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Calamity Hollow Mine Fire Project

(In Five Parts)

4. Quenching the Fire Zone

By Robert F. Chaiken, Edward F. Divers, Ann G. Kim, and Karen E. Soroka

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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 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 can 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 is the fourth in a five-part series that describes the Calamity Hollow Mine Fire Project. The first report, part 1, describes the design and construction of the field installation. Part 2 will present the results of a continuous 4-month burnout operation. (Because part 2 involves the analysis of a substantial body of data, it will not be published until after publication of parts 3, 4, and 5). Part 3 describes the instrumentation used to control and monitor the progress of the burnout operation. This part (part 4) and part 5 both deal with the closeout phase of the field demonstration. The quenching of the fire is described in this report, and part 5 will describe 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 with fume exhaustion is a potentially effective method for cooling large underground fire zones. Further trials of both Burnout Control and water injection with fume exhaustion are planned.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

acfm	actual cubic foot per minute
Btu	British thermal unit
Btu/lb	British thermal unit per pound
Btu/min	British thermal unit per minute
°C	degree Celsius
°C/gal	degree Celsius per gallon
°C/s	degree Celsius per second
cal/g	calorie per gram
cal/g-°C	calorie per gram per degree Celsius
cm	centimeter
cm/s^2	centimeter per second squared
°F	degree Fahrenheit
ft	foot
ft^3	cubic foot
gal	gallon
gal/d	gallon per day
gal/ft^3	gallon per cubic foot
gal/min	gallon per minute
g/s	gram per second
g/cm^3	gram per cubic centimeter
h	hour
hp	horsepower
in	inch
in H_2O	inch of water (pressure)
K	kelvin
kW	kilowatt
mi	mile
MMgal	million gallons
MMBtu	million British thermal units
MW	megawatt
pct	percent
scfm	standard cubic foot per minute

CALAMITY HOLLOW MINE FIRE PROJECT

(In Five Parts)

4. Quenching the Fire Zone

By Robert F. Chaiken,[1] Edward F. Divers,[2] Ann G. Kim,[3] and Karen E. Soroka[4]

ABSTRACT

The Bureau of Mines demonstrated a novel water-injection fume-exhaustion (WIFE) procedure for quenching underground coal fires and fire-heated rock as part of its Calamity Hollow Mine Fire Project. The Bureau's existing Burnout Control ventilation system was operated at a vacuum level just sufficient to exhaust the underground fire zone, and water was introduced into the mine through existing boreholes at a rate of 3 to 4 gal/min per borehole. The resulting steam and heated gases were exhausted from the mine, and this led to a rapid and relatively uniform cooling of the entire fire zone and surrounding rock strata.

An advantage of the WIFE procedure is that the progress of the cooling process can be monitored. Measured exhaust temperatures decreased from 592° to 162° C (1,100° to 324° F) during the 30-day quenching period. Energy balance computations suggested that 50 pct or more of the burning coal mass was extinguished during this period. Analyses indicated that cooling to 100° C (212° F) with possible complete and permanent extinguishment of the approximately 1-acre underground fire zone might have been achieved if the WIFE procedure had been extended for an additional 20 days. Recommendations are given as to how the WIFE procedure may be improved.

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INTRODUCTION

The Bureau of Mines undertook the Calamity Hollow Mine Fire Project (1-2)[5] as the first field trial of its new Burnout Control concept for controlling underground fires in abandoned coal mines. After a 4-month controlled burnout at the site of the Calamity Hollow (PA) fire, the fire was quenched and the fire zone was subsequently excavated and backfilled. This report describes the WIFE procedure used to quench the Calamity Hollow fire and presents the results obtained.

The project site was a 1.8-acre isolated zone of the Pittsburgh Seam under shallow cover (approximately 35 ft) in an area of Jefferson Borough, PA, called Calamity Hollow. The Burnout Control system was designed, constructed, and underwent shakedown tests from December 1979 to December 1981 (1). An operational test was conducted from January to May of 1982 to evaluate equipment, control methods, and instrumentation (2), as well as various aspects of the Burnout Control concept itself. Continuous suction on the mine intensified the existing fire, leading to exhaust temperatures as high as 900° C (1,650° F) and thermal output levels as high as 6 MW, with the fire spread over approximately 1 acre. Of the estimated 17,000 tons of combustibles available at the 1.8-acre site, 1,100 tons was consumed. The effects of subsidence, vacuum level, and inlet borehole placement on the underground burning process were studied.

On May 4, 1982, preparatory to complete excavation and examination of the fire zone, the WIFE procedure was initiated to extinguish the fire and cool the surrounding rock strata. The procedure was novel in that it took advantage of the fume- and heat-exhaustion capabilities of the Burnout Control ventilation system. Water was injected into the fire zone to create steam, which in turn was exhausted from the mine. The steam served several purposes: (1) Its formation from liquid water slowed the combustion process by extracting heat from the fire zone; (2) its presence underground acted to exclude oxygen from the burning coal; and (3) its exhaustion from the mine carried substantial amounts of heat away from the underground hot zones. The fire was not completely extinguished, but substantial cooling was accomplished within a 30-day period using the WIFE procedure.

BACKGROUND

The use of water to quench fires is probably as old as fire itself, so it is not surprising that water injection has often been considered as a means for fighting fires in abandoned underground coal mines. What may be surprising is the general lack of success that has been experienced with the use of water injection (through boreholes and/or surface saturation); the method has only been successful in areas where ground conditions and the mine topography permit total inundation of the mine (3). Such ground conditions rarely exist for coal seams above the ground water table; and below the water table, an abandoned mine would most likely be flooded, and hence it is unlikely that it would be on fire.

The Bureau had previously experimented with underground water sprays and streams injected through boreholes and with surface water saturation as possible methods for extinguishing a fire in a shallow mine (3). In each case the efficacy of the extinguishment procedure was questionable. It was observed that where direct contact between the water and the burning coal was known to occur, extinguishment was achieved; but there was no way to insure such direct contact over a large fire zone--even from boreholes

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

drilled on 10-ft centers through the fire zone. In fact, some evidence points to the possibility that water injection by itself might have enhanced the spread of the fire--presumably by spreading heat to previously unheated areas of the mine. The steam, when formed, pressurizes the fire zone, causing heat and fumes (possibly containing combustible gases such as hydrogen, methane, and carbon monoxide) to flow beyond the boundaries of the original fire zone. Griffith, in his classic report on mine fire control (3), concluded that it would be difficult to use water alone to extinguish a fire in an abandoned coal mine.

The basic problems encountered in using water to extinguish underground coal mine fires are as follows:

1. The water must be evenly distributed over the entire fire zone and cannot run off in channels to areas outside the fire zone.

2. Although the formation of steam by water contacting hot material can cool a fire zone, the sensible heat of the fire remains underground and can be spread throughout the mine to new areas, making them more liable to ignition.

3. To completely extinguish a mine fire and eliminate the possibility of reignition, *all* burning and heated material in the mine must be cooled to temperatures below approximately 100° C (212° F). This could require the delivery of extremely large volumes of water over inordinately long periods of time.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of Joseph P. Slivon, Jr., physical science technician, and John R. Odoski, engineering technician, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA; and Roy Laverick, Timothy Fircak, Harold Smith, and Francis Kelly, operators, Boeing Services, Inc., Pittsburgh, PA, for their contributions in technical and mechanical phases of the field operations at Calamity Hollow. The contribution of Louis E. Dalverny, physicist, Pittsburgh Research Center, is also acknowledged; he gave advice and assisted in the operation of the automated monitoring system.

BURNOUT CONTROL VENTILATION SYSTEM

The Burnout Control concept for controlling abandoned coal mine fires has been discussed in detail in a previous report (4). Briefly, the concept involves complete burnout of the fuel responsible for the fire. The control technique involves exhaust ventilation of the mine fire at vacuum levels of 10 to 50 in H_2O. The ventilation induces air flow over the fire zone, which accelerates burning, while heat and fumes are exhausted to the surface by the fan. A depiction of the Burnout Control system constructed at Calamity Hollow is shown in figure 1.

