities (SOX minus SO_2), which are nearly the same in value. Small errors in the SOX and SO_2 measurements can lead to rather large percentage errors in the computed result for H_2S.

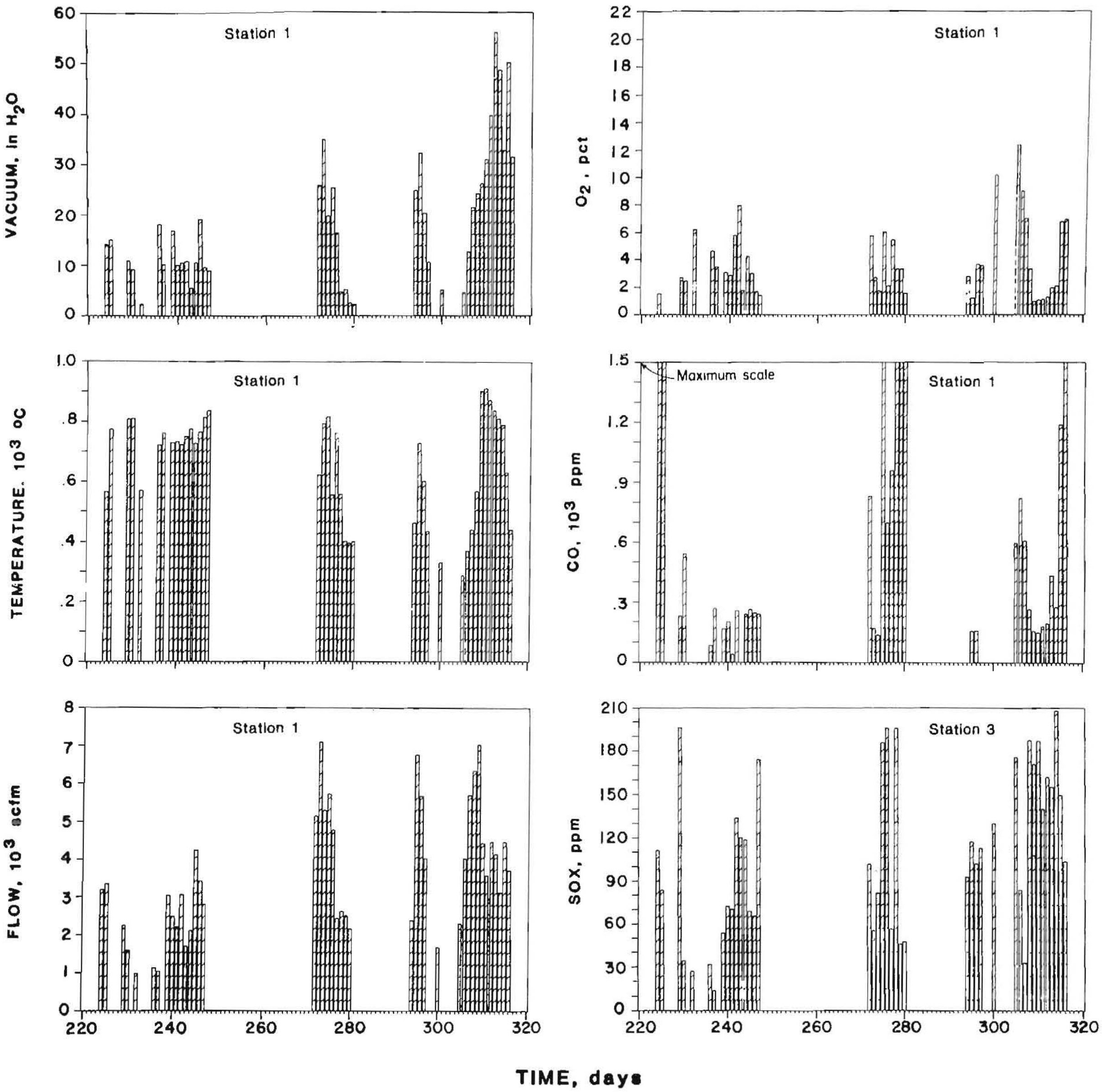

Figure 14.—Albright daily averages for JD6348 to JD7079.

of the fuel-rich gases being drawn from the waste bank. This leads to high temperatures, relatively low concentrations of O_2, and very low concentrations of CO and hydrocarbons in the exhaust flow (less than 200 ppm). However, if for some reason the afterburning reaction is quenched, the added air simply dilutes the fuel-rich gases in the manifold. This in turn leads to elevated O_2 levels, lower temperatures, and relatively high levels of CO and unburnt hydrocarbons (greater than 1,500 ppm).

Unfortunately, the quenching of afterburning on day 277 led to a return of odoriferous stack emissions, which in turn resulted in regulatory constraints on how and when the fan could be operated, even with the scrubber system in operation. To help alleviate these constraints, fan operations were temporarily stopped while the spray nozzle headers, which had suffered considerable corrosion, were reconstructed in stainless steel. Also, electrically operated butterfly valves were installed at V-5 and V-6

