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REPORT OF INVESTIGATIONS/1994

The Effect of Underground Mining Conditions on the Activation of Automatic Sprinklers

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UNITED STATES DEPARTMENT OF THE INTERIOR

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BUREAU OF MINES

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Bruce Babbitt, Secretary

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	L/(min•m^2)	liter per minute per square meter
°C/min	degree Celsius per minute	m	meter
cm	centimeter	m^2	square meter
cm^2	square centimeter	min	minute
°F	degree Fahrenheit	mJ/kg	megajoule per kilogram
°F/min	degree Fahrenheit per minute	m/min	meter per minute
ft	foot	m^3/min	cubic meter per minute
kg	kilogram	m•s	meter second
kJ/kg	kilojoule per kilogram	pct	percent
kPa	kilopascal	s	second
kW	kilowatt		

THE EFFECT OF UNDERGROUND MINING CONDITIONS ON THE ACTIVATION OF AUTOMATIC SPRINKLERS

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

ABSTRACT

The U.S. Bureau of Mines conducted a study to evaluate the effect of underground mining conditions on the activation of automatic sprinkler heads. Sprinklers were exposed to liquid fuel fires in a rectangular tunnel at airflows of 0, 45, 90, 150, and 250 m/min to determine the effect of ventilation and fire size on the time to activation. As the airflows were increased, the time to activate the sprinklers for a given fire size increased. Also, as the fire size increased, the activation time decreased. Temperature profiles of the tunnel showed that the maximum temperature near the roof was shifted downstream as the airflow increased. Experiments to determine the effect of rated activation temperature and response time index (RTI) value on activation time showed that the time to activate increased with increasing activation temperature, and decreased with decreasing RTI value. Exposure to the mine environment showed little effect on the activation times in large-scale experiments, and no significant effect in laboratory experiments. The results showed that airflow can have a significant effect on the activation times of automatic sprinklers. This needs to be considered in the design of effective sprinkler suppression systems for ventilated areas.

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INTRODUCTION

Between 1980 and 1990, the Mine Safety and Health Administration (MSHA) investigated 149 underground coal mine fires (*1*).[5] In 1984, a fire in the Wilberg Mine, Utah, resulted in 27 fatalities (*2*). In 1988, a conveyor belt fire spread rapidly through the Marianna No. 58 Mine, Pennsylvania, and the entire mine had to be sealed and abandoned (*3*). In 1990, a fire at the Mathies Mine, Pennsylvania, injured 11 firefighters and resulted in the mine being sealed and the loss of over 400 jobs (*4*). Many large fires could be avoided if automatic suppression systems were more widely used, and if initial attempts at extinguishment were more effective. The smoke and heat from even a small fire in an underground mine can hinder direct firefighting efforts and may endanger the evacuation of personnel. Research on the development and evaluation of improved and novel automatic fire control and suppression systems is required to reduce the risk of severe coal mine fires and enhance fire safety.

Automatic sprinkler systems are the primary method of protecting lives and property from fire in aboveground facilities. The National Fire Protection Association (NFPA) has no record of a multiple death fire (more than two fatalities), excluding firefighters killed during fire suppression operations by explosions or flash fires, in a completely sprinklered building (*5*). A recent high rise fire in Philadelphia, PA, that started on the 22d floor burned out of control until reaching the sprinklered 30th floor. There, a sprinkler system stopped the vertical spread of the fire, and eventually extinguished it (*6*). The demonstrated effectiveness of sprinkler systems in aboveground applications, along with their reliability and low maintenance, has led to their increased use in underground mines.

Federal regulations for underground coal mines require that either automatic sprinkler systems (wet pipe or dry pipe), deluge-type water spray systems, foam generators, or dry powder chemical systems be installed at all main and secondary conveyor belt drive areas. When sprinkler systems are used, at least one sprinkler must be installed above each belt drive, belt take-up, electrical control, and gear-reducing unit. Additionally, individual sprinklers must be installed at intervals of no more than 2.4 m for the first 15 m of fire-resistant belt or the first 45 m of non-fire-resistant belt, and along all conveyor branch lines. At least one branch line must be above the top belt, and one between the top and bottom belt to provide a uniform discharge of water to the belt surface. The water discharge rate must not be less than 10 L/(min•m^2) of the top surface of the top belt for at least 10 min, and the discharge must be directed at both the upper and bottom surfaces of the top belt and to the upper surface of the bottom belt (*7*).

Fire suppression devices are also required on unattended underground equipment (*8-9*). When water sprinkler systems are used, the water spray devices must be capable of providing at least 10 L/(min•m^2) of water over the top surface of the equipment for at least 10 min.

Federal regulations (*7*) also state that if water sprinkler systems are installed in underground mines, the components must be installed, as far as practical, in accordance with the NFPA-13 standard (*10*). The fundamental design principle of NFPA-13 is to leave no area unprotected. However, NFPA-13 addresses only the amount of water to be discharged by the sprinkler head, and does not consider the effect of ventilation on the activation characteristics or water distribution patterns of the sprinkler.