This same fume exhaust technique, if applied under conditions such that coal burning is inhibited by the presence of water or steam, should result in considerable heat loss from the mine and cooling of the underground heated zones. Some evidence of such a cooling effect was noted during the 4-month controlled burnout at Calamity Hollow. During March 1982 (60 to 87 days into the continuous controlled burnout), several severe rainfalls occurred, each of which resulted in a marked temporary lowering of the exhaust temperature (table 1). Three separate rainfalls (during Julian days 64-65, 76, and 76-77[6]) each resulted in a sudden

[6]All subsequent references to days in the form "day 78" or "days 120 to 155" refer to Julian days (i.e., calendar days in which Jan. 1 is day 1, July 1 is day 187, etc.). Continuous operation of the Calamity Hollow Burnout Control system began on day 4 (Jan. 4, 1982); water injection began on day 125 and was completed on day 154.

decrease in exhaust temperature ranging from 100° to 200° C (212° to 392° F) followed by a slower recovery. Since each of these rainfalls was accompanied by considerable surface water drainage downslope across the ground directly above the fire zone, it was surmised that some of the water was being drawn directly into the mine fire through crevices in the ground.

TABLE 1. - Effect of rainfall on exhaust temperature during continuous burnout

Rainfall	Julian date (day:h:min)	Exhaust temp, °C	Temp drop, °C	Recovery time, h	Average exhaust flow rate, scfm
1....	64:20:00	555			
	64:21:00	418	137	20	5,500
	65:17:00	557			
2....	76:11:50	623			
	76:12:25	523	100	3	7,440
	76:15:00	609			
3....	76:20:00	618			
	76:21:00	412	206	7	7,200
	77:05:10	618			

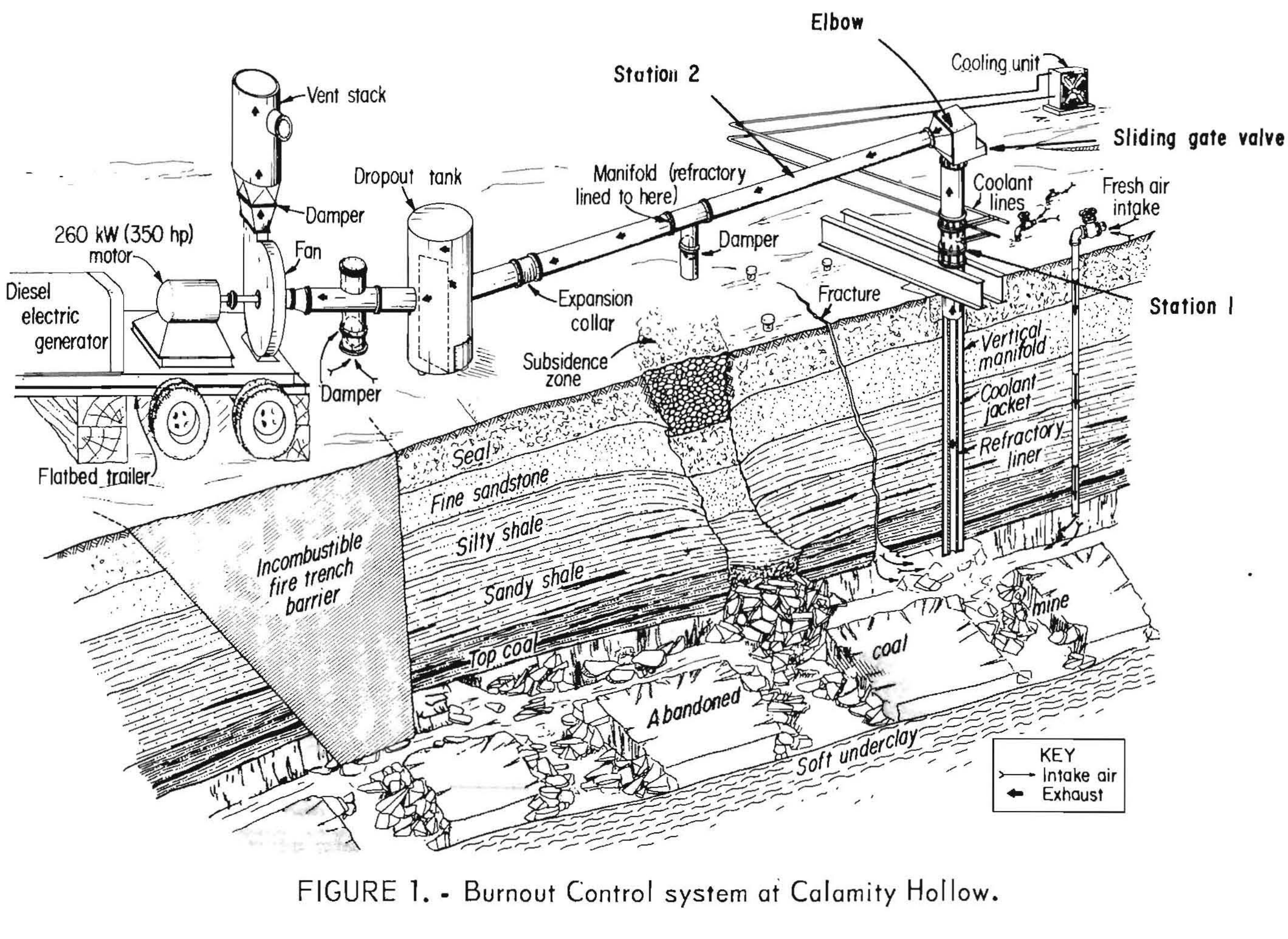

FIGURE 1. - Burnout Control system at Calamity Hollow.

To reduce runoff over the fire zone, a diversion ditch was constructed around the fire zone on day 78. On day 91 it rained intensely, but this rainfall had no observable effect on the exhaust temperature. Apparently the diversion ditch prevented water from entering the fire zone and eliminated the subsequent cooling effect of rain. The cooling effect from the March 1982 rainfalls indicated that the planned WIFE quenching procedure could sufficiently cool the mine to simplify the subsequent excavation phase of the project.

WATER DELIVERY SYSTEM

To apply the WIFE procedure at Calamity Hollow, a water delivery system was developed based upon an available supply from an 8-in diam municipal main approximately 900 ft from the fire zone. The water was stored in an 18,000-gal surface pool at an elevation sufficient for gravity feed through a branched manifold of pipe and tubing to boreholes in the fire zone (fig. 2). The system was designed to distribute a total of up to 150 gal/min of water to as many as 50 boreholes and to use second-hand flexible hosing that could be throttled by simple squeeze clamps (fig. 3).

The storage pool was placed near the high (north) end of the field site, as shown in figure 4. Two 4-in-diam plastic drainpipes extended from the pool to the eastern and western edges of the fire zone. Four-inch-diameter plastic tees were fitted on the top and bottom of a vertical pipe inside the pool. Outside the pool, the pipe extended across a wooden bridge to a 4-in-diam tee fitted with a 4-in-diam plastic plug which served as a fill point for starting siphoning action from the pool. Four-inch-diameter valves in the main line near the manifold controlled the water flow rate from the pool. They were located 150 ft from the pool and were approximately 4 ft lower than the bottom of the pool. Reducing fittings and valves connected the tee to lengths of fire hose. For connections to nearby boreholes, 1-1/2-in-diam hose was used; for connections to more