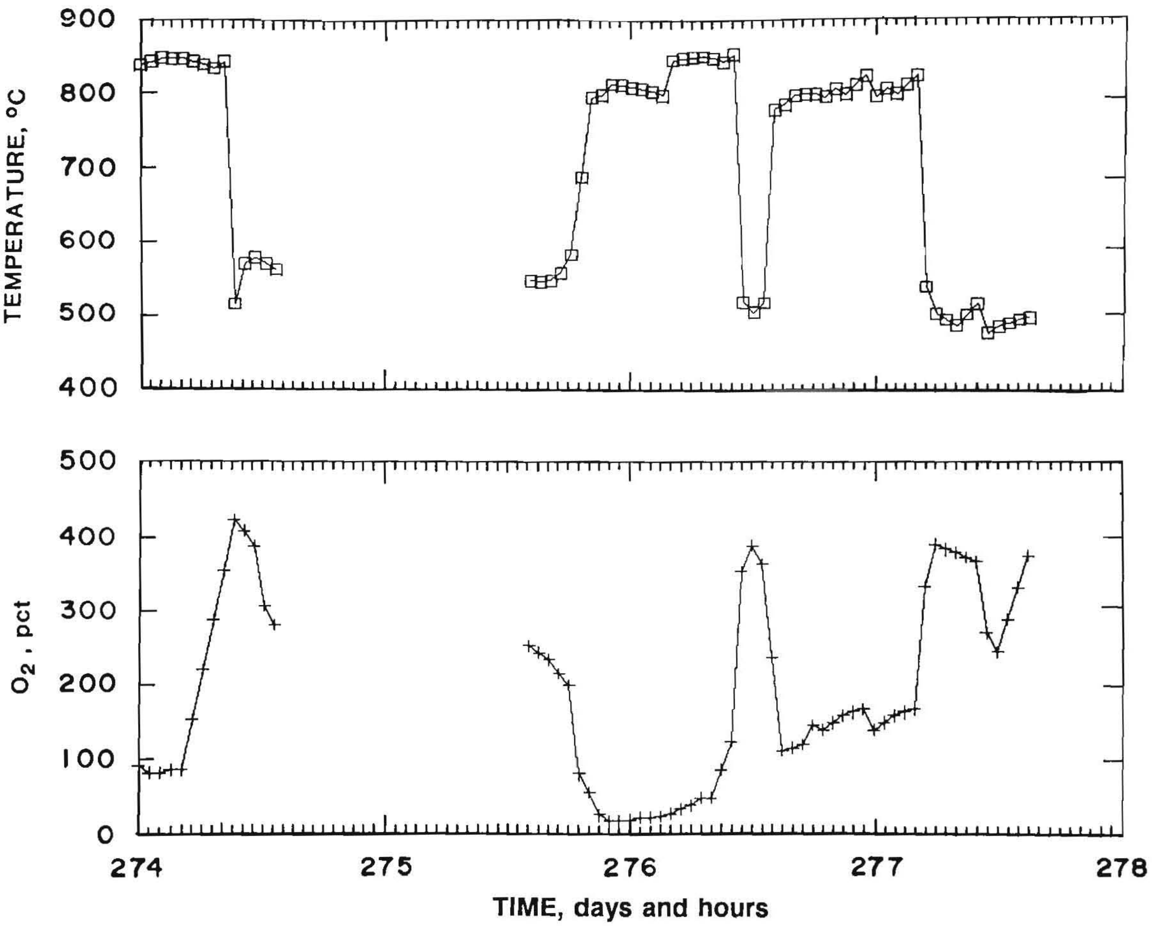

Figure 15.—Albright hourly data for JD7037 to JD7040: temperature and O_2 concentration at station 1. (Tickmarks between days indicate hours.)

(replacing the original manual gate valves) to enable more precise remote control of the afterburner air from the instrumentation trailer. Steady fan operations were continued on day 307 (JD7070) after fabricating and testing these installations.

Figure 16 depicts the recorded hourly output for the next 10 days of operation (days 307 to 317), which turned out to be the last days of the field trial. With the vacuum initially at 20 to 25 in H_2O and both afterburner air ducts open, the temperature at station 1 quickly rose to a level of 450° to 500° C (842° to 932° F), suggesting that the 1,000 to 1,400 scfm of added air through V-5 and V-6 were not reacting with the hot waste bank fuel gases. The on-line CO analyzer was malfunctioning at the time, but GC analyses of grab samples indicated 1.5 to 2.0 pct CO plus hydrocarbons in the exhaust at station 1. After about 1-1/2 days of operation at this level (i.e., during JD7070 and JD7071), afterburning was initiated with a relatively rapid rise in temperature to greater than 900° C (1,652° F). The thermal power level rose to 5 MW in keeping with the combined high flow rate and high temperature, which was now approaching the upper limit of the design specifications. The results of CO gas analyses gave supporting evidence for efficient afterburning, indicating less than 200 ppm on the on-line analyzer and less than 35 ppm in the grab samples (i.e., by GC analyses).

Unfortunately, the high flow output of JD7072 was not sustained as can be seen from the data beyond JD7072 in figure 16. For no apparent reason (at that time), the exhaust flow at station 1 began to decline and continued falling through JD7073, even though the vacuum was increased from 25 to 35 in H_2O. At the same time, the temperatures remained elevated at 850° to 950° C (1,562° to 1,742° F). In an effort to maintain high flows, the vacuum

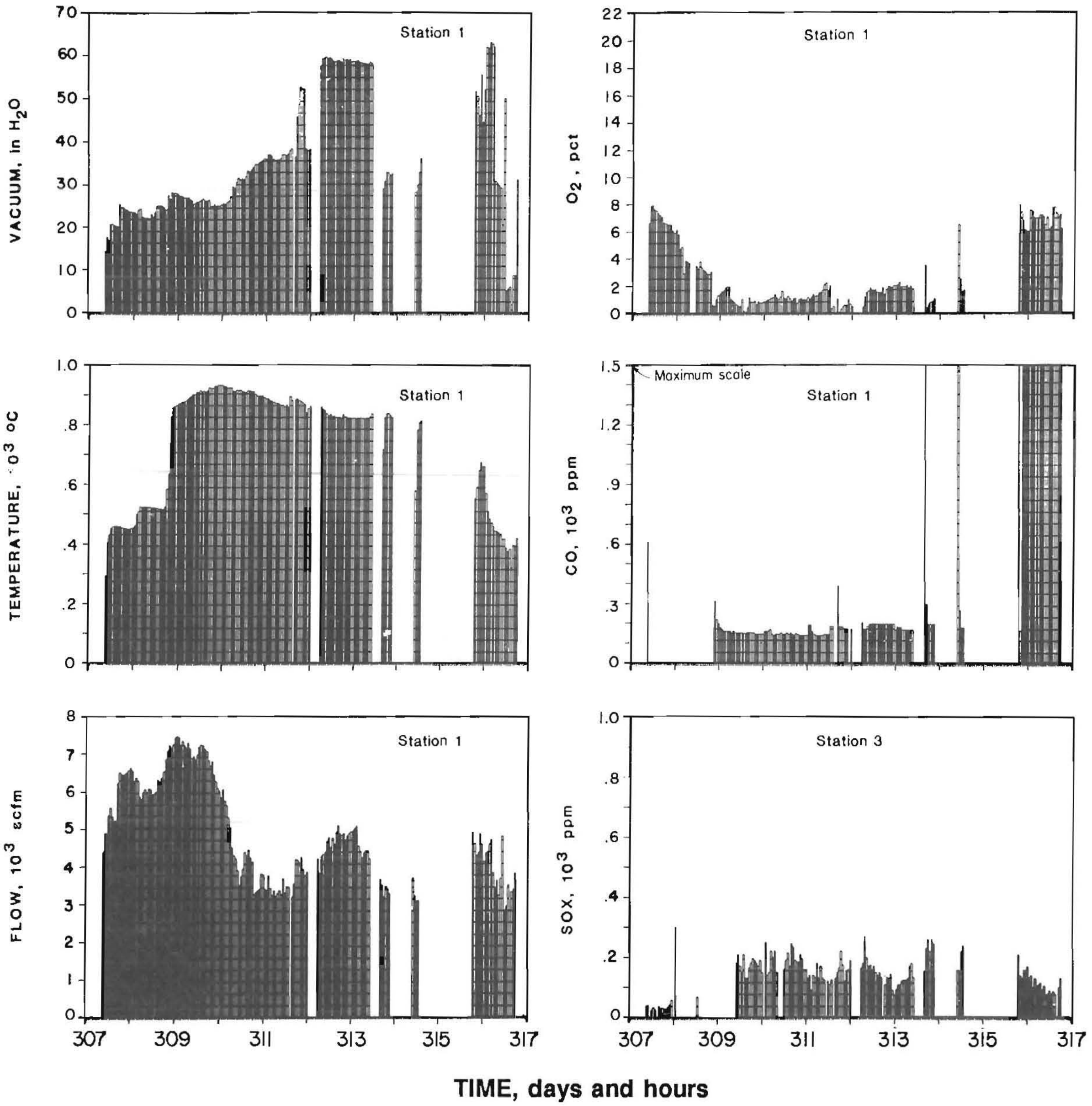

Figure 16.—Albright hourly data for JD7070 to JD7080. (Tickmarks between days indicate hours.)

was increased even higher to 50 in H_2O. This had a slight positive effect on the flow, but much less than what would be expected based on previous measurements of vacuum versus flow (see figure 17). Inasmuch as there was considerable concern about the apparent change in vacuum versus flow response for the waste bank, as well as for the considerable vibration that was occurring with the fan, fan operations were stopped to allow for assessment of the data and for cleaning and balancing of the fan blades, the housing, and the fan louvered damper. On JD7079 (day 316) the fan was restarted and a test of pressure versus flow was made, which indicated that the manifold had probably collapsed (curve for day 316 in figure 17). This was confirmed the next day when the duct at V-1 was disassembled to expose the interior of the manifold. Indeed, the manifold pipe was essentially sucked closed by the force (up to 2.5 psi) imposed by the vacuum at the elevated temperatures achieved (see figure 18).

