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A Method To Evaluate the Performance of Coal Fire Extinguishants

By A. C. Smith, D. Ng, M. W. Ryan, and C. P. Lazzara

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Btu	British thermal unit
Btu/lb	British thermal unit per pound
Btu/(lb)(°C)	British thermal unit per pound degree Celsius
Btu/min	British thermal unit per minute
°C	degree Celsius
ft	foot
ft^2	square foot
ft/min	foot per minute
ft^3/min	cubic foot per minute
gal	gallon
h	hour
in	inch
in/h	inch per hour
lb	pound
lb/ft^3	pound per cubic foot
lb/h	pound per hour
min	minute
wt %	weight percent

A METHOD TO EVALUATE THE PERFORMANCE OF COAL FIRE EXTINGUISHANTS

By A. C. Smith,[1] D. Ng,[2] M. W. Ryan,[3] and C. P. Lazzara[4]

ABSTRACT

The U.S. Bureau of Mines developed an experimental method to evaluate the relative effectiveness of water additives on the extinguishment of coal fires. The experiments were conducted in the fire zone of the multiple-entry section of the Bureau's Bruceton Experimental Mine. Four-hundred-pound Pittsburgh Seam coalbeds were ignited and allowed to burn until well-developed fires were achieved. Extinguishing agent-water solutions were then applied to the fires, and the quantity required to extinguish the fires was compared with the quantity of water alone required to extinguish similar fires. A 20% diammonium phosphate-water solution required an average of 5.8 gal to extinguish the coal fires, while two commercially available additive-water solutions required an average of 8.1 and 8.0 gal, respectively. The average amount of water required to extinguish the fires was 7.4 gal. An analysis of covariance, using the thermal energy of the coalbed to quantify the fire at the time of extinguishment, showed that the diammonium phosphate-water solution was slightly more effective at extinguishing these coal fires than water alone, and the two commercially available additive-water solutions were statistically equivalent to water alone.

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INTRODUCTION

Underground coal mine fires are a serious threat to life, property, and the Nation's energy resources. From 1980 to 1988, the Mine Safety and Health Administration investigated 135 coal mine fires (*1*).[5] In 1984, a fire in the Wilberg Mine, UT, resulted in 27 fatalities (*2*). In 1986, a fire of unknown origin occurred in the Orchard Valley Mine, CO, that resulted in the sealing of the entire mine (*3*).

A small coal fire detected in its incipient stage can usually be fought and controlled with water. However, in many instances the supply of water is limited, while the fuel, coal, is unlimited. If the fire becomes uncontrollable and spreads to other parts of the mine, the only recourse may be to seal the mine. An improvement in the extinguishing effectiveness of water would increase the likelihood of successful extinguishment, limiting the potentially disastrous consequences of coal fires.

Early work by the U.S. Bureau of Mines examined the relative effectiveness of several materials on extinguishing 5,200-lb floor coal fires, 12,000-lb floor and rib coal fires, and 20,000-lb floor, rib, and roof fires. The materials included water, water with a 2% alkyl-aryl-sulfonate wetting agent added, a potassium carbonate-water solution, a whitewash mixture, and soda acid. Water was found to be the most effective of the extinguishing agents, with no substantial difference noted in the experiments with the water additives (*4*). Bryan evaluated the effect of several salts added to water on the extinguishment of standard 200-lb wood crib fires. The results showed that adding the ammonium compounds monoammonium and diammonium phosphate to water increased water's extinguishing effectiveness, while adding calcium chloride and zinc chloride increased water's effectiveness moderately, and adding sodium carbonate decreased water's extinguishing effectiveness (*5*). Tyner also studied the effect of adding chemical additives to water on the extinguishment of wood crib fires. The results showed that the most effective chemicals were boric acid, phosphoric acid, and ammonium phosphate (*6*).

However, no standard experimental method existed for comparing the effectiveness of extinguishing agents with that of water when applied to a coal fire. Consequently, there is insufficient knowledge concerning the relative effectiveness of various new agents being promoted as possessing unique properties for extinguishing coal fires.

The Bureau has developed an experimental method to evaluate the relative effectiveness of water additives on the extinguishment of coal fires. Twenty-six coal fires were extinguished, using water, a diammonium phosphate (DAP)-water solution, or one of two commercially available additive-water solutions. This report describes the experimental method, the results of the extinguishment tests, and a statistical analysis to evaluate the reproducibility of the test method and the relative effectiveness of the extinguishing agents. This work is in support of the Bureau's goal to improve safety in the mining industry.

EXPERIMENTAL FACILITY[6]

The experiments described in this report were conducted in the fire zone of the multiple-entry section of the Bureau's Bruceton Experimental Mine (fig. 1). The roof and floor of the fire zone are lined with refractory firebrick in the form of an arch. The fire zone floor is 30 ft long by 20 ft wide. The arch is 4.9 ft at its highest point and has a cross-sectional area of approximately 100 ft^2. The approximate dimension of the entry before and after the fire zone is 7 ft high by 20 ft wide, with a cross-sectional area of about 140 ft^2.

Two identical coal chambers were positioned side by side longitudinally in the fire zone in each experiment. The two chambers were centrally located, 1 ft into the archway, and elevated 1 ft above the ground, with 2.5 ft between the chambers. The chambers were constructed of 0.5-in mesh wire screen and angle iron, and each chamber measured 1 ft wide by 1.5 ft high by 6 ft long. An aluminum trough was suspended longitudinally beneath each chamber spanning its entire width and length. The trough was sloped at a slight angle to collect any excess extinguishant that otherwise would have been lost from runoff. Figure 2 shows the two coalbeds shortly after ignition.