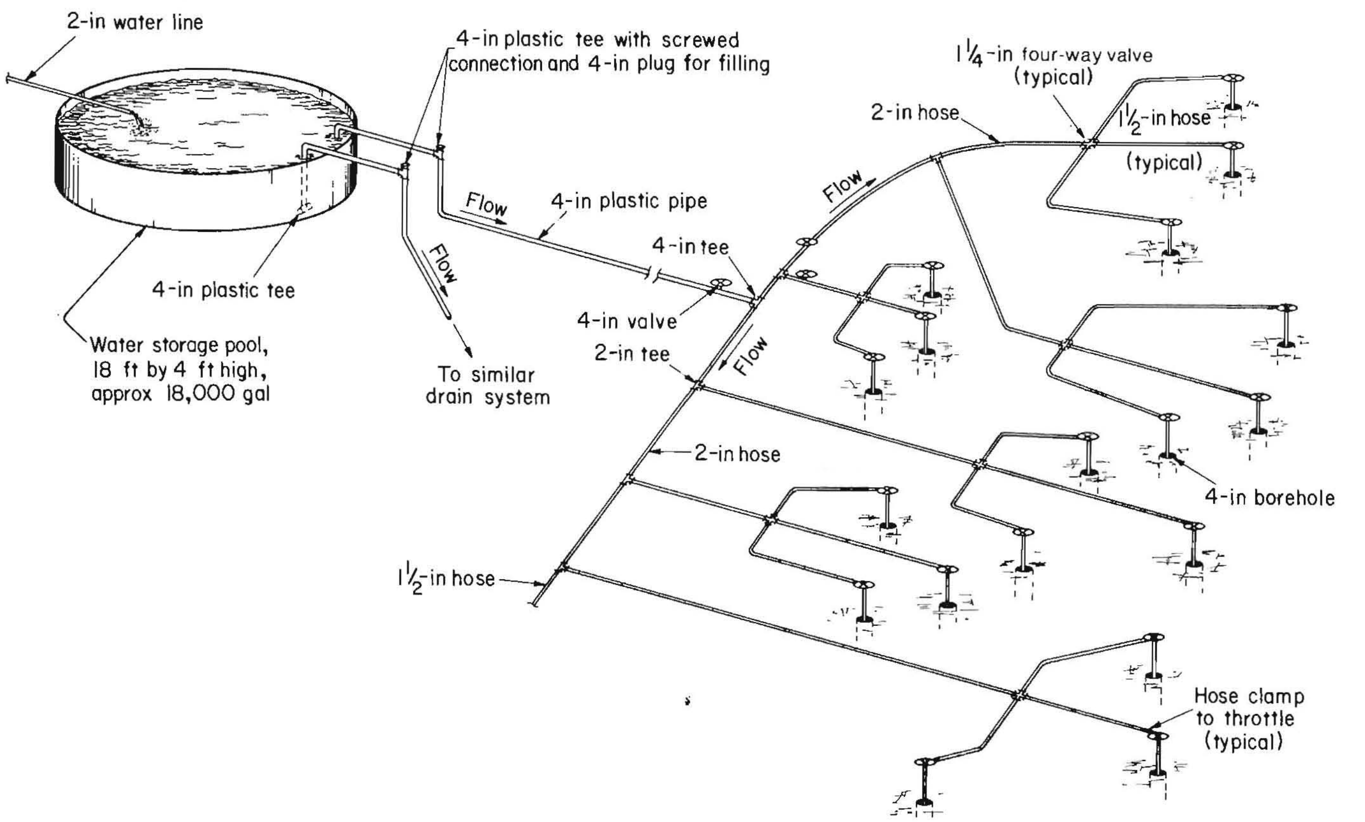

FIGURE 2. - Water distribution system. (All dimensions, except pool height, are diameters).

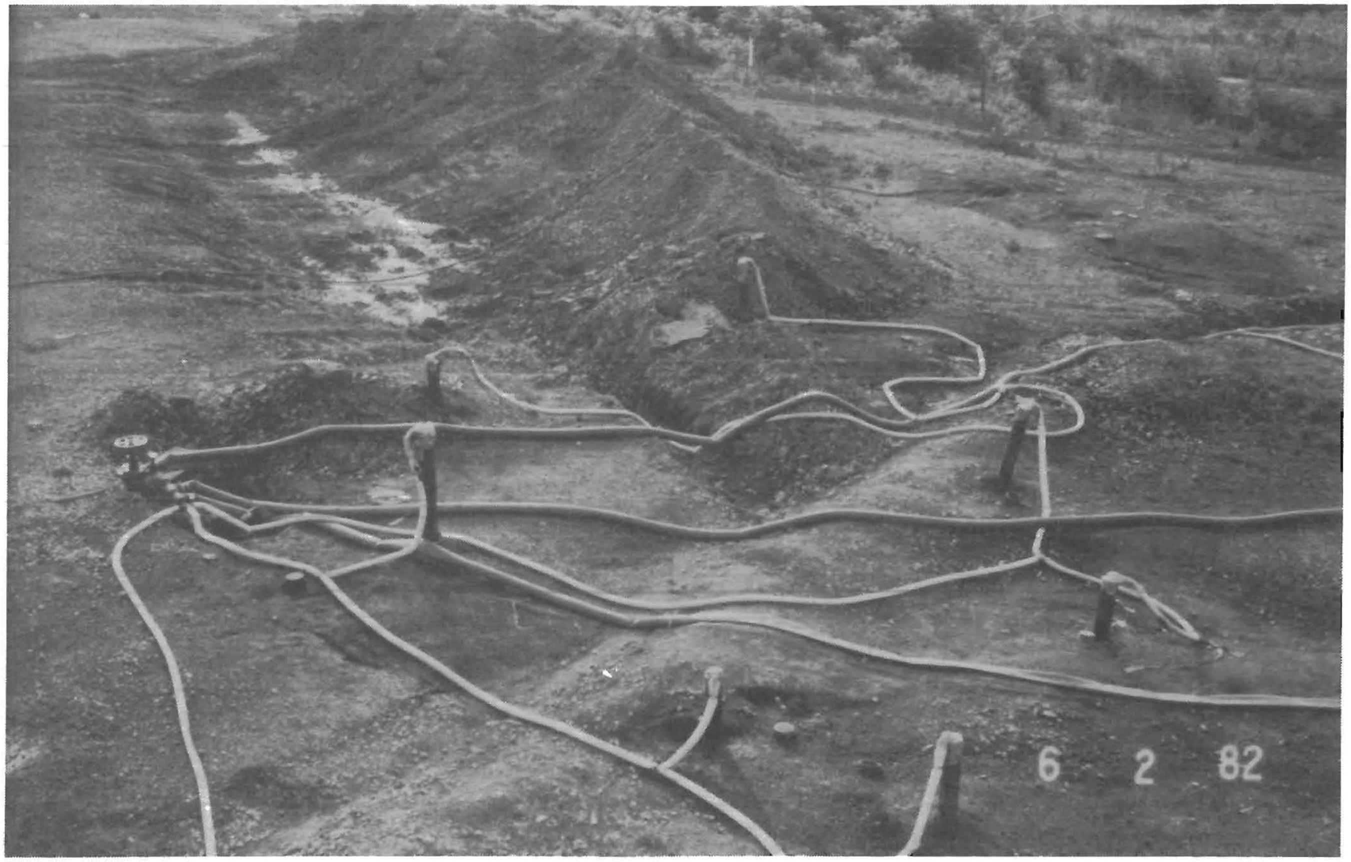

FIGURE 3. - Piping to boreholes.

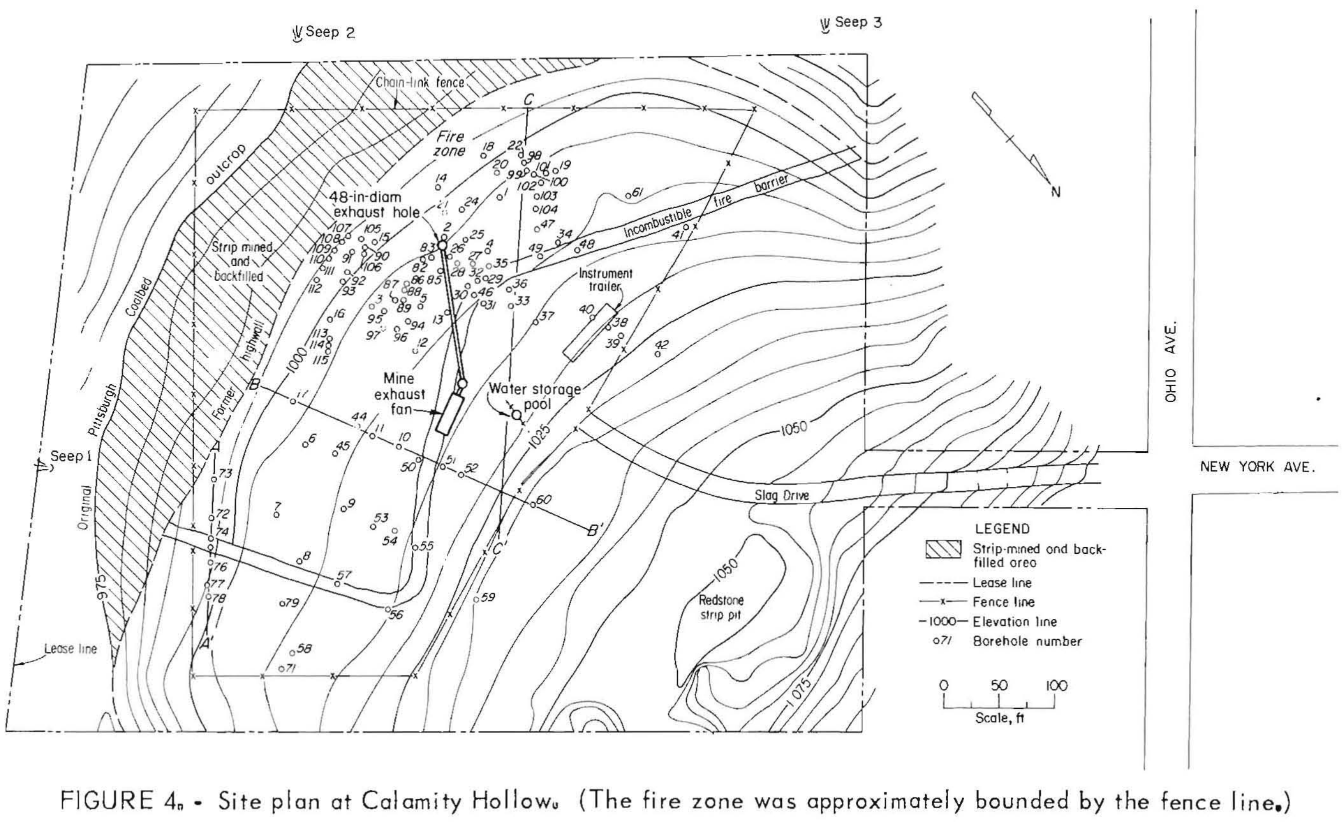

FIGURE 4. - Site plan at Calamity Hollow. (The fire zone was approximately bounded by the fence line.)