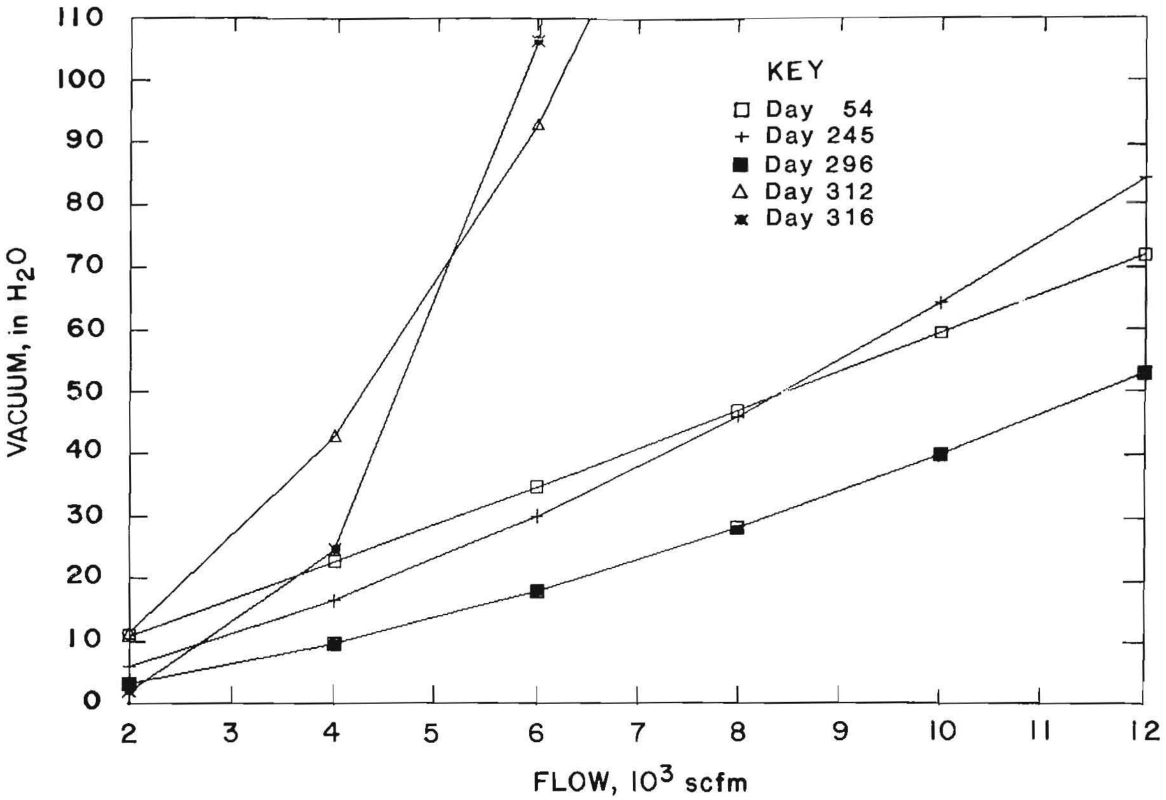

Figure 17.—Flow test data (taken on days 54, 245, 296, 312, and 316).

Inasmuch as the pipe was designed to support a 35-psi vertical load at temperatures in the range 1,500° to 1,800° F (800° to 980° C) (*7*), it must be presumed that the temperature inside the manifold exceeded the temperature measured at station 1. In any event, it was concluded that the field trial should be terminated at this time.

In the days that followed JD7080, the Burnout Control system was dismantled and the property was returned to the owners and to the West Virginia Department of Energy for their action under the Abandoned Mined Land Reclamation Program.

DISCUSSIONS AND CONCLUSIONS

ENERGY CONSIDERATIONS

During the entire 316-day period of testing and operation of the Burnout Control system, the fan was on for a combined total of 1,625 h (21 pct of the available time). Of this time, only 42 days (not always consecutive) involved essentially around-the-clock fan-on operations. From this viewpoint, and from the reasons already described as to why continuous fan operations were not achieved for longer time periods, the Albright field trial might be considered an engineering disaster. On the other hand, coal waste was burned, and according to measured temperatures and flows during fan-on operations, a total 8.12 billion Btu of thermal energy was produced at station 1, corresponding to 700 st of waste consumed directly through Burnout Control. This operational output in turn corresponds to a waste-burning rate of 10.3 st/d (on average), which can be compared with a value of 35.3 st/d achieved when the system operated (albeit for short time periods) at a 5-MW thermal output (i.e., the design level). From subsidence measurements (see "Subsidence Considerations" section) and surface observations made during and after the field trial, it seemed that the burning waste was contained in an inverted trapezoidal-shaped volume centered above the manifold. The trapezoid, having a 60- by 80-ft base (surface expression on the top of the