Recent research by the U.S. Bureau of Mines (USBM) showed that ventilation can have a significant effect on the water discharge patterns of automatic sprinklers, rendering some types of sprinklers ineffective at extinguishing fires upwind of the sprinkler (*11*). Another important parameter to consider in the design of automatic sprinkler systems is the effect of ventilation on the activation of the sprinklers. If a sprinkler head near the fire is not activated quickly enough, or a sprinkler too far downstream from the fire for its coverage area to reach the fire activates, the fire may grow too large for the automatic sprinkler system to control and/or extinguish. High ventilation rates may not allow the heat to collect at the roof and may increase the time required to activate a sprinkler.

Suppression tests of conveyor belt drive fires in ventilated flows using automatic sprinklers, multipurpose dry powder, and high-expansion foam were conducted by Warner in 1974 (*12*). However, that study, funded by the USBM, concentrated on comparing the effectiveness of the different types of suppression systems to extinguish conveyor belt fires and did not focus on the performance of individual components of the sprinkler system.

Automatic sprinklers are designed to activate at specific temperatures, typically ranging from 57° to 150° C (135° to 300° F). The activation temperature for a particular application is determined by the fuel loading, ambient temperature, and other factors. The mode of activation is either by the physical melting of a fusible link, a metal alloy designed to melt at specific temperatures, or by the expansion of a contained liquid that ruptures the container at a specific temperature, discharging the water. In underground coal mines, most systems are installed with 100° C (212° F) fusible-link-type sprinklers. Another design parameter of sprinklers is the sprinkler's response time index (RTI) value, which is a measure of the heat conductivity

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

of the sprinkler, and thus its sensitivity. The lower the RTI value, the faster the response time of the sprinkler.

This report describes the results of large-scale experiments to examine the effect of fire size and ventilation on the activation characteristics of commercially available automatic sprinklers. Experiments were also conducted to determine the effect of the rated activation temperature and RTI values of the sprinklers on their activation times under simulated mine fire conditions. Finally, experiments were conducted on sprinklers obtained from working coal mines where the sprinklers were exposed to the harsh mine environment for periods ranging from 1 to 5 years, to determine the effect of mine exposure on the activation characteristics of the sprinklers. These sprinklers were evaluated in both large-scale fire tests as well as in laboratory oven experiments under more controlled conditions.

This study is part of a larger program to evaluate the performance of automatic sprinkler systems in underground coal mines, and supports the USBM's mission to improve safety in the mining industry.

ACKNOWLEDGMENTS

The authors acknowledge William Rumancik, engineering aid, USBM, for his contributions in the design of the laboratory oven experiments; and Steven J. Luzik, supervisory chemical engineer, and Thomas M. Fircak, engineering technician, U.S. Department of Labor, MSHA, for their input in the design of the large-scale experiments and for their cooperation in the use of the MSHA fire gallery.

SPRINKLERS

The experiments to evaluate the effect of ventilation and fire size on the activation times of commercially available automatic sprinklers were conducted with 57° C (135° F), fast-response, pendent-type sprinklers from the same manufacturer (designated as manufacturer A). The activation mechanism for these sprinklers, known as a fusible link, uses an arrangement of links and levers that are soldered together and held over the sprinkler orifice cap by the frame arm. As the increased temperature of a fire causes the solder to melt, the links and levers separate and release the cap over the sprinkler orifice, allowing water to discharge and strike the deflector. An example of a pendent-type fusible-link sprinkler is shown in figure 1.

Experiments were also conducted to evaluate the effect of activation temperature and RTI value on sprinkler activation times. For these experiments, 57° and 74° C (135° and 165° F) fast-response, and 74° and 100° C (165° and 212° F) standard-response pendent-type sprinklers from manufacturer A were used. The activation temperature of a sprinkler is controlled by varying the composition, and thus the melting temperature, of the metal alloy that holds the fusible element together. The response parameter, or thermal sensitivity of a sprinkler, is defined by its RTI value. The smaller the RTI, the faster the sprinkler will operate. Sprinklers with RTI values in the range of 100 to 400 $(m \cdot s)^{1/2}$ are referred to as "standard-response" sprinklers, while sprinklers with RTI values of 50 $(m \cdot s)^{1/2}$ or below are referred to as "quick-response" sprinklers. The RTI value of the sprinkler is controlled by varying the design of the operating element that holds the fusible link to make the release mechanisms more or less sensitive to heat for a given activation temperature (*13*).

Experiments were also conducted to determine the effect of the mine environment on the activation characteristics of the sprinklers. Sprinklers were obtained from seven different operating coal mines where they had been exposed to the mine environment for periods ranging from 1 to 5 years. Of the seven sets of sprinklers, three sets were from the same manufacturer (designated as manufacturer B) and four sets were from another manufacturer (C). More detailed descriptions of the sprinklers are given in a later section.

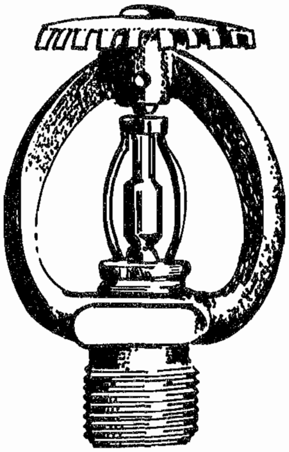

Figure 1.—Pendent-type sprinkler head.