distant boreholes, 2-in-diam hose was used. At some point the 2-in-diam hose was connected through a 1-1/4-in-diam tee to 1-1/2-in-diam hose and a 1-1/2-in-diam steel four-way valve. The three remaining branches of the four-way valve supplied water to the boreholes through 1-1/2-in-diam fire hose (fig. 2). The water flow rate to each borehole was controlled by a stainless steel tangent-adjust hose clamp. A short piece of pipe was inserted under the clamp to insure reasonably tight shutoff, when desired. To minimize inlet air leakage, each hose was sealed to the borehole with duct tape. The branched manifold water system using reducing fittings, tees, four-way valves and different hose sizes was necessary to deliver essentially equal volumes of water to each borehole despite the differences in elevation and distance to the storage pool.

The downhill sloping terrain and 1-1/2-in-diam minimum hose size allowed adequate water flow (1 to 5 gal/min) at grade into each borehole. The water head ranged from 4 ft at the closest boreholes to 12 ft at the furthest. The single storage pool with the manifold system was sufficient to supply water over the entire 1.4-acre area believed to encompass the fire zone.

QUENCHING PROCEDURE

The initial plans for quenching called for injection of about 2 to 3 gal/min of water into each of the boreholes at the boundary of the fire zone. The steam and any combustible volatiles formed would therefore be swept over interior hot zones as they migrated to the exhaust hole (figs. 1 and 4), leading to further heating of the gases and possible incineration of the volatiles. After the boundary zones cooled, the water-injection process would then be extended inward toward the exhaust manifold. Eventually all boreholes (about 50) were to be injected simultaneously. During injection, the exhaust ventilation system would be operated at a vacuum level just sufficient to prevent venting from the boreholes. By observation this level was determined to be about 3 to 4 in H_2O, which corresponded to an exhaust flow of about 4,000 scfm.

However, several factors influenced the implementation of these plans:

1. To reduce operating costs, it was decided that quenching operations would be carried out for only one shift per day within the normal work week. Water injection and fan operation would commence at the beginning of the day shift and stop at the end of the shift. However, the large sliding gate valve at the top of the exhaust manifold (fig. 1) would remain open to allow for continuous natural ventilation (the chimney effect).

2. Quenching was started before installation of a required second connection to the municipal water main. This meant that not all the boundary boreholes could be injected simultaneously at the start of quenching. Additional holes were added as the water supply increased.

3. There was some difficulty in establishing a pre-set uniform water flow to each borehole.

4. After 21 days of single shift operation, during which time the exhaust temperature dropped from 592° to 263° C (1,100° to 505° F), it was decided to attempt round-the-clock water injection and fan operation. About this same time (days 145-146), balancing problems were encountered with the fan which led to discontinuance of forced ventilation, but the water injections were continued. During the remainder of the quenching process, heat was exhausted only through the chimney effect (except for a 1/2-h fan operation on day 155, following the start of the site excavation).

Table 2 summarizes water injection data and resultant temperature decreases.

TABLE 2. - Chronology and results of quenching procedure

Julian day[1]	Water-injection data: Number of boreholes injected	Duration, h	Total volume, gal	Ave rate per borehole, gal/min	Exhaust temp, °C[2]	Comments
125[3]....	8	0.5	1,500	6.2	592-530	1st day of quenching.
126.....	12	2.5	2,500	1.4	562-487	
127.....	13	5.1	13,700	3.4	605-445	
130.....	16	6.7	23,000	3.6	555-430	Monday after idle weekend.
131.....	16	6.5	22,400	3.6	467-412	
132.....	16	3.5	19,400	5.8	405-367	Pool emptied for new water line.
133.....	20	6.7	29,200	3.6	378-362	
134.....	27	6.7	40,800	3.8	353-350	
137.....	26	6.8	37,200	3.5	317-326	Monday after idle weekend.
138.....	32	7.0	54,000	4.0	279-320	
139.....	36	1.8	20,100	5.2	278-308	Fan startup problem.
140.....	35	7.0	66,500	4.5	264-301	
141.....	35	6.0	18,800	1.5	259-256	Fan off for balancing.
144.....	48	7.2	75,500	3.6	230-266	Monday after idle weekend.
145.....	48	6.5	88,500	4.7	248-263	Attempted continuous operation.
145-146.	48	15.5	238,200	5.3	246	Fan breakdown. Start of continuous water injection with fan off.
147.....	48	24	351,800	5.0	238	
148.....	48	24	393,200	5.4	213	
149.....	48	24	227,000	3.3	199	
150.....	48	24	227,000	3.3	188	
151.....	48	24	227,000	3.3	180	
152.....	48	24	227,000	3.3	174	
153.....	42	24	153,400	2.5	165	
154.....	20	24	190,000	6.6	163	
155.....	10	24	73,100	5.1	162	Excavation started. Temperature after 0.5 h of fan operation.

[1]Only working days are listed.
[2]Where 2 temperatures are shown, they are the 0730 (time) and 1430 temperatures, respectively; single temperatures are 0730 readings.
[3]May 5, 1982.

Almost 2.8 million gal of water was injected over the 30-day period, leading to a drop in exhaust temperature from 592° to 162° C (1,100° to 324° F). Data on accumulated water and heat flows during the entire quenching operation, as discussed in the next two sections, yield some insight into how the WIFE procedure worked at Calamity Hollow.

WATER FLOW

Cumulative water flow curves were constructed (fig. 5) from the daily data on water injection (table 2) and from daily measurements of the water flow rate from three seam-level surface seeps located along the southern area of the old strip operation highwall (fig. 4). Total flow