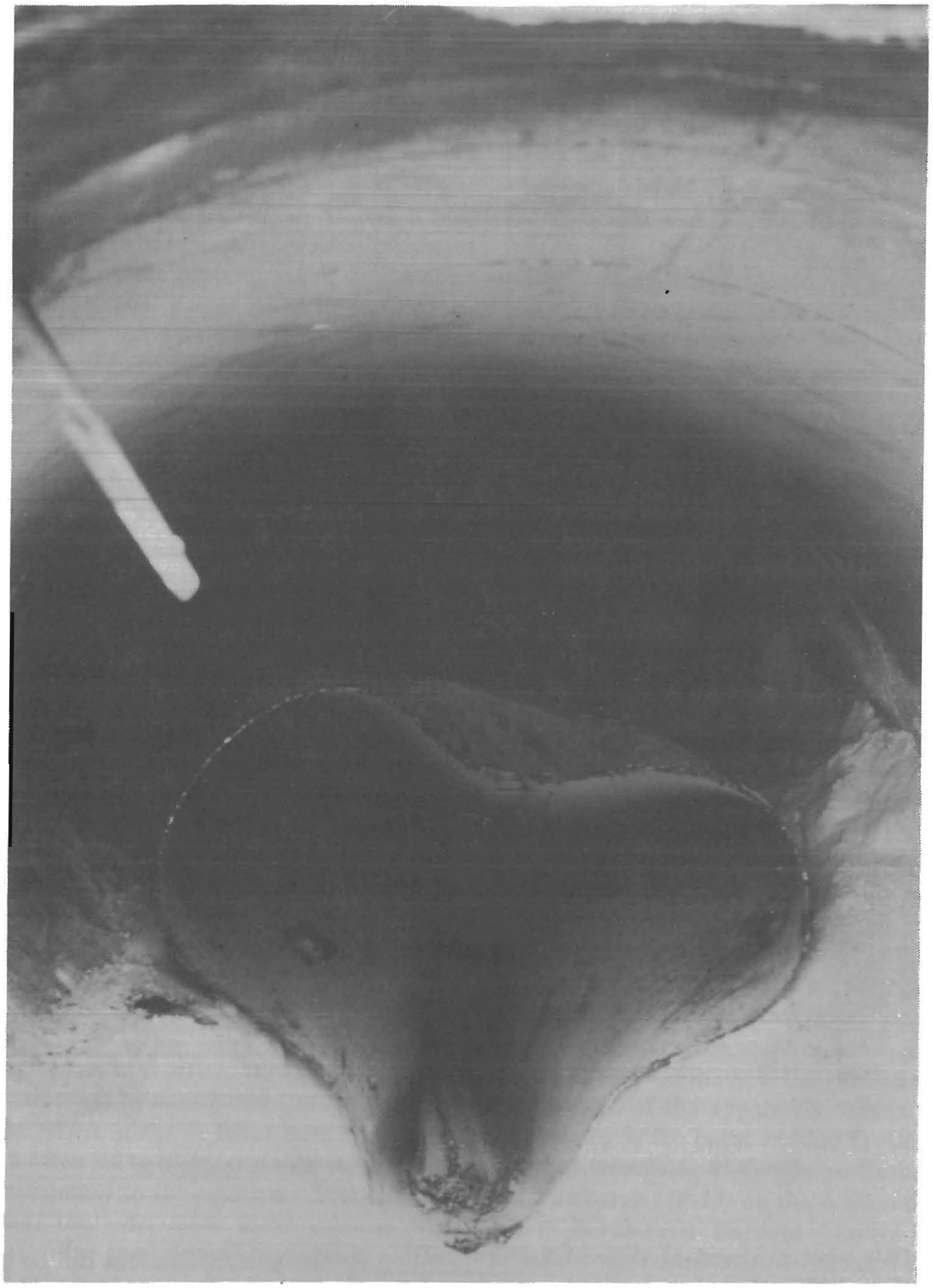

Figure 18.—Manifold cross section at position 15 ft into waste bank (during disassembly of system).

pile) and a 40-ft height, was estimated to contain at least 9,800 st of waste, which, in principle at 5-MW output, would have taken three-quarters of a year to burn to completion under Burnout Control and would have produced 113 billion Btu (or 33 million kW·h) of exhaust thermal energy.

Figure 19 shows several additional bar graphs depicting the output of the Burnout Control system during the latter operational period JD6348 to JD7079 after both scrubber and additional afterburner air ducts were installed. The time line on these bar graphs can be compared directly with those in figure 14. It can be noted that high thermal

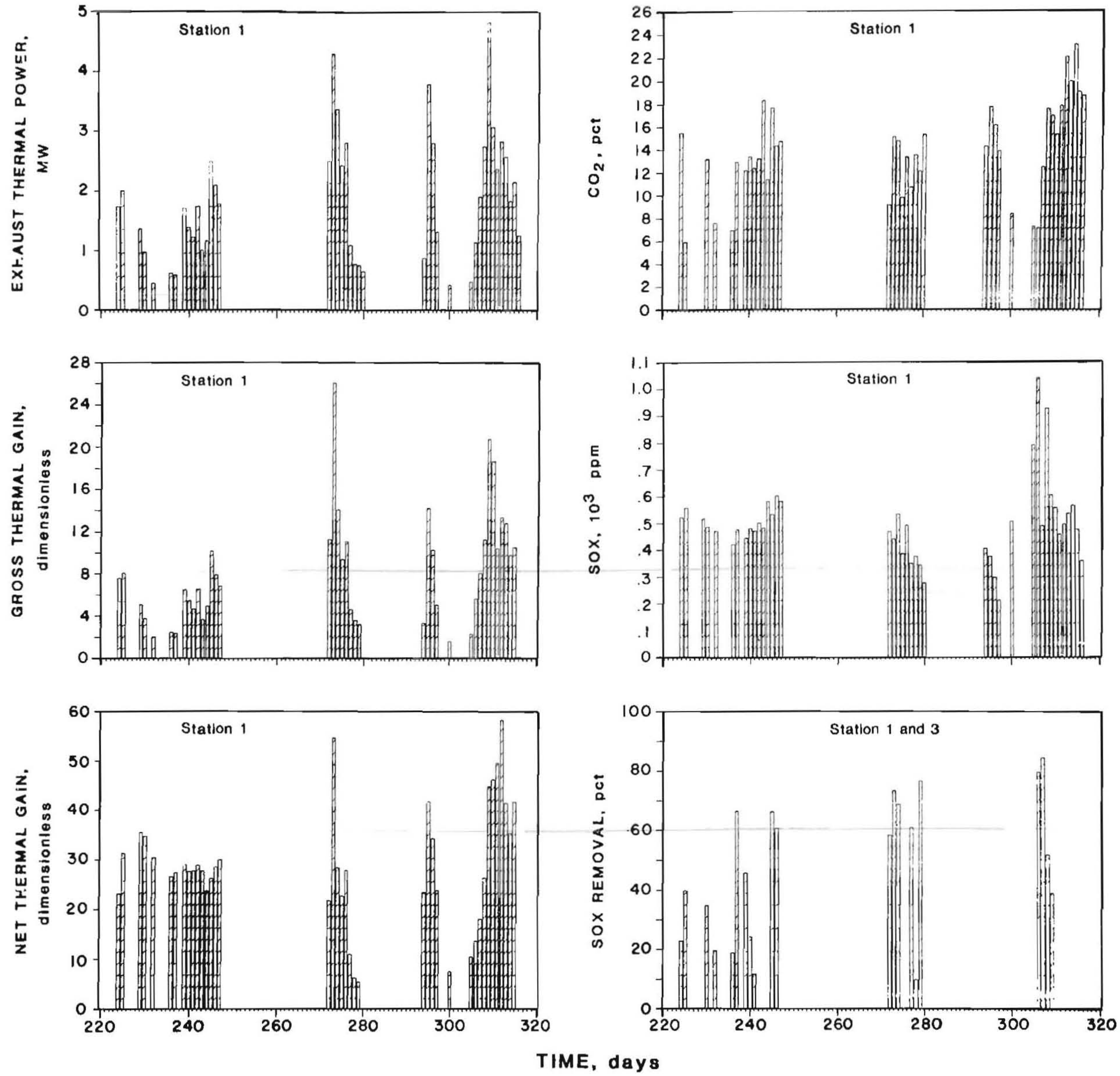

Figure 19.—Additional Albright daily averages for JD6348 to JD7079.

outputs (4 to 5 MW) were achieved at three different times (days 273, 295, and 309) when the station 1 vacuum was at about 30 in H_2O, the flow at about 7,000 scfm, and the temperature at 700° to 900° C (1,292° to 1,652° F). Each of these time periods also corresponds with the occurrence of efficient afterburning in the exhaust manifold as evidenced by the simultaneous low levels of CO (100 to 200 ppm) and O_2 (2 to 3 pct). While it is unfortunate that these high outputs were not sustained (mostly due to malfunction of one or more pieces of equipment), the fact that they were achievable and that the individual parameter values (i.e., vacuum, flow, temperature, etc.) were all within the design specifications can be taken as evidence of the feasibility of Burnout Control as applied to coal waste bank fires.