EXPERIMENTAL APPARATUS AND PROCEDURES

LARGE-SCALE EXPERIMENTS

The large-scale activation experiments were conducted in the MSHA fire gallery at the USBM's Pittsburgh Research Center. The gallery, shown in figure 2, is a modified X-shaped structure constructed of 1.2-m-high concrete-filled cement-block walls, and an arch-shaped corrugated steel roof. To simulate the rectangular geometry of an underground mine entry for the experiments, a 10-m-long, 2.3-m-wide, 1.8-m-high tunnel was constructed in the interior of the north section of the gallery. This tunnel was constructed using 1.3-cm plywood on a steel frame. The roof and walls 1.8 m upstream and downstream of the fire were protected with a 1.3-cm-thick fire-resistant material attached to the plywood. Thermocouples were placed at 0.6-m intervals, 10 cm from the roof, along the centerline of the tunnel, from 1.8 m upstream of the fire to 7.2 m downstream from the fire, to provide a profile of the temperatures near the roof of the tunnel.

The heat source for the experiments was a liquid fuel tray fire. The fuel was contained on a water layer in various-sized square and rectangular trays, ranging from 410 cm^2 to 0.84 m^2. The water layer depth was adjusted so that the fuel layer was 5 cm from the top of the tray for each experiment. The size of the trays and the amount of fuel were varied to produce a range of fire sizes to adequately assess the effect of fire size on the activation parameters being evaluated. The fire sizes for these experiments ranged from 20 to 945 kW. The fuel was a commercial light aliphatic hydrocarbon solvent composed of C_5 to C_8 hydrocarbons, with a heating value of 45 mJ/kg.

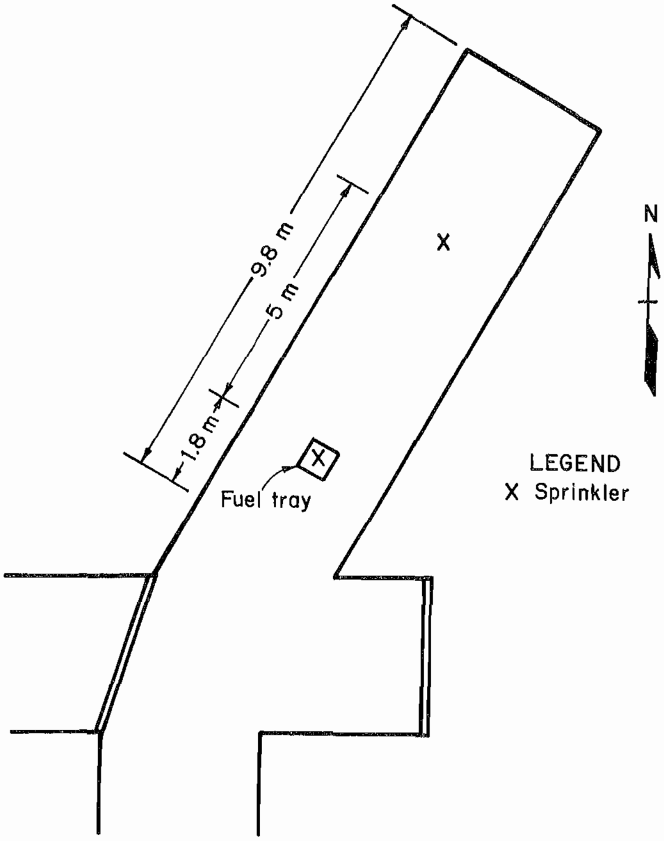

Figure 2.—Fire gallery facility.

The activation time of the sprinklers in each experiment was determined by monitoring the resistance of an electrical circuit across the sprinklers. One lead of the circuit was connected to the frame of the sprinkler while the other lead was connected to the fusible element of the sprinkler. When the sprinkler activated and the fusible element was released, the circuit was detected by a resistance measuring meter. No water was discharged from the sprinklers in any of the experiments in this study.

Ventilation was provided by a high-capacity fan, capable of producing up to 2,800 m^3/min at a pressure drop of 2 kPa, located in the south section of the gallery. The air velocity for the experiments was then set to within 10 pct of the desired value by adjusting the regulator and regulator doors, shown in figure 2. The airflow was measured using a vane anemometer at nine locations across the cross section of the tunnel where the fire was located.

In the experiments to determine the effect of ventilation and fire size on the activation times of new sprinklers at airflows of 0 and 45 m/min, a sprinkler was located directly above the center of the fuel tray and 5 m downstream from the center of the fuel tray, along the centerline of the tunnel, as shown in figure 3. The distance from the top of the fuel layer to the deflector of the sprinkler directly above the fire was 1.68 m. For the experiments at 90, 150, and 250 m/min airflow, only the sprinkler 5 m downstream from the center of the fuel tray was installed. The experiments to evaluate the effect of activation temperature and RTI value on the activation times of the sprinklers were conducted under nonventilated conditions. For these experiments, only the sprinkler directly above the fuel tray was installed.

Experiments were also conducted to determine the effect of the mine environment on the activation times of sprinkler heads. These experiments were conducted under nonflow conditions (0 m/min) using identical fires, to compare the time for the used sprinklers to activate to the activation times of the new sprinklers. For these experiments, the exposed sprinklers from the mines and corresponding new sprinklers were located in a 950-cm^2 area directly above the fuel tray. The number of sprinklers obtained from the mines and the corresponding new sprinklers used in each experiment varied depending on the availability of the exposed sprinklers.