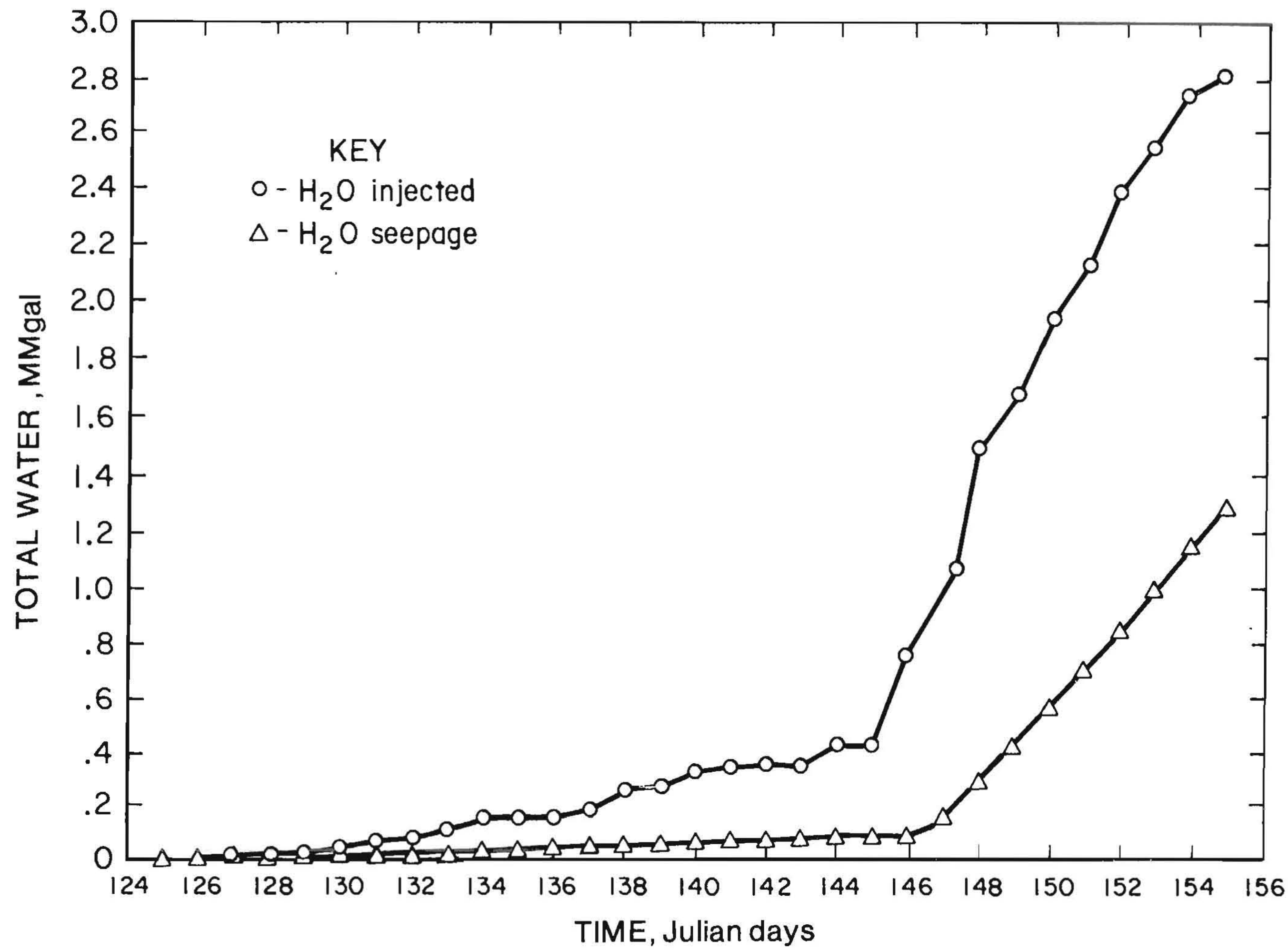

FIGURE 5. - Cumulative water flows.

from these seeps increased to about 150,000 gal/d. This increase in surface flow coincided with increased borehole injection to approximately 230,000 gal/d (days 145-147). The water discharge had a temperature only slightly above normal, and its pH was approximately 6, which was slightly below normal.

The difference between the injection and seep flows (1,500,000 gal total) represents the sum of (1) water that vaporized, (2) water that was absorbed underground in the region of the fire zone, and (3) water that flowed out of the fire zone to other areas of the mine (e.g., through the isolation barrier). The amount of water that evaporated could not exceed the exhaust mass flow rate of about 3,000 g/s maximum, or about 68,000 gal/d. The actual water in the exhaust was not measured; however, if it is assumed that 10 pct of the exhaust mass flow was water, a total of approximately 200,000 gal of water was exhausted during the 30-day period. This would leave 1,300,000 gal to be accounted for by runoff to other areas of the mine or absorption by the strata in the fire zone. Estimating that the ground strata in the approximately 1-acre injection area could contain as much as 10 pct water, by volume, would account for 1,000,000 gal,[7] leaving 300,000 gal of water as runoff to other areas of the mine. At an estimated rate of 20 gal/min, this underground runoff could not cause significant

[7] 44,000 ft^2 × 30 ft (overburden) × 0.1 × 7.48 gal/ft^3 ≃ 1,000,000 gal.

subsidence or other damage to the mine; no water-related damage was observed during excavation.

Comparing the decreases in exhaust temperature and the daily amounts of water injected (table 2), it cannot be assumed that if a small amount of water is helpful for extinguishment, then more water is better. The water-utilization efficiency defined by the daily rate of temperature drop with respect to the amount of water injected averaged about 5×10^{-4} °C/gal for the 10 days prior to day 146 and 5×10^{-5} °C/gal for the 10 days following day 145. This factor-of-10 decrease in water-utilization efficiency may have been due in part to stoppage of the fan operation (after day 145), but from a comparison of figure 5 and the heat-flow data shown in figure 6 it is obvious that 65 pct or more of the water injected at high rates after day 145 was simply channeled out of the mine and so was not useful for quenching purposes.

HEAT FLOW

Determination of cumulative heat exhaustion over the entire quenching period (fig. 6) was complicated by the intermittent fan operation and the final fan stoppage after day 145. While the instruments in the exhaust manifold were suitable for measuring volume flows greater than 2,000 scfm, their accuracy at the lower flow rates which resulted from natural ventilation was highly questionable. However, estimates of the natural ventilation flow rates were made from consideration of the buoyancy forces developed by the density difference and pressure head which existed along the exhaust manifold with the fan off.

The upward buoyancy force (ΔP) developed by the difference in gas density at station 1 (fig. 1) in the manifold (ρ_1) and at the top of the manifold, in the elbow (ρ_e), can be written as

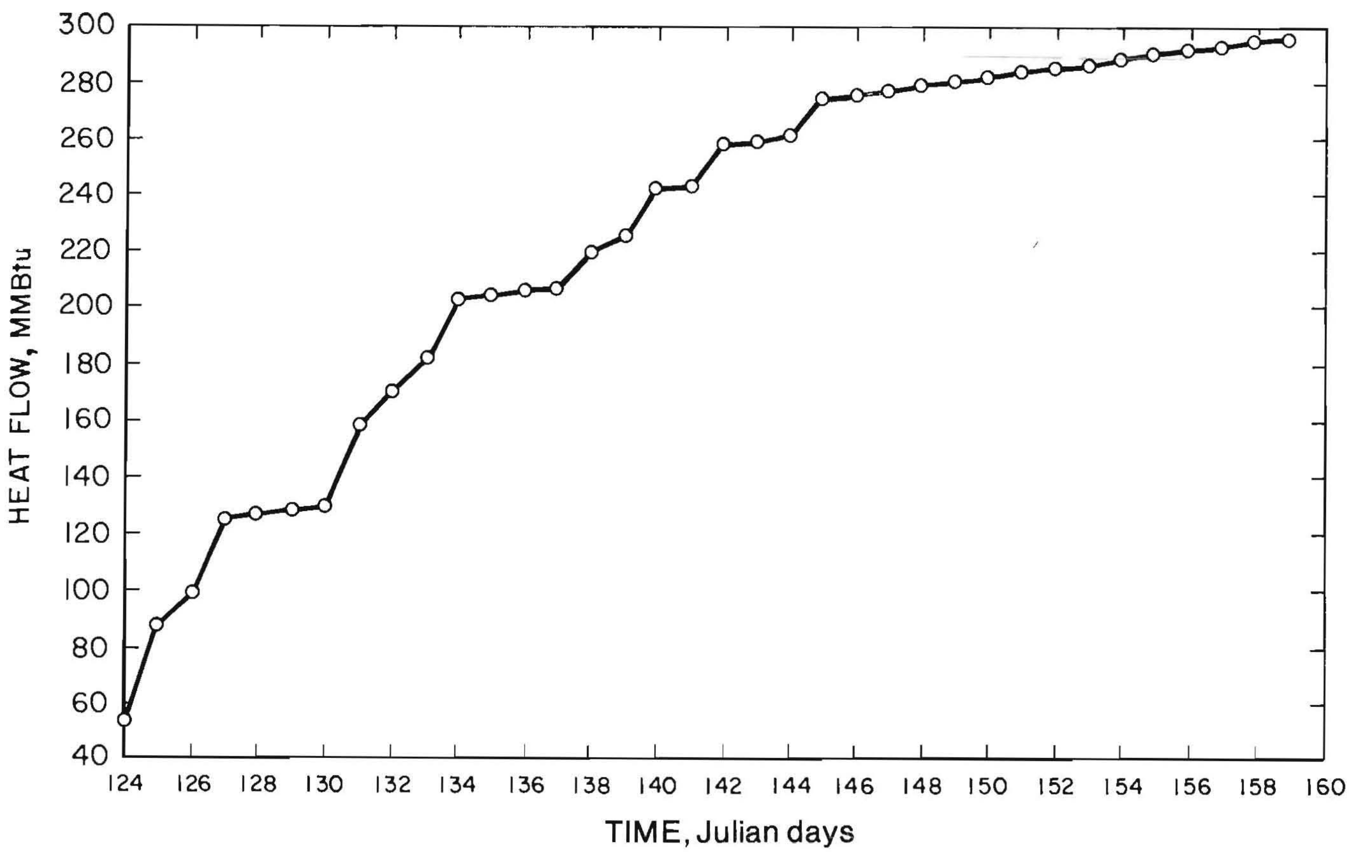

FIGURE 6. - Cumulative heat flows.

$$\Delta P = (\rho_e - \rho_1)\, g\ell, \tag{1}$$

where ℓ = height of the manifold elbow above station 1, cm,

and g = gravitational constant (980 cm/s^2).