The measured energy gain of the Burnout Control process (a matter of considerable concern if the exhaust thermal energy is to be utilized, e.g., for powering a steam turbine-electrical generator) can be examined in terms of gross thermal gain (GTE) and net thermal gain (NTE) (*3*). The GTE is defined by the ratio of exhaust thermal power to fan motor electrical power expended, i.e.,

GTE = (station 1 power)/(fan motor power).

Here, it is assumed that the largest expenditure of energy by far is for operating the exhaust ventilation fan. However, as applied to the Albright field trial, the fan is used to draw not only the hot exhaust from the pile, but also cold dilution air, which mixes with and cools the hot exhaust at a point downstream from station 1. If the thermal energy of the exhaust was to be utilized, a heat exchanger would normally be incorporated into the exhaust duct system serving the same purpose as the cold dilution air. This would mean that power spent by the fan for drawing in cold dilution air would not be needed. Thus, NTE can be calculated from GTE, which corrects for the use of the exhaust ventilation fan to supply cooling air (*4*), i.e.,

$$\text{NTE} = (\text{GTE})\cdot(\text{station 3 scfm})/(\text{station 1 scfm}).$$

Figure 19 shows values of both GTE and NTE obtained for the last 90 days of operations.[16] During those days of maximum thermal output (4 to 5 MW), NTE's of 40- to 60-fold were achieved, comparable with those observed during Burnout Control of an underground mine fire (*4*). A net *electrical* energy gain (NEE) that might be expected from use of Burnout Control is obtained by multiplying NTE by a suitable thermal-to-electrical energy conversion factor. Assuming thermal power levels can be maintained for efficient operation of conversion equipment, 25 pct conversion efficiency may be a suitable value for a small powerplant. This would yield an NEE of 10- to 15-fold, approaching the value of about 20-fold for large electrical utility powerplants.

ENVIRONMENTAL CONSIDERATIONS

A significant problem in this field trial at Albright was the numerous complaints by nearby residents of bad odor arising from the stack gases. River valley climactic conditions, which often led to buildup of an inversion layer in the valley, contributed to the problem. From a combustion viewpoint, the odor gave clear evidence that reduced forms of sulfur combustion products (e.g., H_2S, COS, R-SH) were being formed due to lack of adequate O_2 flow into the burning solid waste. The odor was lessened, but certainly not eliminated, by the exhaust scrubber alone. The operational effectiveness of the scrubber in removing exhausted sulfur gases was not very high—averaging 48 ± 24 pct for the data shown in the sulfur removal bar graph of figure 19. It was not until effective afterburning conditions were achieved in the combustion manifold (i.e., adequate temperature and additional airflow) that the odor disappeared.

As can be seen from figures 14 and 19, SOX levels at stations 1 and 3 were about 500 and 200 ppm, respectively, during periods of both effective and noneffective afterburning. If the sulfur emissions are SO_2 only (as versus H_2S and/or other reduced sulfur gases), these levels of emission should have presented only a minimal local environmental problem.[17] At the high outputs (5 MW, 7,000 scfm, 900° C or 1,652° F), a 500-ppm level of SO_2 at station 1 can be considered equivalent to an emission rate of 2.2 lb SO_2 per million British thermal units, about twice the maximum permissible level (1.2 lb SO_2 per million British thermal units) for steam coal powerplants,[18] but considerably less than the 7.1 lb SO_2 per million British thermal units that could be possible on the basis of the 2.1 pct sulfur in the Albright coal waste (see table 2). While a sulfur balance was not made to account for the fate of all the sulfur during burning, it would appear from the station 1 data obtained under complete burning conditions that about 30 pct of the original sulfur (i.e., 2.2 lb SO_2/7.1 lb SO_2) appeared in the exhaust, and about 70 pct must have remained with the burnt solid residue. Estimates of sulfur retention in burnt residues from previous multiton trench-scale experiments (*9*) and 25-lb bench-scale experiments (*10*) of Burnout Control are 44 and 22 to 33 pct, respectively. With the 48 pct exhaust sulfur removal efficiency achieved at Albright, stack emissions (at high thermal output) were only 1.3 lb SO_2 per million British thermal units, just slightly higher than the NSPS maximum permissible level. This means that the total "effective" sulfur removal (i.e., sulfur left behind in the burnt residue plus that scrubbed from the exhaust) at Albright was as high as 82 pct. The total effective sulfur removal could have been even greater if the exhaust scrubber system was more efficient.

No effort was made in the Bureau studies to determine the nature of the apparently sizable quantities of sulfur remaining in the burnt residue at Albright. However, an extensive leaching study was performed at the University of Pittsburgh (*10-13*) on the solid residues produced in a 25-lb bench-scale Burnout Control combustor (*10-13*). Those coal wastes came from nine different abandoned bituminous waste banks in Pennsylvania. Utilizing standard American Society for Testing and Materials and

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[16] The increase in NTE over GTE could be offset to some degree by an increase in fan pressure drop due to use of a heat exchanger.

[17] The contribution of these emissions to the local environment are negligible compared with those from a 500-MW powerplant located just one-half mile upstream of the Albright site on the Cheat River. However, under proposed National Source Performance Standards (NSPS), these levels of emission will undoubtedly imply the need for sulfur removal from the exhaust gases.

[18] NSPS actually refers to a million British thermal units of heat input (e.g., coal heating value) as versus heat output (i.e., exhaust gas energy) as used here. It is not clear how the standards, which depend on initial sulfur, fuel heating value, and rate of burning would be applied to the Burnout Control process.

U.S. Environmental Protection Agency leach test procedures, it was concluded (*10*) that the (1) "postburn leachates would require little to no treatment before being discharged to local streams," and (2) the leachates "do not contain metal concentrations in excess of 100 times the drinking water standard and therefore the residual ash material from Burnout Control would be nonhazardous under RCRA regulations." While these findings and conclusions are very promising for the Burnout Control process, it should be emphasized that they are based on laboratory trial burns, which may not adequately simulate burnout of an actual waste bank.

SUBSIDENCE CONSIDERATIONS

As expected, surface subsidence occurred during burnout. Monitoring the subsidence was accomplished through 12 elevation survey monuments positioned along the pile surface in a 60- by 80-ft grid pattern over the combustion manifold, as shown in figure 20. Several elevation surveys were made during the course of the field trial; the results are shown in table 3.

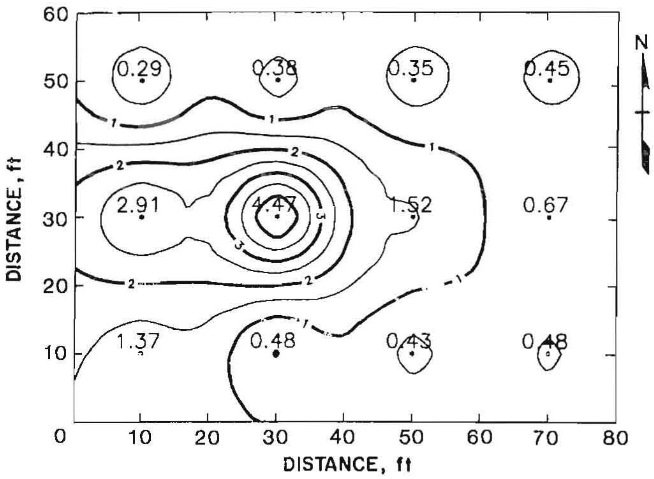

Figure 20.—Computer-drawn contour map of surface subsidence for JD7082 (contours drawn at 0.5-ft intervals; manifold extends east-west at 30-ft distance level). (See table 3, day 319 data.)