The ventilation system in the Bruceton Experimental Mine was set to route the ventilation flow through the fire zone (fig. 1). The mine ventilation fan for each experiment delivered an airflow volume of approximately 32,000 ft^3/min. The ventilation velocity around the coalbeds was measured prior to ignition with a vane-type anemometer, at the positions indicated in figure 3. The ventilation was measured four times at each position and the average velocity at that position calculated. The values

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

[6]The authors would like to acknowledge Pittsburgh Research Center personnel, Charles Luster, exhibits maker, and Kenneth E. Mura, physical science technician, for their valuable contributions to the design and construction of the experimental apparatus.

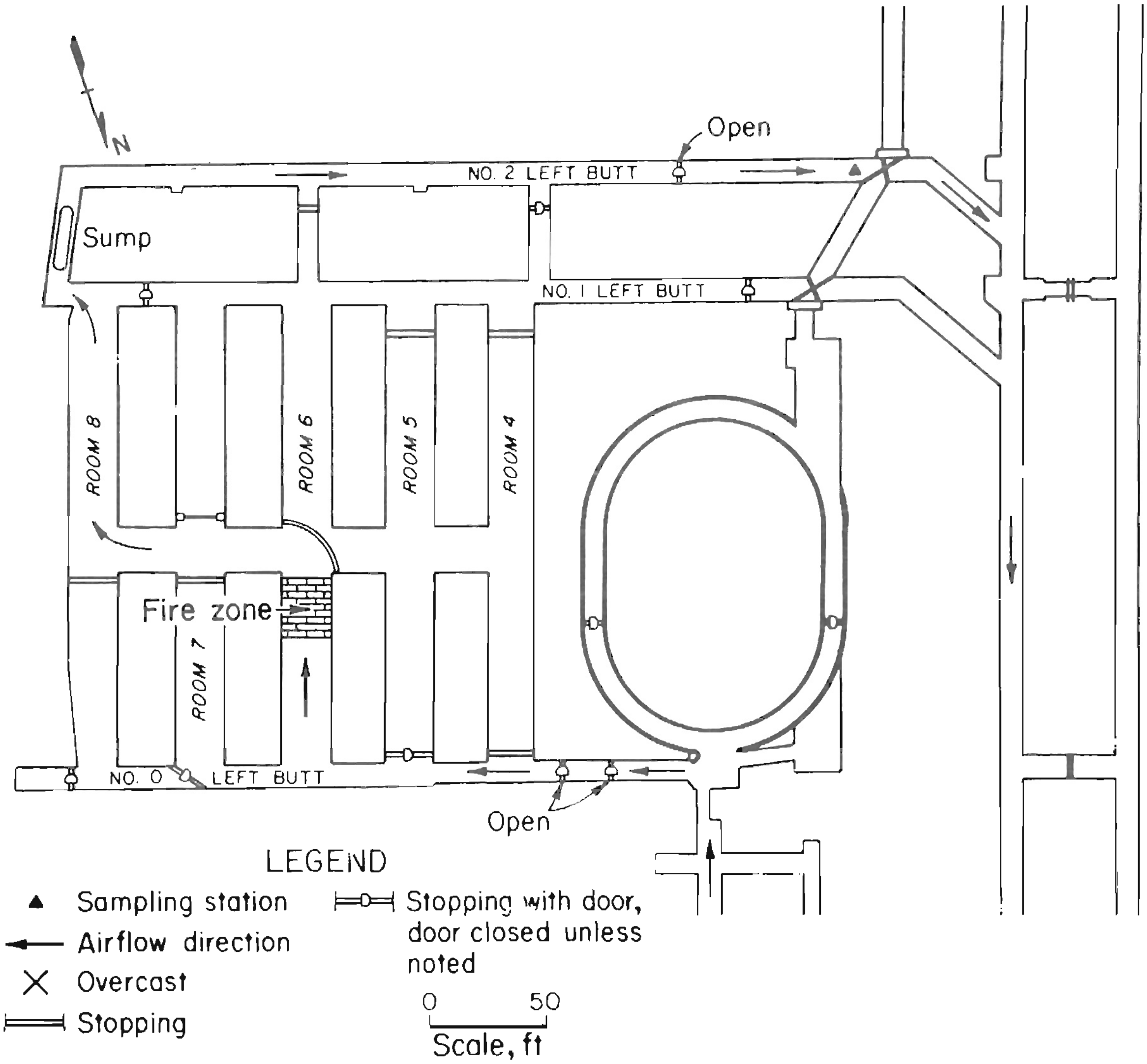

Figure 1.—Multiple-entry section of Bruceton Experimental Mine.

Figure 2.—Coal chambers prior to experiments as viewed from upstream side of fire zone.