The pressure drop for gas flow between two points (5) is given by

$$\Delta P = f\, \bar{\rho} v^2\, \ell/a, \tag{2}$$

where f = friction factor, dimensionless (taken as 0.03),

$\bar{\rho}$ = average density of flowing gas, g/cm^3,

a = inside radius of manifold (33 cm),

and v = gas velocity, cm/s.

The following expressions are used to describe the densities $\bar{\rho}$ and $\bar{\rho}_e$, which actually refer to positions between the monitoring stations:

$$\bar{\rho} = \frac{(\rho_1 + \rho_e)}{2} \tag{3}$$

and

$$\rho_e = \frac{(\rho_1 + \rho_2)}{2}. \tag{4}$$

The density ρ_e is not measured directly; it is estimated to be the average of the densities measured at stations 1 and 2 (fig. 1). Equating equations 1 and 2, and using equations 3 and 4, yields

$$v^2 = \left[\frac{(\rho_2/\rho_1) - 1}{(\rho_2/\rho_1) + 3}\right] \frac{2ag}{f} \tag{5}$$

or

$$v^2 = \left[\frac{(T_1/T_2) - 1}{(T_1/T_2) + 3}\right] \frac{2ag}{f}, \tag{6}$$

where T_1 and T_2 are the measured absolute temperatures, in kelvins, at stations 1 and 2, respectively.

The actual volumetric flow rate (in actual cubic feet per minute) is then

$$V\ (\text{acfm}) = (2.12 \times 10^{-3})\, \pi a^2 v, \tag{7}$$

where the numerical factor converts cm^3/sec to ft^3/min, which when converted to standard conditions becomes (numerically)

$$V\ (\text{scfm}) = \left[\frac{1.16 \times 10^7}{T_2}\right] \left[\frac{(T_1/T_2) - 1}{(T_1/T_2) + 3}\right]^{1/2} \frac{1}{(3T_1/T_2) + 1}. \tag{8}$$

Here, the temperatures must be expressed in kelvins. Using the recorded daily temperature data for stations 1 and 2 during the times when the fan was off yielded an almost constant value for the natural ventilation flow (1,960±80 scfm). This calculated constant flow velocity with the fan off was integrated with the flow values measured with the fan on to yield the cumulative result shown in figure 6. During the quenching period, 300 million Btu of heat was exhausted from the mine.

ANALYSIS OF RESULTS

GENERAL

Figure 7 shows the recorded exhaust temperature and the mass flow and heat flow rates versus time for the 30-day quenching period (days 125-155). Although the fan was not operating all the time, significant quenching was achieved, as shown by the consistent daily decreases in exhaust temperature.

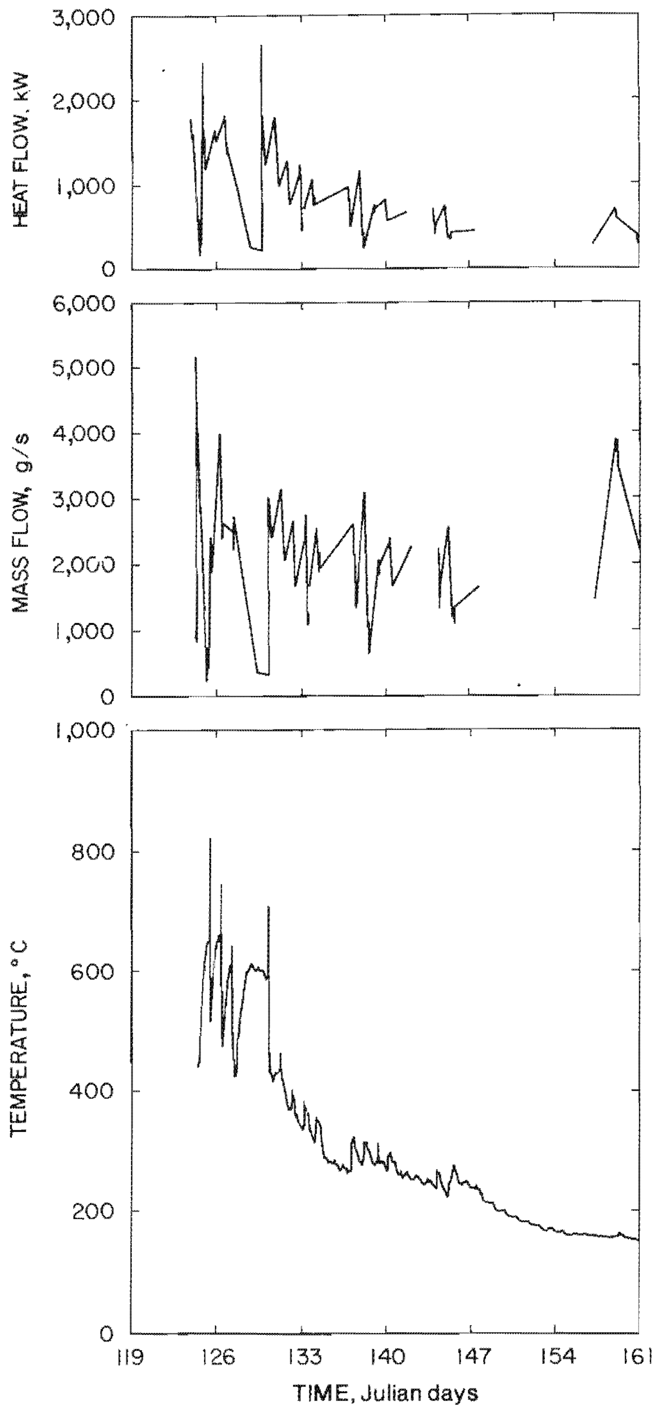

FIGURE 7. - Exhaust temperature, mass flow, and heat flow during quenching period.

The short-term peaking temperatures observed each day, particularly early in the quenching period, were associated with the morning fan startup. The temperature peaks were very similar to those observed during startup tests of the Burnout Control system (1, p. 28, figure 28), which at the time of those tests were attributed to the ignition of volatiles built up in the mine when the fan was not operating. The appearance of these peaking temperatures would then indicate active coal pyrolysis and solid coal temperatures probably in excess of 300° C (572° F). The fact that these peaking temperatures tended to decrease significantly with time is additional evidence that the burning coal was being extinguished.

ENERGY BALANCE

One of the advantages of the WIFE procedure is that monitoring of the amount of heat drawn from the mine may allow the determination of the degree of extinguishment that has been achieved. To illustrate this point, consider the energy balance for a control volume that encompasses the entire underground mine fire and affected rock overburden. The energy balance can be expressed as

$$\dot{Q}_c = \dot{Q}_l + \dot{Q}_v + \dot{Q}_R,^8 \qquad (9)$$

where $\dot{Q}_c$ = rate of heat release by combustion,

$\dot{Q}_l$ = rate of heat exhaust through the ventilation system (i.e., through the exhaust manifold),

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[8]A dot above the variable denotes the derivative of the variable with respect to time.

$\dot{Q}_v$ = rate of heat absorbed by water evaporation,

and $\dot{Q}_R$ = rate of heat absorbed by rock overburden.

In terms of measurable and/or definable quantities, equation 9 can be written as

$$\dot{M}_c \Delta H_c = \dot{M}_1 C_p (T_1 - T_o) + \dot{M}_v \Delta H_v + M_R C_p \dot{T}_R, \tag{10}$$

where $\dot{M}_c$ = mass rate of coal combustion, g/s[9]

ΔH_c = heat of combustion, cal/g,

$\dot{M}_1$ = mass rate of gas exhaust at station 1, g/s,

C_p = average heat capacity (assumed uniform throughout control volume), cal/g-°C,

T_1 = exhaust gas temperature at station 1, °C,

T_o = ambient reference temperature, °C,

$\dot{M}_v$ = mass rate of water evaporation, g/s,

ΔH_v = heat of vaporization of water, cal/g,

M_R = mass of rock overburden, g,

and $\dot{T}_R$ = rising rate of rock temperature, °C/s.

One form of the above energy balance which is of interest is

$$\frac{\dot{M}_c}{\dot{M}_a} = \frac{(T_1 - T_o) + (\dot{M}_v/\dot{M}_a)\left[(\Delta H_v/C_p) + (T_1 - T_o)\right] + M_R \dot{T}_R/\dot{M}_a}{(\Delta H_c/C_p) - (T_1 - T_o)}. \tag{11}$$

Here $\dot{M}_1$ is equated to the sum of its components: air ($\dot{M}_a$), coal combustion products ($\dot{M}_c$), and water vapor ($\dot{M}_v$).