Table 3.—Albright cumulative subsidence data,[1] feet

Survey monument	Day 99	Day 210	Day 243	Day 319
1	0.31	0.36	0.36	1.37
2	.35	.54	.88	2.91
3	.24	.27	.26	.29
4	.28	.35	.34	.38
5	.59	1.24	2.71	4.47
6	.35	.45	.45	.48
7	.28	.38	.39	.43
8	.51	.68	.78	1.52
9	.26	.32	.32	.35
10	.22	.32	.33	.45
11	.34	.44	.43	.67
12	.22	.36	.37	.48

[1] Subsidence relative to monument survey readings on day 6.

Subsidence was most severe (as much as 4.5 ft) along the line of the combustion manifold (monuments 2, 5, 8, and 11) and varied with time, apparently accelerating after day 243. Figure 20 is a computer-generated contour map of the subsidence data for JD7082, 3 days after termination of the fan operations. The contours show a relatively symmetrical pattern of subsidence about the combustion manifold over an area of about 4,800 ft^2. An exception to the symmetry is the somewhat higher level of subsidence at the southwest portion of the grid (1.37 ft at monument 1), which could reflect the influence of an exposed gully in that direction on airflow into the waste pile. The higher the airflow, the faster the burning. This would also account for the fact that subsidence holes were observed to form in the vicinity of the three vertical inspection boreholes (near monuments 2, 5, and 8) that were air-rotary drilled from the surface of the pile to the base of the pile. As mentioned previously, the drilling of these holes undoubtedly increased the permeability of the coal waste in the vicinity of the boreholes, leading to higher airflow, and hence to faster burnout.

Subsidence holes, when they occurred, are believed to have had an effect on the Burnout Control process through alteration of the airflow into the waste pile and by short-circuiting air away from other areas of the pile. However, these effects were readily handled at Albright by simply filling in the voids with fly ash and/or unburnt waste obtained from other areas of the pile. One had to be cautious in how this was accomplished, but through careful probing of the surface to test for adequate support and applying appropriate bulldozer and backhoe procedures, the surface of the waste pile was maintained without incident for the whole operational time period. Even 2 years later (1989), when temporary remedial action was taken to reduce venting from the pile, sealing was accomplished without incident by utilizing the same techniques.[19]

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[19] The remedial action was taken by the U.S. Bureau of Mines in response to complaints by local residents who were awaiting reclamation of the site by the State of West Virginia.

VACUUM-GAS FLOW CONSIDERATIONS

The approach taken in appendix A to develop size specifications for the combustion manifold was quite successful as can be seen from tables 4 and 5, which depict curve-fit results of the field tests of gas flow (see figure 17) as compared with that of equation A-3 for cylindrical Darcy flow with radial symmetry (appendix A). The comparison is quite good, particularly for day 54 (early in the fan operations), when the waste bank conditions might closely resemble those at the time of the site assessment. At that time, it appears that Darcy flow (i.e., $N = 1$) was applicable to the waste bank, but as time went on, the flow behaved somewhat between Darcy and pipe flow ($N = 1.5$), eventually becoming 100 pct pipe flow ($N = 2$) on day 312. It is probable that the collapsing combustion manifold was the cause for the flow exponent, N, to have a value of 2 or greater as observed for days 312 and 316. The plots of vacuum versus flow for these 2 days, as shown in figure 17, are quite similar to each other and quite different from the other test days. The cause of the increase in the flow exponent, N, from 1.0 to 1.5 is not known at this time. The excellent fit of the curves for days 245 and 296 (see R^2 values in table 4) suggests that the increase in N is real and significant, but as can be seen from the plotted data in figure 17, the curves for days 245 and 296 do resemble the curve for day 54 ($N = 1$) fairly closely.

Table 4.—Best fit parameter values for pvac1 = $C \cdot (\text{scfm1})^N$ (based on curve fit of test data)

Parameter	Day 54	Day 245	Day 296	Day 297	Day 312	Day 316	Calc[1]
C•(1,000)	3.5380	0.0708	0.0211	0.0806	0.0055	0.0000	5.0000
N	1.0564	1.4895	1.5691	1.4229	1.9127	3.6165	1.0000
R^2 (fit)	.9997	.9600	.9979	.9946	.9900	.8804	NAp

C	Constant.
N	Exponent.
NAp	Not applicable.
pvac1	Vacuum at station 1.
R^2	Correlation coefficient.
scfm1	Exhaust flow rate at station 1.

[1] From equation A-3.

Table 5.—Vacuum versus flow (based on curve fit of test data)

(pvac1, inches of water (pressure))

Flow, scfm	Day 54	Day 245	Day 296	Day 297	Day 312	Day 316	Calc[1]
2,000	11	6	3	4	11	2	10
4,000	23	16	9	11	43	25	20
6,000	35	30	18	20	93	106	30
8,000	47	46	28	30	161	301	40
10,000	59	64	40	42	247	675	50
12,000	72	84	53	54	351	1,305	60

pvac1	Vacuum at station 1.

[1] From equation A-3.

SUMMARY OF CONCLUSIONS

The field trial of Burnout Control of a coal waste bank fire at Albright, WV, had many engineering and construction problems that prevented the achievement of long-term, continuous, and effective burnout operations. However, there were many valuable lessons learned from these technical problems, as well as from both the successful and unsuccessful efforts to resolve them in the field. The fact remains that despite the problems experienced with the technical designs and the implementation of those designs, a number of positive results were obtained, albeit some of them for only relatively short periods of time:

1. Controlled burnout was achieved;
2. Spread of burning in the waste was faster than the mass rate of burning; the burning pile behaves as a gasifier;
3. Afterburning of fuel-rich gases drawn from the pile was accomplished and resulted in high combustion efficiencies;
4. Thermal energy and power were produced at design levels;
5. Utilizing the thermal energy produced could lead to energy gains comparable with those obtained by utility powerplants;
6. Incinerated waste or red dog (presumed benign) was produced;
7. Observed vacuum, gas flow, and thermal flow capacities were in accordance with predictions;
8. Considerably less sulfur was observed in the exhaust than what might be expected based on the sulfur content in the fuel;
9. With efficient afterburning of the exhaust and "conventional" stack exhaust controls, sulfur emissions and their environmental impact should be minimal; and
10. Surface subsidence during burnout can be handled with simple backfilling techniques.

One of the major objectives of the field trial at Albright was to learn how the basic Burnout Control process could be applied to a real situation and what alterations would be required to make the process work in a technically and environmentally acceptable manner. The achievement of design parameters, even for short periods of time, at a difficult location such as Albright (a river valley with poor air-dispersive capability, near residential areas, and in a heterogeneous refuse pile containing fly ash) indicates the potential for utilizing Burnout Control in almost any setting. On a purely experimental basis, it would perhaps have been better to have selected a more remote site where the process could have been manipulated more thoroughly without affecting neighboring residents; however, the practical experiences and lessons learned at Albright will aid immeasurably toward achieving success in future trials. Future demonstrations of Burnout Control, as applied to coal waste bank fires, will be needed to better establish the engineering designs and developments that will enable successful application of the process.