LABORATORY OVEN EXPERIMENTS

Experiments to determine the effect of the mine environment on the activation times of sprinklers were also conducted in a controlled laboratory oven. In these experiments, an exposed sprinkler and two corresponding new sprinklers were placed in a convection-type laboratory oven at room temperature, and the oven was set to rise to a temperature of 300° C (572° F) at a rate of 3.5° C/min (6° F/min).

The interior dimensions of the oven were 36 cm long by 35 cm wide by 35 cm high. The sprinklers were suspended vertically from a steel tray in the middle of the oven, in a linear configuration, 5.1 cm apart. Thermocouples were placed near the fusible link of each sprinkler to measure the oven temperature at the time of activation. The activation of the sprinklers was noted visually through a window in the front of the oven, and the time and temperature at activation recorded. A schematic of the sprinkler arrangement and thermocouple locations, denoted *A*, *B*, and *C*, is shown in figure 4.

EXPERIMENTAL RESULTS AND DISCUSSION

EFFECT OF VENTILATION AND FIRE SIZE ON ACTIVATION TIMES

Experiments were conducted in the fire tunnel at airflows of 0, 45, 90, 150, and 250 m/min to examine the effect of fire size and ventilation on the activation times of commercially available automatic sprinklers. Fast-response, 57° C (135° F), pendent-type sprinklers were installed directly above and/or 5 m downstream from the liquid fuel fires, and the time from the start of the fires to the activation of the first sprinkler was measured. The sprinkler locations were selected based on the results of experiments to evaluate the effect of ventilation on the water spray patterns of automatic sprinklers (*11*). The 5-m distance was the maximum distance that the water spray of a horizontal sidewall sprinkler head reached when directed into the airstream at airflows up to 150 m/min.

The 57° C (135° F) activation temperature and fast-response type of the sprinklers used in these experiments were selected to examine the ventilation effects using sprinklers with the lowest activation temperature and RTI values, because of the fire size limitations of the tunnel. Federal regulations require that sprinklers used in mines activate at temperatures of not less than 65° C (150° F) and not more than 149° C (300° F). Selected experiments were conducted using sprinklers with higher activation

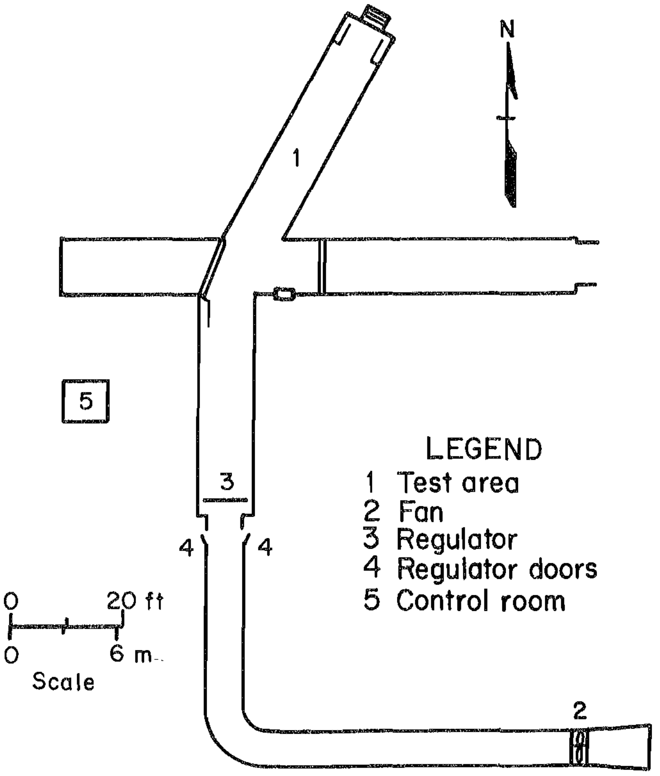

Figure 3.—Sprinkler and fuel tray locations in fire tunnel.

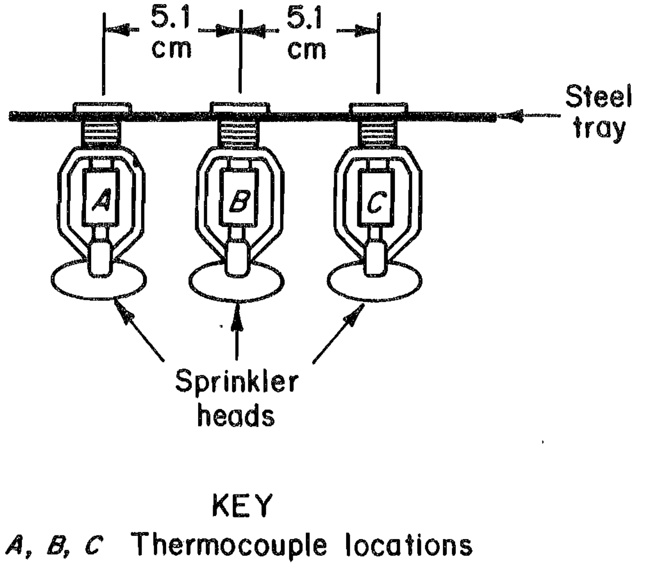

Figure 4.—Schematic of laboratory oven and sprinklers.

temperatures and RTI values to allow for the extrapolation of these results to those sprinklers used in underground mines. It should be noted that these experiments were specific to this tunnel configuration and these experimental conditions, and that the results are intended to show only expected trends in actual mines.