Under conditions such that the major portion of the exhausted heat comes from the heat of combustion, such as would occur during steady-state burning or possibly in the early stages of quenching, the term containing $\dot{T}_R$ can be neglected and equation 11 becomes

$$\phi = \frac{\dot{M}_c}{\dot{M}_a} = \frac{(T_1 - T_o)\left[1 + (\dot{M}_v/\dot{M}_a)\right] + (\dot{M}_v/\dot{M}_a)(\Delta H_v/C_p)}{(\Delta H_c/C_p) - (T_1 - T_o)}, \tag{12}$$

where ϕ is the effective fuel-to-air ratio (M_c/M_a) for the combustion process.[10]

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[9]For convenience, units of the centimeter-gram-second (CGS) system are used in this section.

[10]This might be better visualized for stoichiometric combustion of coal, with values of $\dot{M}_v = 0$, $\Delta H_c = 6{,}900$ cal/g, $C_p = 0.35$ cal/g-°C, and $(T_1 - T_o) = 2{,}200°$ C. This yields a value of $\phi = 0.11$; i.e., ideally it takes about 9 g of air to burn 1 g of coal.

For various burning conditions where $\dot{M}_a$ is kept constant, equation 12 relates the amount of coal burning directly to the exhaust temperature T_1. Thus, it is possible to define a quenching efficiency (Φ) in terms of measurable quantities by normalizing the Φ determined at any time (t) by its initial value, provided $\dot{M}_a$ is kept the same:

$$\Phi \equiv 1 - (\dot{M}_c)_t/(\dot{M}_c)_o$$

$$= 1 - \phi_t/\phi_o. \quad (13)$$

Applying equation 13 to the data presented in table 2 is somewhat tenuous because (1) water vapor in the exhaust ($\dot{M}_v$) was not measured, (2) the daily on-and-off operation of the fan would upset the establishment of a quasi-steady-state energy flow, and (3) there is uncertainty about when heat transfer from the rock overburden becomes significant. However, since the mine vacuum level was kept reasonably constant during fan operation, it is believed that $\dot{M}_a$ and the size of the effective control volume were approximately constant during fan operation. This means equation 13 could be applied to the data taken over the first 21 days of the quenching operations, with the assumptions that (1) the final value of T_1 each day (i.e., at the end of the fan operation) represented the quasi-steady-state exhaust condition and (2) the value of $\dot{M}_v$ can be estimated from the water-injection rate. The data shown in figure 5 indicate an approximately constant rate of accumulation of water in the mine for days 125-145 corresponding to an overall injection rate of 18,000 gal/d or 800 g/s. Taking this value for $\dot{M}_v$ and the following values for the other parameters:

$$\dot{M}_a = 3,000 \text{ g/s},$$

$$\Delta H_v = 540 \text{ cal/g},$$

$$C_p = 0.35 \text{ cal/g-°C},$$

$$\Delta H_c = 6,900 \text{ cal/g},$$

$$T_o = 20° \text{ C},$$

$$(T_1)_o = 530° \text{ C};$$

equation 13 yields

$$\Phi_t = 1 - \left[\frac{23\Delta T_t + 7,450}{19,700 - \Delta T_t}\right], \quad (14)$$

where $\Delta T_t = (T_1)_t - T_o$.

Figure 8 shows a plot of equation 14 using the final exhaust temperature data from table 2, for the first 21 days of quenching. The data suggest that about 33 pct of the burning coal was extinguished during this period; however, these results are rather sensitive to the assumptions that were made. For example, decreasing the assumed value of $\dot{M}_v$ by a factor of 10 significantly increases the quenching efficiency to 48 pct at the end of the same period. This is also shown in figure 8. In addition, equation 13 (and equation 14) implies that heat transfer between the rock and the venting gases can be neglected. This is questionable for exhaust temperatures below approximately 350° C (662° F); below 350° C significant burning might not occur. Significant heating of the exhaust by the rock will result in cooling of the rock or a negative value for the $\dot{T}_R$ term in equation 11. This in turn would lead to lower values of ϕ_t for the later stages of quenching and hence higher quenching efficiencies (Φ_t) than those calculated using equation 12.

There is insufficient information at this time to quantify the effect of $\dot{T}_R$ on the quenching efficiency; however, some consideration can be given to the temperature of the exhaust gas when it is heated primarily by the rock and not by coal combustion. The energy balance described in equation 10 can be rewritten as

$$\dot{T}_R + \frac{\dot{M}_1}{M_R}(T_1 - T_o) = \frac{\dot{M}_c\Delta H_c - \dot{M}_v\Delta H_v}{M_R C_p}. \quad (15)$$

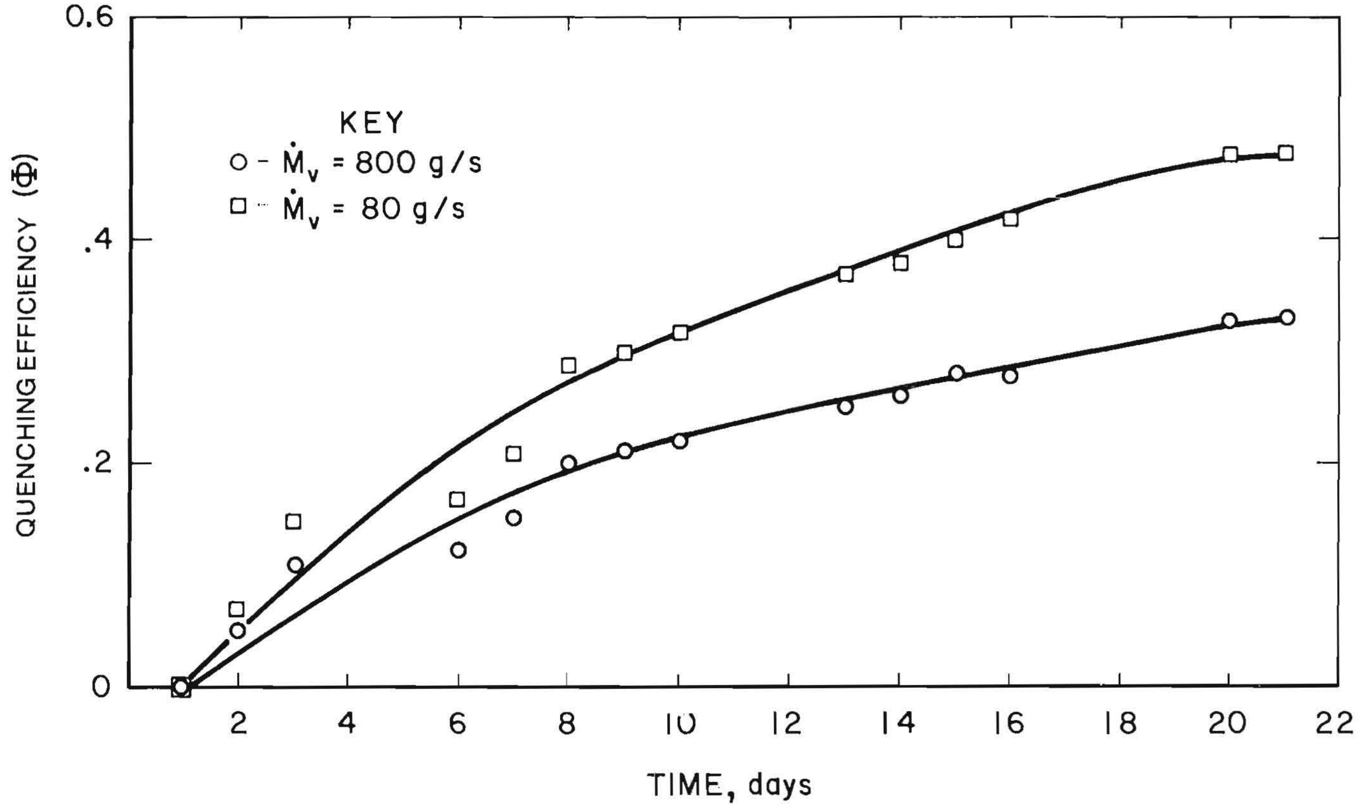

FIGURE 8. - Quenching efficiency versus time.

Considering a period during quenching in which $T_1 \simeq T_R$ (i.e., there is significant heat transfer from the rock to the venting gas), and assuming $\dot{M}_c$, $\dot{M}_v$, $\dot{M}_1$, and M_R (related to the size of the effective control volume) are all constant with time, equation 15 can be integrated to yield

$$\Delta T_R = T_R(t) - T_o = \frac{\dot{M}_c \Delta H_c - \dot{M}_v \Delta H_v}{\dot{M}_1 C_p} + B \exp\left(-\dot{M}_1 t/M_R\right), \qquad (16)$$

where B is an integration constant to be determined by applicable boundary conditions.