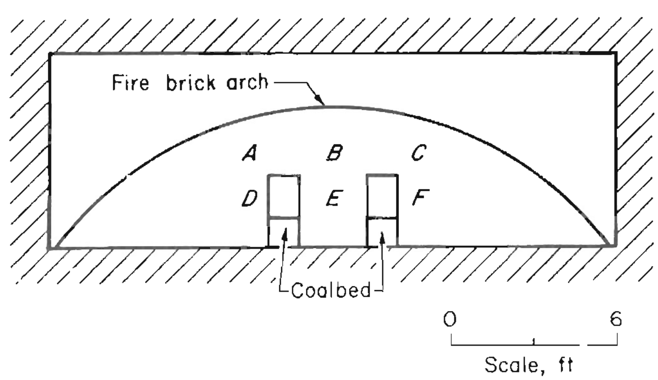

Figure 3.—Locations (*A-F*) of air velocity measurements.

of positions *A*, *B*, *D*, and *E* and positions *B*, *C*, *E*, and *F* were then averaged to determine the airflow for each coalbed in the experiment. The average airflow for these experiments was 380 ± 20 ft/min.

Each coalbed was instrumented with twelve 0.25-in-OD, stainless-steel-sheathed, type-K thermocouples to monitor the temperatures of the coalbeds during an experiment. The thermocouples were located in the center of each coalbed at 6-in intervals, longitudinally.

The composite CO_2 and CO concentrations from the two coal fires were measured at a sampling station located approximately 500 ft downstream from the fire zone. At that point, it was assumed that complete mixing of the combustion products with the ventilating air had occurred. The sample was drawn by a pump, through plastic tubing, to gas analyzers located in the aboveground control room.

Analog signals from the thermocouples and gas analyzers were received by a 40-channel microprocessor, digitized, and transmitted to a personal computer, where the data were displayed and entered into a data base spreadsheet. The system logged thermocouple and gas sampling data every 5 min during the experiment. A video camera was positioned just upstream of the fire zone to record the experiments and allow real-time viewing of the experiments from the aboveground control room. The experiments were recorded on videotape for short time periods at certain intervals before extinguishment began, and continuously during extinguishment.

MATERIALS

COAL

The coal used in all the fire experiments was Pittsburgh Seam coal, a high-volatile A bituminous coal, from the Bureau's Safety Research Coal Mine. Table 1 shows the as-received proximate and ultimate analyses and heating value of a representative sample of the coal. The mined coal was crushed and sieved, and 400 lb of the 4- by 1-in coal was loaded into the coal chamber.

Table 1.—Analyses of as-received Pittsburgh Seam coal

Proximate analysis, wt %:	
Moisture	1.7
Volatile matter	38.8
Fixed carbon	53.9
Ash	5.6
Ultimate analysis, wt %:	
Hydrogen	5.4
Carbon	78.0
Nitrogen	1.6
Sulfur	1.3
Oxygen	8.2
Heating value . . Btu/lb	13,950

APPLICATION EQUIPMENT

Commercially available 2.5-gal plastic spray containers were used to dispense the extinguishants onto the coal fires. The containers were pressurized by an internal hand pump after the extinguishants were placed in them. The containers were equipped with a flexible hose, metal wand, valve, and spray nozzle to dispense the extinguishants. The container, pump, and dispenser are shown in figure 4.

EXTINGUISHING AGENTS

Four extinguishants were used in these experiments: water, a 20%-by-weight DAP-water solution, and two commercially available additive-water solutions. The additives, water-soluble liquids containing surfactants and other ingredients, were nonflammable, nontoxic, and biodegradable. The two commercial additives will be referred to as "additive A" and "additive B" in the rest of this report. The additive A-water solution was prepared as recommended by the manufacturer as a 0.2%-by-volume solution. The additive B-water solution was prepared as

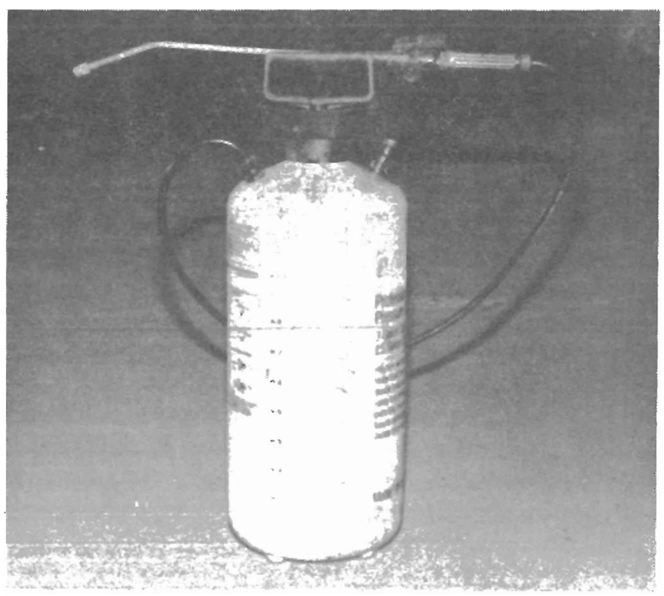

Figure 4.—Extinguishing agent container and applicator.

recommended by the manufacturer as a 6%-by-volume solution.

For the experiments using water alone as the extinguishant, tap water was measured and poured directly into the application container. Tap water was also used in the DAP- and commercial additive-water solutions. To prepare the commercial additive-water solutions, the water was poured into the containers first and then the determined amount of concentrated additive was added to limit foam generation. The containers were then shaken to mix the solution thoroughly. To prepare the DAP-water solution, a 37.5%-by-weight water solution of DAP was prepared aboveground in a 5-gal container using hot tap water. This solution was further diluted to a 20%-by-weight mixture in the mine.

The densities of the commercial additive-water solutions were approximately the same as the density of water alone. The density of the DAP-water solution was 74.8 lb/ft^3, slightly greater than that of water alone (62.4 lb/ft^3).