The fire sizes for these experiments ranged from 20 to 945 kW. Only the times to activate the first sprinkler were noted, since the activation of the first sprinkler and its subsequent water discharge would effectively change the temperature of the air and inactivated sprinklers, as well as the ventilation patterns in the tunnel. In these experiments no water was discharged from the sprinklers and the fires were allowed to burn to completion.

The fire size, time to sprinkler activation, and location of the sprinkler that activated are shown in table 1. Plots of the time to activate the sprinklers versus fire size for the given flows are shown in figure 5. The fire size was based on the amount of fuel burned over a given time and was calculated from the expression

$$Q = m \cdot \Delta H_c/t,$$

where Q is the fire size in kW, m is the amount of fuel in kg, ΔH_c is the heat of combustion of the fuel in kJ/kg, and t is the time to burn to completion in s. Complete combustion was assumed, and no corrections were made for the effect of the tray dimensions.

Figure 5 shows the temperature profiles of the tunnel at the time the first sprinkler activated for representative fire sizes at each airflow. Because of the large amount of data, only one plot at each airflow is shown. The plots shown were selected to represent experiments with fire sizes in the range where a change in fire size had a significant effect on the time to activation for a given airflow, rather than in the asymptotic portions of the fire size-time curves. The temperature profiles are typical of the profiles at other fire sizes for a given airflow in terms of where the highest temperatures were measured. In general, the relative temperatures increased or decreased for larger and smaller fire sizes, respectively.

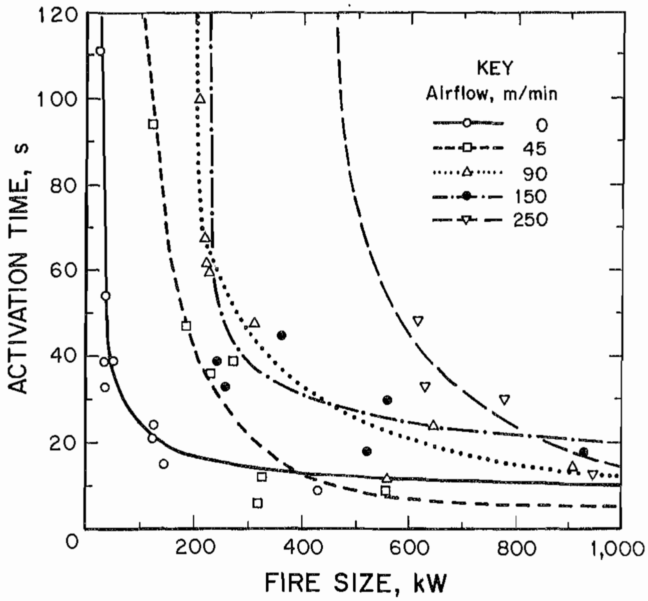

Figure 5.—Activation time versus fire size at various airflows.

Table 1.—Fire size and sprinkler activation times at various airflows

Airflow, m/min	Fire size, kW	Activation time, s	Location of sprinkler, m
0	20	111	0
	30	39	0
	35	54	0
	35	33	0
	50	39	0
	120	21	0
	125	24	0
	145	15	0
	430	9	0
45	65	DNA	NA
	75	DNA	NA
	115	94	0
	180	47	0
	225	36	0
	270	39	0
	315	6	0
	325	12	0
	555	9	0
90	200	DNA	NA
	215	68	5
	220	62	5
	225	60	5
	305	48	5
	560	12	5
	645	24	5
	905	15	5
150	200	DNA	NA
	215	DNA	NA
	230	DNA	NA
	240	39	5
	250	DNA	NA
	255	33	5
	270	DNA	NA
	360	45	5
	520	18	5
	555	30	5
	925	18	5
250	440	DNA	NA
	610	48	5
	630	33	5
	645	DNA	NA
	775	30	5
	945	12	5

DNA Did not activate.
NA Not applicable.

Effect of Fire Size on Activation Times

Airflow at 0 m/min

Experiments were carried out under nonventilated conditions (0 m/min) at fire sizes ranging from 20 to 430 kW. Only one sprinkler was installed, directly above the fire. The sprinkler activated at each fire size, as shown in table 1, with the times to activate ranging from 9 s for the largest fire, 430 kW, to 111 s for the smallest fire, 20 kW. Figure 5 shows a plot of times to activate versus fire size. The curves represent a regression fit of the data in the form $y=a/(x-c)^b$. The asymptotes delineate the limits of activation of these sprinklers with respect to time and fire size under these experimental conditions. For example, at 0 m/min, fires less than about 20 kW would not activate the sprinkler, while there would be a time delay of approximately 10 s for fires up to 1,000 kW, because of the response time of the sprinkler.

Thermocouple measurements showed that the temperature was about 80° C (176° F) near the sprinkler when it activated for all fire sizes except the 430-kW fire. The temperature near the sprinkler for the 430-kW fire was 150° C (302° F) when it activated. This higher temperature was attributed to the rapid rise in temperature for this fire due to its large size. These temperatures are well above the rated activation temperature of 57° C (135° F), showing the effect of the rapid temperature rise characteristic of liquid fuel fires on the response time of the sprinkler. The temperature profile of the tunnel at the time of activation for the 120-kW fire at 0 m/min, displayed in figure 6, showed that the highest temperatures were at or very near the sprinkler head under these nonventilated conditions. The temperature near the sprinkler at the time of activation was 79° C (175° F), tapering off rapidly just a few feet from the fire.