Under conditions of constant fan operation, equation 16 might be applicable to the latter stages of the quenching period, during which the heat release by combustion ($\dot{M}_c \Delta H_c$) might be smaller than the rock-cooling value ($M_R C_p \dot{T}_R$). It is useful then to examine the temperature data shown in table 2 for days 137 to 145—late in the quenching period when the fan was still operating. Here, time is considered to run continuously (as versus intermittently), and the constant parameters are taken as

$$\dot{M}_v = 800 \text{ g/s},$$

$$\dot{M}_1 = 1{,}300 \text{ g/s},^{11}$$

$$\Delta H_c = 6{,}900 \text{ cal/g},$$

$$\Delta H_v = 540 \text{ cal/g},$$

$$C_p = 0.35 \text{ cal/g-°C};$$

leading to

$$\Delta T_R - A = B \exp\left(-1{,}300\ t/M_R\right), \qquad (17)$$

where $A = 15.2\ \dot{M}_c - 950$.

[11] Time-weighted average rate of mass exhaust based upon both forced and natural ventilation.

TABLE 3. - Least-square curve-fitted constants for equation 17[1]

$\dot{M}_c$, g/s	A, °C	$\dot{M}_1/M_R$, days	B, °C	Variance (R_2)	M_R, tons	Predicted T_1, °C[2]	R_Q[3]	t required for T_R to equal 100° C, days
0.....	-950	0.0067	1,260	0.99	18,500	179	0	30
10....	-798	.0077	1,110	.99	16,100	181	.14	30
25....	-570	.0097	885	.99	12,800	186	.43	32
50....	-190	.0178	506	.99	6,950	191	1.50	35

[1]Temperature data taken from table 2 for days 137 (t = 1 day) to 145 (t = 9 days).

[2]Day 155.

[3]R_Q Dimensionless ratio of coal combustion to rate of rock cooling =

$$\frac{\dot{M}_c \Delta H_c}{M_R C_p \Delta \dot{T}_R \ (t = 0)}.$$

Table 3 lists the least-square constants for equation 17 when it is curve fitted to the data from table 2, taking $T_1 = T_R = 326°$ C at t = 1 day, and allowing $\dot{M}_c$ to take on various constant values from 0 to 50 g/s. It is readily seen from the variance R_2 that the T_1 data are fit equally well for all chosen values of $\dot{M}_c$; however, for values of $\dot{M}_c > 25$ g/s, a number of inconsistencies appear. First, the value of R_Q indicates that the assumption that $\dot{M}_c \Delta H_c$ is less than $M_R C_p \dot{T}_R$ is not upheld. Second, the calculated value of exhaust temperature T_1 at day 155 (the last day the fan was operated) is somewhat higher than the measured value. Third, the calculated effective mass of heated rock (M_R in table 3) is far too low.

During the excavation phase of the project it was observed that about 1 acre of mine area at Calamity Hollow was thermally affected to a height of about 10 ft over the bottom of the coal seam. This would correspond to an effective control volume of about 4.4×10^5 ft^3, or about 20,000 tons, of rock and coal.

The fact that the calculated values of M_R and T_1 (for day 155), when $\dot{M}_c$ was less than 25 g/s, are reasonably consistent with observations suggests that equation 17 may describe the quenching period after day 137. Based on the measured exhaust heat-flow rate corresponding to T_1 = 530° C at day 125 (about 10^5 Btu/min), it was estimated that the burning rate of the coal shortly after the start of the quenching procedure was approximately 66 g/s. Thus the calculations in table 3 (the case of rock cooling being predominant) would indicate that a quenching efficiency of 60 pct or better was achieved by day 145 (21 days into the quench operation). This value is about twice the value of Φ shown in figure 8 (the case of coal burning being predominant, with $\dot{M}_v$ = 800 g/s). The uncertainty as to the value of $\dot{M}_v$ appropriate for these calculations makes it highly speculative to compare the two cases; however, it does suggest that the rock cooling term in equation 11 ($M_R C_p \dot{T}_R$) may have been significant even during the early stages of quenching. Regardless, the two mathematical approaches presented demonstrate the potential diagnostic capabilities in the WIFE procedure. They also indicate the necessity of determining rates of water evaporation and air flow if full advantage is to be gained from the procedure.

EXTRAPOLATION OF DATA

The curve-fitted constants for equation 17 (table 3) can be extrapolated to determine the time necessary for the control volume to achieve a rock temperature of 100° C (212° F), which might be taken to represent permanent extinguishment. This was done for each of the values of $\dot{M}_c$ shown in the first column of table 3; the calculated extinguishment times are given in the last column of the table. The required extinguishment time, which varies from 30 to 35 days, would correspond to days 167 to 172, well into the excavation phase of the project (which was initiated on day 154 and completed on day 189). While the required conditions for applying equation 17 are not consistent with those of the actual quenching operations beyond day 146, very few underground temperatures higher than 150° C (302° F) were noted during the excavation operation.

Based on the above results, the estimated total time necessary for permanent extinguishment of the fire at Calamity Hollow using the WIFE procedure would be 42 to 47 days from the start of quenching (on day 125). This can be compared with the 2-yr time requirement often quoted for permanent extinguishment using conventional surface-sealing techniques (6), in which underground heat is dissipated primarily by thermal conduction through the overburden to the surface.[12]

The temperature of 162° C (324° F) recorded on day 155 (table 2), the last day the fan was operated, just prior to extensive disruption of the overburden by excavation, might be considered to be representative of the temperature of the total mass M_R of the original control volume. From the value of M_R calculated by equation 16 and the measured accumulated heat flows (fig. 6), the total heat stored in the ground during the Burnout Control operation can be determined. The heat content of the control volume at day 155 can be expressed as $M_R C_p \Delta T_R$, or 1.8×10^5 M_R Btu, where M_R is given in tons. Thus, M_R = 18,500 tons (from table 3, for $\dot{M}_c = 0$), the heat remaining underground is estimated to be 3.3×10^9 Btu. Adding to this the 3×10^8 Btu exhausted during days 125 to 155 (fig. 5) yields 3.6×10^9 Btu as the total amount of heat stored underground during the nearly 4-month burnout operation which consumed an estimated 1,100 tons of combustible materials (according to data that will be reported in part 2 of this report series). At an average heating value of 12,000 Btu/lb, this amount of combustible represents 2.6×10^{10} Btu, which would put the underground heat loss from in situ coal combustion at 14 pct. This heat loss value is consistent with theoretical considerations of burning in an underground channel (7); the previously calculated value was 10 pct for a fire in a 6-ft-high by 11-ft-wide underground coal channel.

CONCLUSIONS

The water-injection fume-exhaustion (WIFE) procedure used to quench and cool the abandoned coal mine fire at Calamity Hollow proved successful in terms of lowering the temperature of the approximately 1-acre fire zone and the surrounding rock strata prior to excavation of the site. Time and funding limitations allowed for only 30 days of water injection under combined forced and natural exhaust-ventilation conditions; but even so, exhaust gas temperatures were decreased from 592° to 162° C (1,100° to 324° F), and perhaps more than 50 pct of the burning coal mass was extinguished. While complete extinguishment of the Calamity Hollow mine fire was not achieved during this short period, data analyses of the time dependency of the falling exhaust temperature in conjunction with an overall energy balance for the underground heated zone suggest that complete and permanent extinguishment might have been achieved if the WIFE procedure were

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[12] An effective surface seal must prevent atmospheric air from permeating through the overburden to the fire zone. This implies that the seal will also inhibit convective cooling of the fire zone by the permeation of hot gases through the overburden to the surface.

extended an additional 20 days, to 50 days total. Even at two or three times this total time period, extinguishment would be far faster than if conventional surface-sealing techniques were used.

The WIFE procedure has a distinct advantage over other methods of fire extinguishment in that its efficiency can be monitored continuously. The relatively simple theoretical analyses presented in this report demonstrate the type of mine fire diagnostics that can be conducted. Significant refinements can be made through theoretical considerations of underground conductive and convective heat transport. However, regardless of how simple or complex the theoretical considerations concerning the underground thermal transport processes are, accurate measurements of the rate and composition of the exhausted gases will be required. Of particular importance is the concentration of water vapor, which will yield the rate of water evaporation under quasi-steady-state conditions. Although water-vapor concentration was not measured at Calamity Hollow, reasonable estimates of the water evaporation rate did lead to consistent results in terms of the rock cooling rate, the amount of rock heated, and the total heat loss during the continuous burnout operation. The WIFE procedure is a novel and potentially useful method of extinguishing abandoned coal mine fires which apparently can overcome the major problems associated with previous water-injection techniques.

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