EXPERIMENTAL PROCEDURE

FIRE IGNITION

The coalbeds were ignited by a 1.6-gal liquid fuel tray fire in the first 16 fires and by a 1.3-gal liquid fuel tray fire in the last 18 fires. An opening was provided at the upstream end of each chamber into which a tray (18 by 12 by 4 in) was inserted. The fuel was a mixture of 3 parts kerosene and 1 part gasoline. A funnel with a long pipe was placed above the fuel tray, and coal was packed around the funnel to hold it in place. At the start of the experiment, fuel was poured down the funnel into the tray and the funnel was removed. The fuel was ignited with a small propane torch. It took about 40 min for the tray fire to involve the coal in a self-sustained flaming fire. The empty fuel tray was then removed to avoid impeding the airflow through the coalbed.

EXTINGUISHMENT

The extinguishants were carefully applied using the previously described container and nozzle attachment (fig. 5). The application began from the upstream end of the coalbed and moved slowly toward the rear of the chamber as all hot spots were extinguished. The length of time required to expel all the extinguishant from a container was typically 20 to 25 min. When the container was empty, it was refilled and the application process was continued. The extinguishants were applied until temperatures in the coalbed were below 50° C and until CO was not detected by a hand-held sensor held directly above the coal. The extinguishment of the fires lasted approximately 2 h. The total quantity of extinguishant applied less the quantity recovered from the trough was the minimum quantity necessary to extinguish the fire. The criterion for successful extinguishment of the fire was failure of the coal to reignite.

After successful extinguishment, the coalbed was divided into six equal sections and the combined coal and ash remaining in each section was weighed. These weights, together with the thermocouple temperatures, allowed calculation of the quantity of thermal energy possessed by the coalbeds at the time of extinguishment.

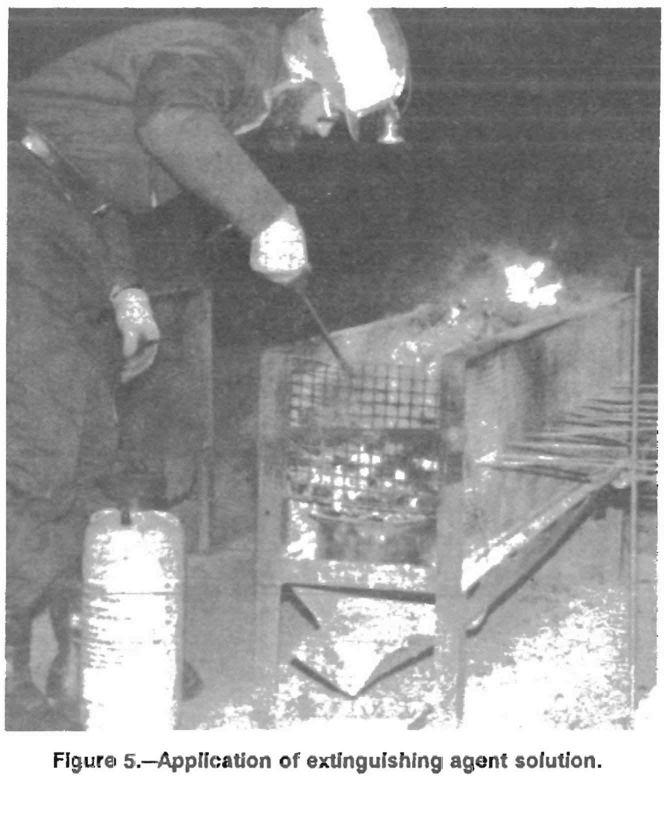

Figure 5.—Application of extinguishing agent solution.

RESULTS

FIRE CHARACTERIZATION

Initial experiments focused on developing a reproducible, well-characterized fire and on establishing the optimum time and conditions for extinguishment. Quantifying these factors ensured that the relative effectiveness of an extinguishing agent for a particular fire could be compared with that agent's effectiveness on another fire, or with the effectiveness of another extinguishing agent.

The temperature-time profiles of two 5-ft coalbeds that were allowed to burn to completion are shown in figure 6. These coalbeds each contained 330 lb of coal. The temperature-time profiles depict a slowly moving thermal wave propagating down the length of each coalbed. The burning velocity of the left coalbed was 2.1 in/h, while the right had a burning velocity of about 1.9 in/h. It appeared that the entire coalbed had been involved in the fire by 30 h and that most temperatures had returned to near ambient after 45 h.