Airflow at 45 m/min

The experiments at the 45-m/min tunnel airflow were conducted at fire sizes ranging from 65 to 555 kW. As shown in table 1, the sprinkler heads did not activate at fire intensities below 115 kW. At fire intensities of 115 kW and greater, the sprinkler directly above the fire activated, with the time to activate reaching a limit of 6 to 12 s for fires greater than 300 kW. The plot of the time to activate versus fire size is shown in figure 5. Comparing these results to those under nonventilated conditions, a slightly larger fire was required to activate the sprinkler directly above the fire, approximately 115 kW compared to 20 kW. At the higher fire intensities, greater than 300 kW, little change in the response time was seen.

Temperature data showed that the temperature near the sprinklers at the time of activation in these experiments ranged from 65° to 93° C (150° to 200° F), generally increasing with increasing fire size. In the experiments in which the sprinklers did not activate (65 and 75 kW), the maximum temperature reached near the sprinklers was 60° and 63° C (140° and 145° F), respectively. A temperature near the sprinkler of 57° C (135° F) or greater was observed for at least 1 min during each of these experiments, before the fuel was consumed.

Figure 6 shows the temperature profile of the tunnel at the time of activation for the 225-kW fire. The temperature at the sprinkler was 93° C (200° F) when it activated, well above its rated activation temperature. The temperature near the sprinkler reached 57° C (135° F), the activation temperature of the sprinkler, 6 s after the fire was ignited. The sprinkler activated 36 s after ignition of the fuel. The highest measured temperature was 1.8 m downstream from the fire, 103° C (217° F). This trend was also seen in the other experiments at this airflow, with the temperatures varying with fire intensity. For the 225-kW fire, it appeared that the fire size would have been sufficient to eventually activate a sprinkler located anywhere from 1.2 m upstream of the fire to 3 m downstream from the fire at this airflow.

In all the experiments at this airflow, the temperature data also showed that for the fires below 300 kW, the temperature 2.4 m downstream from the fire was slightly

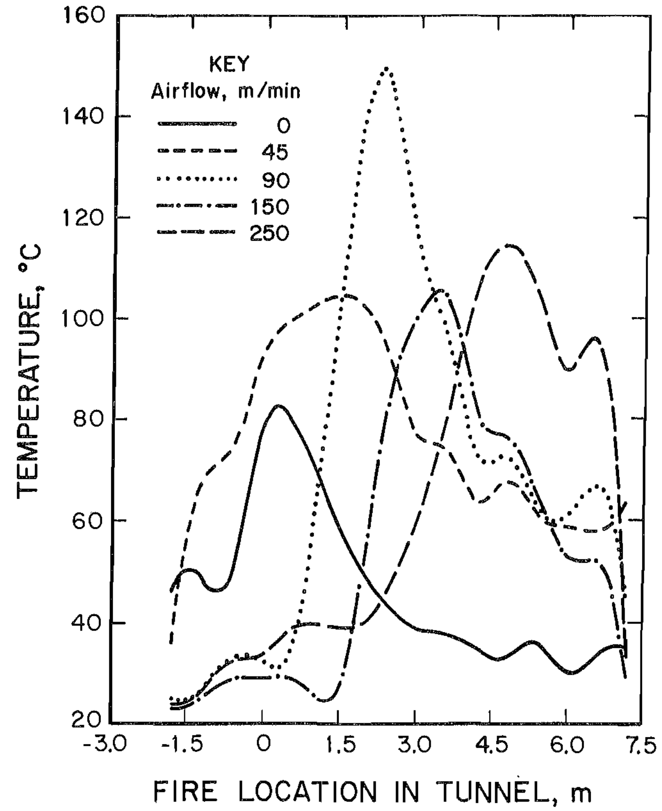

Figure 6.—Temperature profile near roof of tunnel at time of activation.

higher than the temperature directly above the fire, where the sprinkler was located. This indicates that had a sprinkler head been located there, it would have activated slightly in advance of the sprinkler directly above the fire, probably preventing the sprinkler above the fire from activating. However, the water coverage data at this airflow from reference 11 indicate that the water coverage pattern from a sprinkler 2.4 m downstream would have been sufficient to reach the fire.

Airflow at 90 m/min

The most significant effect of ventilation on the activation of the sprinklers under these experimental conditions was observed at the 90 m/min airflow. Preliminary experiments were conducted without sprinklers at this airflow with fire sizes ranging from 200 to 600 kW, to measure temperatures near the roof of the tunnel. The results indicated that the fires would not activate a sprinkler directly above the fire before the sprinkler 5 m downstream would activate.

The plot of fire size versus sprinkler activation time for this airflow is seen in figure 5. A 200-kW fire did not activate the downstream sprinkler, and temperature data indicated that a sprinkler directly above the fire would not have activated. The times to activate the downstream sprinkler ranged from 60 to 70 s for fire intensities slightly above 200 kW, to 12 to 24 s for fires greater than 500 kW.