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APPENDIX A.—AIR-PERMEABILITY ASSESSMENT OF WASTE BANK

Prior to designing the Burnout Control system for Albright, air-permeability tests were made on the Albright waste bank utilizing a small-scale suction procedure that simulated the Burnout Control suction process. The devised suction tests were somewhat unusual and yielded useful and apparently consistent results for the air permeability of the waste in situ. The measurement technique and results are described in detail in this appendix.

Vertical boreholes (4-in ID) were drilled from the top of the waste bank to a desired depth using a hollow-stem auger. A spoon sample was then taken with a 3-in split-spoon sampler to a distance of 18 in below the bottom of the hollow-stem auger. A 1-1/4-in-diameter steel pipe with expandable packer was lowered into the hollow-stem auger and sealed to the bottom auger flight (see figure A-1). The 1-1/4-in-diameter pipe was then connected through standard plastic and steel pipe sections and connectors (as shown) to an exhaust fan (400 scfm at 55 in H_2O) having a 4-in-diameter valved inlet. Static pressure, differential pressure (pitot tube), and thermocouple readings were taken of the gas flowing from the waste bank and through the pipe arrangement under the influence of the exhaust fan. At each depth, the imposed vacuum was varied (generally between 20 and 40 in H_2O at the fan) to yield experimental data on flow rate as a function of static pressure (i.e., applied vacuum). After obtaining sufficient data at one depth, the borehole was augured further to another desired depth and the measurement process was repeated. Permeability measurements were carried out through six separate boreholes covering the area of interest and at three or four depths (between 10 to 40 ft) at each borehole.

Interpretation of the experimental data was patterned after the spherical Darcy flow model developed previously at the Bureau of Mines (*1*).[1] It is assumed that steady suction at the end of a borehole inserted into a waste bank causes gases within the bank to converge radially toward the point of suction. Under steady-state conditions, the total mass flow rate across any spherical surface centered on the point of suction will be constant. Darcy's law can be expressed as

$$Q = k \cdot A \cdot (1/mu) \cdot (dP/dx), \qquad \text{(A-1)}$$

where Q = volumetric flow rate, cm^3/s,

k = permeability, D,

A = effective x-sectional flow area, cm^2,

mu = gas viscosity, cP (0.01 for air),

and (dP/dx) = pressure drop in flow direction, x, atm/cm.

For spherically symmetric flow, $A = 4 \cdot pi \cdot b \cdot x^2$, equation A-1 can then be integrated while holding Q constant to yield

$$k = [(1/x_0) - (1/x_1)] \cdot mu \cdot Q/[4 \cdot pi \cdot b \cdot (P_v)], \qquad \text{(A-2)}$$

where x_0 = distance from point of suction defining region of uniform applied vacuum, cm, taken as borehole radius,

x_1 = affected distance from borehole, cm, taken as nearest point, where P = ambient pressure, 1 atm,

pi = constant (3.14159),

b = solid angle in steridians that defines flow region around borehole (b = 1 for whole sphere; b = 0.5 for hemisphere),

and P_v = vacuum (positive quantity) at bottom of borehole, atm, taken as uniform over distance x_0 from point of suction.

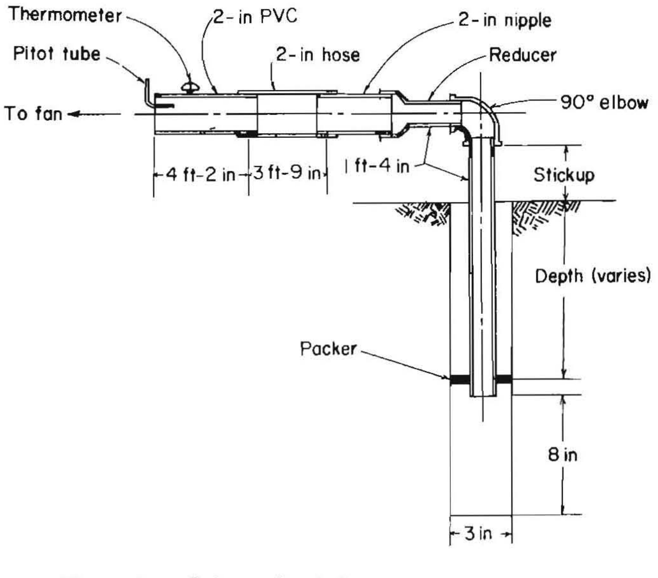

Figure A-1.--Schematic of air-permeability test setup.

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

In utilizing the experimental measurements with equation A-2, several corrections were made to the data. First, the pitot tube flow measurements were corrected to standard temperature and pressure conditions. Static pressures at the pitot tube varied between 0.90 and 0.95 atm and gas temperatures, between 24° and 50° C (75° and 122° F). Second, the measured vacuum (in the pitot tube section) was corrected for the pressure drop in bringing the gas from the bottom of the borehole to the point of vacuum measurement. At the observed flows (10 to 100 scfm), this pressure drop amounted from 1 to 35 in H_2O (i.e., 2 to 90 pct of the applied vacuum).

Figure A-2 summarizes the results of these calculations with the flow being spheroidal (b = 1) and with the air viscosity, mu, taken as 0.01 cP. The data include six different borehole locations and three different depths (10 to 40 ft), generally with two to four readings at each depth. The error bars on the data points shown in figure A-2 depict the scatter of the measurements. For the 17 separate data points, the average scatter about the mean is approximately 10 pct. Except for one obvious discrepancy, all the points indicate an almost linear trend of permeability decreasing with increasing depth, from 250 D at 10-ft depth to 50 D at 35-ft depth, which is on the order of the permeability of a pile of sand.

The above results were utilized in sizing the Burnout Control ventilation system to be designed. It was desired to have a system capable of handling 5-MW (thermal) output. At 900° C (1,652° F) exhaust, this would require obtaining a flow rate of about 5,000 scfm (2.33 million cm^3/s) through the waste. For a spherical flow geometry (equation A-2), the borehole pipe diameter would have to be about 10 ft, which would be somewhat excessive for the Albright waste bank site. However, for cylindrically radial flow (equation A-1, with A = 2·pi·b·x·L; L = pipe length), the required diameter of the suction pipe would be much less. The equivalent of equation A-2 for cylindrically radial flow is

$$k = [Q \cdot mu \cdot \ln(x_1/x_0)]/[2 \cdot pi \cdot L \cdot P_v]. \qquad \text{(A-3)}$$