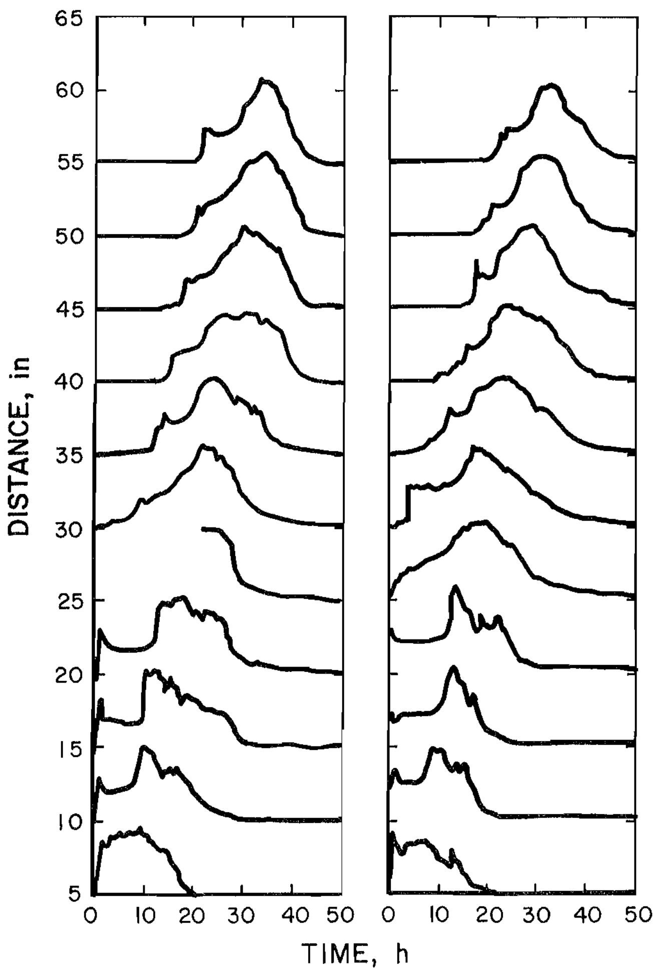

Figure 6.—Temperature-time profiles of coalbeds for coal fire that burned to completion.

Figure 7 shows the longitudinal cross-sectional temperature profile of the left coalbed at 15, 19.5, and 24 h. From these data, the burning velocity, based on the time to reach peak temperatures over the 15- to 24-h time interval, was 2.1 in/h, in good agreement with the value obtained from figure 6. It can be seen that a steady-state fire was achieved over this 15- to 24-h period, with an active intense burning zone between an advancing and retreating edge.

Approximately 580 lb of coal from these two coalbeds was consumed in 50 h, a mass-loss rate of 11.6 lb/h. Using the heating value of 13,950 Btu/lb for Pittsburgh coal from table 1, the mass loss converts to a heat-release rate of 2,700 Btu/min. The amount of coal and ash remaining in the two coalbeds after this experiment was about 13%, slightly higher than the 5.6% value from table 1, indicating that about 7% of the coal, or about 25 lb in each coalbed, was not completely burned in the experiment.

A plot of the composite heat-release rate of the two coal fires for the first 40 h of the test is shown in figure 8. The heat-release rate was calculated from the CO and CO_2 concentrations observed at the sampling station located 500 ft downstream of the fire zone by the expression

$$q = V_0A_0 [5.7 \times 10^{-4}(\Delta CO_2) + 2.3 \times 10^{-4}(\Delta CO)], \quad (1)$$

where q is the heat release rate, in British thermal units per minute, and V_0A_0 is the airflow, in cubic feet per minute (7). A peak heat-release rate of about 5,000 Btu/min

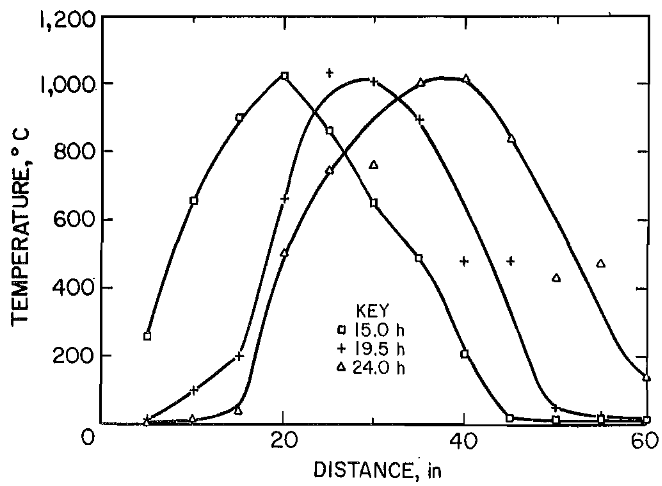

Figure 7.—Longitudinal cross-sectional temperature profile of coal fire that burned to completion.

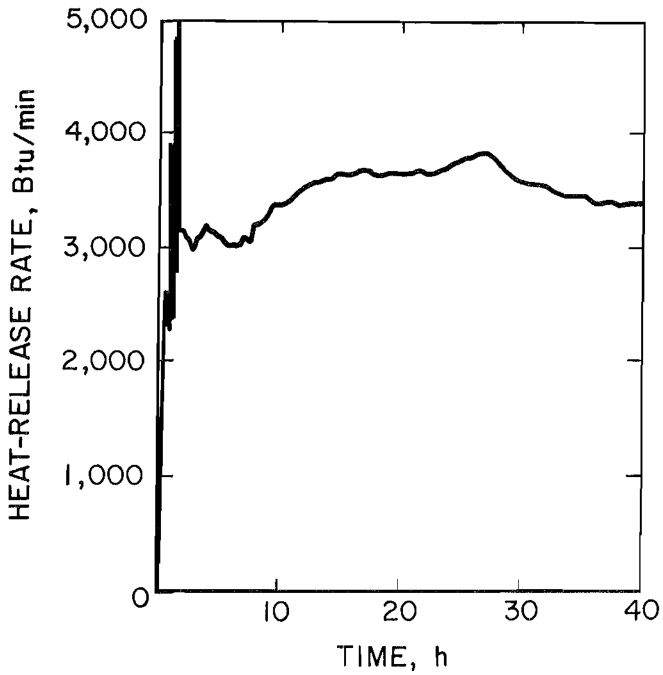

Figure 8.—Composite heat-release rate versus time for two coal fires that burned to completion.

was observed just after ignition, because of the effects of the liquid fuel fire. The heat-release rate due to coal combustion increased steadily over the first 12 to 14 h before leveling off at about 3,700 Btu/min. A slight increase in the heat-release rate was observed from 25 to 30 h, when most of the coalbed was actively involved in the fire. The heat-release rate then fell slowly for the remainder of the test. Thus, it appears that a steady-state heat-release rate existed from about 14 to 24 h.