In these experiments, the temperature near the downstream sprinkler when the sprinkler activated ranged from 70° to 90° C (158° to 194° F), while the temperature near the roof directly above the fire was well below 50° C (122° F), with the exception of the experiment with the 645-kW fire. In this experiment, the temperature above the fire had reached 80° C (176° F) when the sprinkler 5 m downstream activated at a temperature of 180° C (356° F). The longer sprinkler activation time for the 645-kW fire relative to the activation time for the 560-kW fire and the higher temperature required to activate the sprinkler indicate that something abnormal, such as a mechanical problem or a problem with the composition of the fusible-link alloy, delayed the activation of the sprinkler used in that experiment. In the experiment with a 200-kW fire size, the maximum temperature near the sprinkler located 5 m downstream from the fire was 145° F (63° C), and the temperature there was above 57° C (135° F) for approximately 1 min.

Figure 6 shows the temperature profile of the tunnel at the time the sprinkler 5 m downstream from the fire activated for the 305-kW fire. The highest temperatures were observed from 1.8 to 3 m downstream from the fire, with the highest temperature, 148° C (298° F) located 2.4 m downstream. Given that the sprinkler at 5 m activated at the time that this temperature profile was taken, at a temperature of 73° C (163° F), it appears that if the first sprinkler was located downstream from the fire anywhere between 1.2 and 5 m it would have activated sooner (between the start of the experiment and this time). Note that the temperatures directly above the fire and 0.6 m downstream are only 5° to 10° C (9° to 18° F) higher than ambient temperature. Even for the 905-kW fire, the temperature above the fire had reached only 50° C (122° F) when the sprinkler 5 m downstream activated at 15 s. This demonstrates the significant effect that ventilation can have on the activation characteristics of automatic sprinkler systems.

Airflow at 150 m/min

At the 150-m/min airflow, the minimum fire intensity that activated the sprinkler 5 m downstream from the fire was 240 kW. Five other fires, ranging in size from 200 to 270 kW, failed to activate the sprinkler at this airflow. Maximum temperatures near the sprinkler in these experiments ranged from 65° to 72° C (149° to 162° F), and temperatures greater than the rated activation temperature of these sprinklers were observed for at least 1 min in each experiment. For the 240- and 255-kW fires, the thermocouples near the sprinkler measured temperatures of 72° and 73° C (162° and 163° F) when the sprinklers activated. Experiments at larger fire sizes showed a decrease in the activation times, reaching a minimum of about 18 s for fires larger than 600 kW, as shown in figure 5. It is likely that the asymptotic value for the minimum activation time would be lower, but the tunnel limitations prohibited fires above 1,000 kW.

The temperature profile at the roof of the tunnel for the 360-kW fire (shown in figure 6) at the time the sprinkler 5 m downstream from the fire activated shows a shift in the highest temperature to about 3.7 m downstream from the fire. Based on these data, it appears that the fire would have activated a sprinkler located between 2.5 and 5 m downstream under these conditions. Note that as far as 1.2 m downstream from the fire it is not evident, based on temperature data near the tunnel roof, that there is a fire.

Airflow at 250 m/min

Experiments were conducted at an airflow of 250 m/min with fires ranging from 440 to 945 kW. At this airflow, the minimum fire size required to activate the sprinkler 5 m downstream from the fire was about 600 kW. This demonstrates a much larger effect of ventilation on the sprinkler activation characteristics than was seen at the lower airflows, since about twice the fire size was required to activate the sprinkler in going from 150 to 250 m/min, as shown in figure 5.

Thermocouple data indicated that the sprinklers activated at much higher temperatures, over 100° C (212° F), than at the other airflows, with the exception of the 945-kW fire. In that experiment, the temperature at the sprinkler at the time of activation was 70° C (158° F), similar to those observed in the experiments at 150 m/min. The higher temperatures required to activate the sprinklers were probably due to the thermal response characteristics of the sprinklers and the fact that with these larger fires the higher temperatures were reached much more quickly.

In the experiment with the 440-kW fire size where the sprinkler did not activate, the maximum temperature near the sprinkler was 72° C (162° F). For the 645-kW fire, where again the sprinkler did not activate, the maximum temperature near the sprinkler was 100° C (212° F), well above the rated activation temperature of the sprinkler, and the temperature was above 90° C (194° F) for over 30 s. These data indicate that the failure of the sprinkler to activate at this temperature may have been due to a sprinkler malfunction, such as a quality control problem, and not because the fire size was not large enough.

The temperature profile of the tunnel roof for the 775-kW fire, displayed in figure 6, showed that the highest temperature was 5 m downstream from the fire under these conditions. Because of the intensity of the fire, temperature measurements near the fire showed slightly elevated temperatures, although not nearly high enough to activate a sprinkler. The data indicate that temperatures were not high enough to activate a sprinkler until 3.7 m downstream from the fire.

Effect of Ventilation on Activation Times

Experiments were not conducted at similar fire sizes at each flow, but this information can be extrapolated from the curves in figure 5 to examine the effect of ventilation on the activation times for a given fire size under these experimental conditions. For example, for relatively small fires, such as 200 kW, the sprinkler above the fire would activate in about 17 s under nonventilated conditions. At an airflow of 45 m/min, the same size fire would activate the sprinkler in about 40 s. At 90 m/min or higher airflows, a 200-kW fire would not activate a sprinkler under these conditions.