For a 5-MW (thermal) output and a value of k = 80 D (near the bottom of the waste pile), the ratio x_1/x_0 (i.e., the ratio of pipe diameter to depth of waste pile) is related to the pipe length (in feet) by

$$L = 21.2 \cdot [\ln(x_1/x_0)]. \qquad \text{(A-4)}$$

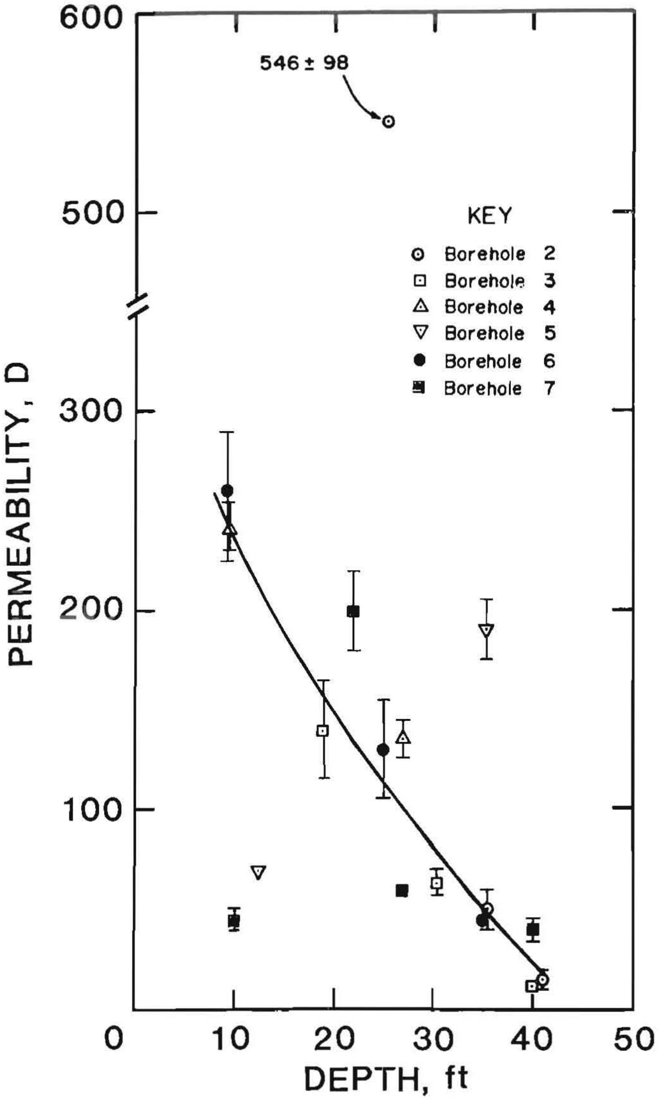

Figure A-2.—Vacuum-flow test data obtained during site assessment.

For x_1/x_0 = 11, which would correspond to a pipe diameter of about 3 ft, the length of suction pipe would be about 50 ft. This pipe size could be accommodated at the Albright site by placing the pipe along the ground under the waste pile.

APPENDIX B.—SCRUBBER SYSTEM

Figure 9 depicts the scrubber system that was designed and constructed. Basically, it consisted of 30 spray heads mounted in 3 pipes positioned across the 36-in-diameter entrance to the dropout tank. The spray heads were supplied with 20 to 25 gal/min of alkaline scrubber liquor at 150 psi by a displacement piston pump recirculating the liquor from a pool that filled the bottom one-third of the dropout tank. An 18-ft^2 stainless steel demister pad, positioned just upstream of the 36-in-diameter exit of the dropout tank, enabled additional contact between the exhaust gases and the scrubbing liquor. The scrubbing liquor consisted of an aqueous solution of NaOH maintained at pH greater than 8. Makeup alkali was valved into the dropout tank under gravity feed from an adjacent 4,000-gal storage tank containing 50 pct NaOH solution, delivered to the site by truck. Makeup water was introduced into the dropout tank through sprays located at the underside of the demister pads. Fresh water introduced this way helped to keep the pads unclogged. A particle filter in the pipeline from the displacement pump to the scrubber sprays helped to keep the spray heads from clogging. Measurement and maintenance of pH and water level in the dropout tank were carried out manually approximately every hour. Periodically, the bottom of the dropout tank would be partially drained—the spent liquor with suspended solids being piped directly to the 30,000-ft^3 storage capacity settlement pond located about 200 ft downhill from the site (see figure 5).

Although the scrubber sprays would cool the exhaust gases, there was still the matter of up to 5 MW of thermal power to dissipate from the Burnout Control ventilation system. Continued dissipation of the enthalpy to the atmosphere would involve high rates of steam ejection through the stack, with much of the SOX probably remaining in the gaseous state. To avoid this, a tube-in-shell heat exchanger was positioned upstream of the dropout tank to remove much of the heat content of the exhaust gases prior to their being scrubbed. This involved (1) field fabricating a heat exchanger to replace a 20-ft section of the refractory lined duct upstream of the dropout tank (fig. B-1), (2) repositioning the 2-ft-diameter dilution air duct so that air cooling of the hot exhaust could take place at a point upstream of the heat exchanger (fig. 10), and (3) installing a water recirculation system to supply 1,000 gal/min of cold water from the Cheat River to the heat exchanger. In this latter connection, river water was recirculated with a 480-V, 50-hp rotary pump, which required 100 kW of additional transformer power to be installed on the site, installation of some 500 ft of buried 8-in water pipeline, and installation of an unclog-gable foot valve-filter water intake system that was submerged in a pooled area constructed in the river.

Design, fabrication, and installation of the scrubber system took a total of 11 weeks, after which testing of the entire system was resumed. Numerous problems were encountered with clogging of the foot valve by river water debris, including corrosion of heat exchanger tubes and spray heads, breakdown of the piston pump that supplied NaOH solution to the spray heads, and overheating of 8-in plastic water line with subsequent breaking of the line. Each incident was repairable, but often required complete shutdown of the fan operation.

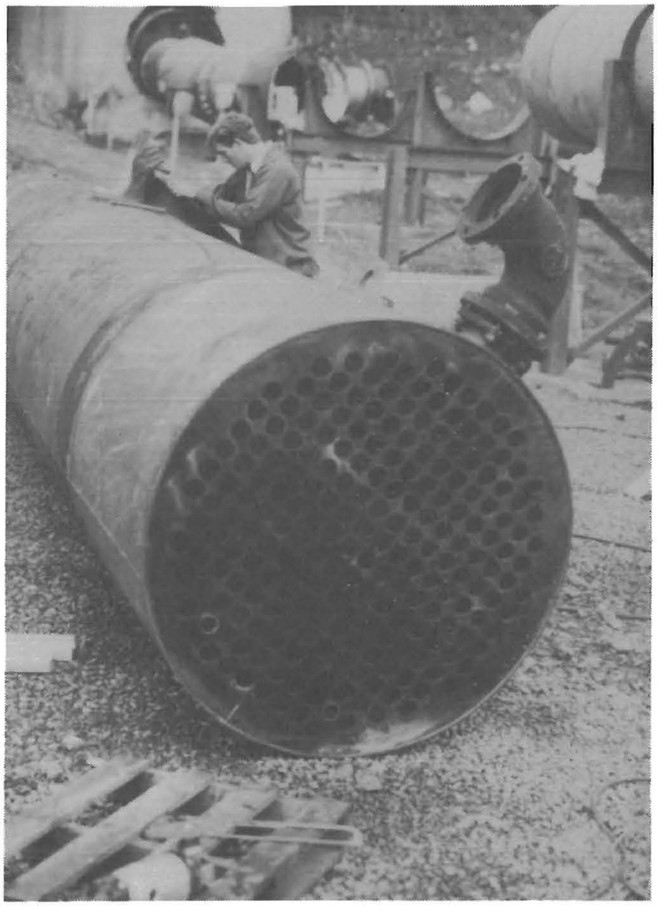

Figure B-1.—Heat exchanger for cooling hot exhaust (during fabrication of air-pollution scrubber system).

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