From these results, an extinguishment period of between 20 and 24 h was selected. This ensured that a steady-state burning condition existed at the time of extinguishment and that a large area of each coalbed, approximately 3 ft, was actively involved in each fire.

EXTINGUISHMENT EXPERIMENTS

Seventeen experiments on coal fire extinguishment were conducted, for a total of 34 coal fires. Of these, 11 coal fires were successfully extinguished with water, 4 with the 20% DAP-water solution, 5 with the 0.2% additive A-water solution, and 6 with the 6% additive B-water solution. Eight of the coalbeds reignited after the extinguishment attempt.

Table 2 shows the quantity of water or extinguishing agent-water solution used, the average mass-loss rate, and the thermal energy, Q, at the time of extinguishment for each successfully extinguished coal fire.

The average mass-loss rate, M, was calculated by the expression

$$M = (400 - W)/t_{ex}, \qquad (2)$$

where 400 is the weight, in pounds, of coal in the coalbed at the start of the experiment; W is the total weight, in pounds, of coal and ash remaining in each coalbed after extinguishment; and t_{ex} is the time, in hours, that the fire burned prior to extinguishant application. The values ranged from 4.4 lb/h for a fire extinguished with the additive B-water solution to 10.6 lb/h for another fire also extinguished with the additive B-water solution.

Table 2.—Results of successfully extinguished coal fires

Extinguishing agent and amount required, gal	Mass-loss rate (M), lb/h	Thermal energy (Q) at time of extinguishment, Btu
Water:		
5.5	5.5	55,810
5.8	6.8	57,000
6.1	5.1	64,910
6.6	6.5	71,700
6.8	6.0	77,720
6.8	6.9	68,880
7.3	5.9	53,660
7.5	6.0	79,610
8.6	6.0	74,320
10.0	7.3	87,600
10.4	5.6	67,010
20% DAP and water:		
4.4	4.8	59,020
4.9	5.2	76,910
6.2	5.4	89,000
7.7	6.8	77,480
0.2% additive A and water:		
6.4	6.1	63,280
7.3	4.6	58,760
8.4	5.7	64,740
8.6	6.9	87,420
10.0	6.2	79,150
6% additive B and water:		
7.1	4.4	73,330
7.8	6.8	84,600
7.9	7.0	82,050
8.3	5.6	88,400
9.0	6.6	82,100
9.1	10.6	73,000

To quantify each fire at the time of extinguishment, measurements were made to calculate the thermal energy, Q, at the time of extinguishment, based on the temperatures in the coalbed and the amount of coal and ash remaining in the coalbed after extinguishment. The thermal energy, Q, was calculated from the formula

$$Q = \sum_{i=1}^{6} m_i T_i s_i, \qquad (3)$$

where i denotes a particular section of the coalbed; m_i is the quantity of coal and ash, in pounds, remaining in that section of the coalbed; T_i is the average temperature, in degrees Celsius, of the coal located in that section; and s_i is the specific heat, in British thermal units per pound degree Celsius, of coal relative to water in that section. The specific heat of coal has been shown to be temperature dependent (*8-9*), and the values used in these calculations for the temperature range observed in these experiments were obtained from a model by Merrick (*10*) and ranged from 0.45 to 0.95 Btu/(lb)(°C). The values of Q ranged from 53,660 Btu for a fire extinguished with water to 89,000 Btu for a fire extinguished with the DAP-water solution.

STATISTICAL ANALYSIS

The main concerns, in developing a method to evaluate the performance of the extinguishing agents were to ensure that the experimental conditions be reproducible, that comparisons between the fires and between the various agents be referenced to quantifiable values, and that the data be substantiated with good statistics. The average mass-loss rate provides a global description of the coal fires from ignition to the time of extinguishment, and was used to evaluate the reproducibility of the fires. The thermal energy, Q, of the coalbeds was used to quantify the coal fires at the time of extinguishment to provide a basis for comparing the relative effectiveness of the extinguishing agents.

The data in table 2 appear to show considerable variability, both within a group of fires extinguished with a particular extinguishing agent and between groups of fires extinguished with the various agents. Initially, a statistical analysis of the data, using Nalimov's Test, was conducted to determine if any of the data showing large deviations from the mean values could be classified as outliers (*11*).[7]

[7]An outlier is defined as a point that does not fit the data population, because of human error, improper measurement, equipment malfunction, or some other unknown reason, and may be removed.

From the analysis, the mass-loss rate of 10.6 lb/h for the fire extinguished with the additive B-water solution was identified as an outlier, both from the population mean within the group of fires extinguished with the additive B-water solution, and from the total population mean. Consequently, the data for that experiment were removed from the data set, and the mean and standard deviation values for the fires extinguished with the additive B-water solution and for the total population were recalculated. Table 3 shows the mean and standard deviation for the values within each group of fires extinguished with a particular agent and for the total population.

To compare the reproducibility of the coal fires, the average mass-loss rates of the fires were compared. Using the comparison of means method, the Student's t-test was applied to the hypothesis that the mean of the mass-loss rates of the fires extinguished with the various agent-water solutions was statistically equivalent to the mean of the average mass loss-rates of the fires extinguished with water alone (*12*). If the hypothesis is accepted, for a given confidence level, 100 - p, there is a (100 - p)% probability that the correct hypothesis was chosen, or that the average mass-loss rates are statistically equivalent. If the hypothesis is rejected, there is a (100 - p)% probability that the average mass-loss rates are not equivalent.

Table 3.—Mean and standard deviation values of results of successfully extinguished coal fires

Extinguishing agent	Number of fires	Required for extinguishment, gal		Av mass-loss rate (M), lb/h		Thermal energy (Q) at time of extinguishment, Btu	
		Mean	SD	Mean	SD	Mean	SD
Water	11	7.4	1.6	6.2	0.7	68,930	10,700
DAP and water	4	5.8	1.5	5.6	.9	75,600	12,380
Additive A and water . .	5	8.1	1.4	5.9	.9	70,670	12,080
Additive B and water[1] . .	5	8.0	.7	6.1	1.1	82,090	5,540
Total or av[1]	25	7.4	1.6	6.0	.8	72,980	11,110

SD Standard deviation.
[1]Adjusted values after removal of outlier data.

To test the hypothesis, t was calculated from the expression

$$t = \frac{(c + d - 2)cd}{(c + d)(cs_w^2 + ds_a^2)} [M_w - M_a] \qquad (4)$$

where c is the number of fires extinguished with water, d is the number of fires extinguished with the agent being compared, M_w is the mean of the average mass-loss rates of the fires extinguished with water, M_a is the mean of the average mass-loss rates of the fires extinguished with the agent being compared, s_w is the standard deviation of the average mass-loss rates of the fires extinguished with water, and s_a is the standard deviation of the average mass-loss rates of the fires extinguished with the agent being compared. If $|t|$ is greater than t_p for a given probability, 100 - p, and number of degrees of freedom, c + d - 2, the hypothesis is rejected. Conversely, if $|t|$ is less than t_p, the hypothesis is accepted. Table 4 shows the number of degrees of freedom, the value of t_p at p = 5 (the 95% confidence level), and $|t|$ for the average mass-loss rate comparisons of the fires extinguished with the various agent-water solutions compared with the fires extinguished with water alone.

Table 4.—Statistical comparison of average mass-loss rates of successfully extinguished coal fires

Extinguishing agent	Degrees of freedom	t_5	$\|t\|$
DAP and water	13	2.16	1.26
Additive A and water . .	14	2.145	.68
Additive B and water . .	14	2.145	.42

The results show that $|t|$ was less than t_5 for each of the fires extinguished with the agent-water solutions. Thus, the average mass-loss rates of these fires were statistically equivalent to the average mass-loss rate of the fires extinguished with water at a 95% confidence level.

To compare the relative effectiveness of the various extinguishing agent-water solutions with the effectiveness of water alone, the F test was used to compare the mean values of the quantities of the agent-water solutions required to extinguish the fires with the mean value of the quantity of water required to extinguish the fires. The F statistic is the ratio of the mean square to the error mean square, and the F statistic is equivalent to the Student's t-test when comparing only two classes by the relationship $F = t^2$. Prior to the F test analysis, an analysis of covariance was conducted to determine if the quantity of agent required to extinguish a coal fire was dependent on the thermal energy, Q, of the coalbed at the time of extinguishment. The analysis of covariance is a method that uses regression techniques to determine, in this case, if the quantity of an agent was linearly related to the fire's thermal energy at the time of extinguishment. A more detailed description is found elsewhere (*13*). If a linear relationship existed, the analysis of covariance adjusted the mean of the amount of a particular agent necessary to extinguish the fires, to obtain a more precise comparison of the amounts of the various agents required.

Table 5 shows the mean, adjusted mean, and F value determined from the analysis of covariance, and the 5% significance level for the F test when comparing the quantity of water with the quantity of the agent-water solutions. If the F value is less than the 5% significance level value, then there is a 95% probability that the hypothesis (i.e., there is no difference between the amount of agent and the amount of water required to extinguish the coal fires) is correct. Conversely, there is a 5% probability that the hypothesis is incorrect.

Table 5.—Statistical comparison of effectiveness of extinguishing agent-water solutions relative to water alone for successfully extinguished coal fires

Extinguishing agent	Mean quantity, gal	Adjusted mean quantity, gal	F value	F_5
Water	7.4	7.5	6.27	4.75
DAP and water	5.8	5.4		
Water	7.4	7.4	.70	4.67
Additive A and water . .	8.1	8.0		
Water	7.4	7.7	.31	4.67
Additive B and water . .	8.0	7.3		

The results show that the amounts of additive A-water and additive B-water solutions required to extinguish the coal fires were statistically equivalent to the amount of water required to extinguish similar fires, based on the F value. There was a statistically significant difference in the amount of DAP-water solution required to extinguish the fires, compared with water, with the DAP-water solution being a more effective extinguishing agent than water alone.

DISCUSSION

The evaluation of the relative effectiveness of fire-extinguishing agents requires a reproducible, well-characterized fire and a reproducible, objective application technique. Fire is a dynamic process that is difficult to control and reproduce. However, by careful design and monitoring and the use of statistical methods, a fire can be reproduced and well quantified, within certain confidence levels.

Initial experiments focused on the development of a steady-state burning condition containing a large active burning area and areas representative of other stages of combustion. The plots of the composite heat-release rate and the temperatures throughout the coalbeds for the two 5-ft fires that were allowed to burn to completion showed a steady-state condition from about 14 to 24 h, with approximately 3 ft of the coalbed actively involved in the fire, and a flame propagation rate of about 2.1 in/h. For the 6-ft coalbeds used in the extinguishment experiments, it would be expected that the steady-state condition would be extended for another 5 to 6 h, based on the flame propagation rate. The steady-state heat-release rate, calculated from the CO_2 and CO measurements, of about 3,700 Btu/min agreed fairly well with the theoretical heat-release rate calculated from the heating value of the coal and the amount of coal consumed, 2,700 Btu/min.

The average mass-loss rate from the time of ignition to the time of extinguishant application was used as a measure of the reproducibility of the fires. The mass-loss rate would be expected to increase as the fire developed, reaching a steady-state condition coincidental with the heat-release rate. However, a real-time measurement of the mass-loss rate was not possible in these experiments, so the average mass-loss rate gives only a gross description of each fire.

The results of the comparison of the average mass-loss rates of the fires extinguished with the additive-water solutions and those extinguished with the water alone showed that the fires were statistically equivalent, at a 95% confidence level. The average mass-loss rate for the total population of fires was 6.0 lb/h, with a standard deviation of 0.8 lb/h. The composite average mass-loss rate for the two fires that were allowed to burn to completion was 11.6 lb/h, or 5.8 lb/h per coalbed, in good agreement with the average from the extinguished fires.

The thermal energy, Q, of each coalbed was used to quantify the fires at the time of extinguishment. Ideally, a real-time measurement of Q would have allowed each fire to be extinguished when it had reached a specific heat output, allowing a direct comparison of the quantities of extinguishing agent-water solution. However, a real-time calculation of Q was not possible in this experimental design, for two reasons. First, since there were two coalbeds, the values of Q based on downstream gas concentrations did not allow differentiation of the thermal output of the individual coalbeds, and second, a real-time calculation of Q based on temperature and mass requires a real-time value of the mass of the coalbed, which could not be measured.

The statistical technique of the analysis of covariance was used to compare the relative effectiveness of the extinguishing agents with that of water alone. The analysis of covariance is similar to normalization, in that it adjusts the mean of the quantity of an agent required to extinguish a fire based on the thermal energy of the fire. However, normalization assumes that a linear relationship exists between the quantity of extinguishing agent and the thermal energy of the coalbed, whereas covariance determines if linear dependence exists, and uses the results of regression analysis to adjust the mean of the quantity of extinguishing agent required.

To test the validity of the method for calculating the thermal energy, Q, of the coalbed, the calculated Q values for the fires extinguished with water were compared with the theoretical value derived from the cooling capacity of water and the amount required to extinguish the fires. Based on a heat capacity of 1.8 Btu/(lb)(°C) and a latent heat of vaporization of 970 Btu/lb at 100° C and atmospheric pressure, 1 gal of water has a cooling capacity of 1,060 Btu/lb, or 8,850 Btu/gal, to cool the coalbed to 50° C. Thus, the mean quantity of water required to extinguish the fires, as defined by the coalbed temperatures reaching 50° C, 7.4 gal, had a cooling capacity of 65,500 Btu. This value is in excellent agreement with the average thermal energy of the water-extinguished coalbeds at the time of extinguishment, found in table 3, of 68,930 Btu.

It has been demonstrated that the standard coal fires used in these experiments are reproducible, within statistical limits, and that the quantification of the heat energy of the fires is reasonable. From the results of the extinguishment experiments, it was shown that two commercial additives that supposedly increase the fire-fighting effectiveness of water, in fact, had no effect on water's extinguishing effectiveness. The question then arises whether the experiments truly evaluate the properties that lead to the increased effectiveness of the commercial additive-water solutions.

In most cases, the dominant mechanism of any fire-extinguishing process is cooling. Since the proportion of additives in the water solutions was relatively small, as little as 0.2% for additive A, it is unlikely that the physical properties of the solutions, such as their cooling capacities, would affect their extinguishing effectiveness. The other principal extinguishing mechanism is a chemical mechanism. If the effectiveness of the commercial additives depends on a chemical mechanism, it might be argued that the coal fires were not representative of fires that adequately exploited those mechanisms. However, the coal fires had regions containing virtually all stages of coal combustion. In addition, the DAP-water solutions, which have been shown to inhibit combustion based on a chemical mechanism, were more effective than water at extinguishing these coal fires. Thus, it appears that the coal fires were adequate to judge the fire-extinguishing effectiveness of the additive-water solutions, and that the commercial additives did not enhance the extinguishing effectiveness of water.

CONCLUSIONS

The Bureau developed an experimental method to evaluate the relative effectiveness of water additives on the extinguishment of coal fires. Twenty-six coal fires were extinguished, using either water, a 20% DAP-water solution, or one of two commercially available extinguishant-water solutions.

The 20% DAP-water solution required an average of 5.8 gal to extinguish the coal fires, while the two commercially available additive-water solutions required an average of 8.1 and 8.0 gal, respectively. The average amount of water required to extinguish the fires was 7.4 gal. A statistical analysis of the data indicated that the DAP-water solution was more effective than water alone for extinguishing these coal fires, while the effectiveness of the two commercially available additive-water solutions were statistically equivalent to the effectiveness of the water alone.

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