For a 400-kW fire, the times to sprinkler activation are nearly the same at airflows of 0 and 45 m/min, approximately 12 s, and nearly the same at 90- and 150-m/min airflows, about 30 s. The most significant effect in this case, in addition to the time delay, is that the sprinkler 5 m downstream activated at airflows of 90 and 150 m/min. Also notable is that for this size fire under these conditions, neither sprinkler activated at the 250-m/min airflow.

For fire sizes larger than 400 kW, relative to this experimental configuration, the ventilation had only a small effect on the time to activate the sprinkler system. Again, the most significant effect was seen in which sprinkler activated. At 0- and 45-m/min airflows, the sprinkler above the fire activated, while at 90-m/min airflow and higher, the sprinkler 5 m downstream activated.

These results showed that the most significant effects of ventilation on the time to activate the sprinkler system occurred for the smaller fires. Of more importance was the fact that as the ventilation increased, larger fires were required to activate the sprinklers.

EFFECT OF SPRINKLER ACTIVATION TEMPERATURE AND RTI VALUE

Experiments were conducted to determine the effect of activation temperature and RTI value on the activation times of the sprinklers as a function of airflow. In these tests, 57° and 74° C (135° and 165° F) fast-response (RTI value less than 50 $(m \cdot s)^{1/2}$) and 74° and 100° C (165° and 212° F) standard-response (RTI value greater than 100 $(m \cdot s)^{1/2}$ and less than 400 $(m \cdot s)^{1/2}$) sprinklers from manufacturer A were investigated at airflows of 0, 45, 90, 150, and 250 m/min. The results are shown in table 2. At each airflow the fire sizes were selected to be large enough to activate the 100° C (212° F) standard-response sprinkler. The same size fuel tray and amount of fuel were used for each test at a given airflow. However, the intensities of the fires did fluctuate somewhat, so the average fire sizes for each airflow are shown in the table. The sprinkler directly above the fire activated in the tests at the 0- and 45-m/min airflows, while the sprinkler located 5 m downstream was the first to activate at airflows of 90 m/min and greater.

Table 2.—Experimental data to determine effect of activation temperature and RTI value on activation time

Airflow, m/min	Fire size, kW	Activation time, s			
		57° C (135° F) fast[1] response	74° C (165° F) fast[1] response	74° C (165° F) standard[2] response	100° C (212° F) standard[2] response
0	110	21	24	51	99
45	340	12	15	54	75
90	535	12	15	57	96
150 . . .	565	30	33	78	87
250 . . .	800	30	21	39	69

[1] RTI value less than 50 $(m \cdot s)^{1/2}$.
[2] RTI value between 100 and 400 $(m \cdot s)^{1/2}$.

The data showed that there was no significant difference in the time to activate for the 57° and 74° C (135° and 165° F) fast-response heads under these conditions at the same airflow. Because the fires were large enough to activate the 100° C (212° F) standard-response sprinklers, the fires were much larger than required to activate the lower temperature rated fast-response sprinklers. Thus, the temperatures near the sprinklers when they activated were well above the rated activation temperatures. There was a significant delay in the activation times of the 100° C (212° F) rated sprinklers compared to the 74° C (165° F) sprinklers at the same airflow, ranging from a 12-pct delay at 150 m/min to 94 pct under nonventilated conditions.

The largest effect is seen in the comparison of the fast-response 74° C (165° F) versus standard-response 74° C (165° F) sprinklers. The increase in the time to activate the standard-response sprinkler compared to the fast-response sprinkler ranged from 86 pct at 250 m/min to 280 pct at 90 m/min. Even under nonventilated conditions with the sprinkler directly above the fire, the activation time was doubled for the standard-response sprinkler. These results verify that the RTI value of a sprinkler is an extremely important parameter in designing the responsiveness of a sprinkler system.

The results of the experiments to evaluate the effect of activation temperature and RTI on the activation times of the sprinklers can be extrapolated to the results on the effect of ventilation and fire size on the activation times of the higher temperature and RTI rated sprinklers. The shapes of the curves in figure 5 would remain the same for the higher rated sprinklers, but the x-asymptotes would be shifted significantly upward for the 74° and 100° C (165° and 212° F) standard-response sprinklers, because of the increased time to activation for these sprinklers. However, it can not be determined directly from these experiments if the y-asymptotes would be shifted to the right for the higher rated activation sprinklers, or what minimum fire size would be required to activate the less responsive sprinklers for a given airflow.

EFFECT OF MINE ENVIRONMENT ON ACTIVATION TIMES

Large-Scale Experiments

Large-scale experiments were conducted with sprinklers obtained from seven underground coal mines to evaluate the effect of the mining environment on sprinkler activation times. The sprinklers had been exposed to the harsh mine environment for periods of time ranging from 2 to 5 years, and the condition of the sprinklers ranged from light coatings of rock dust to severe internal and external corrosion.

Because of the limited number of exposed sprinklers, tests were first conducted using new sprinklers identical in type and activation characteristics to the exposed sprinklers at various fire sizes, under nonventilated conditions, to determine optimum fire sizes to evaluate each exposed sprinkler type. Fire sizes were then selected to fall in the portion of the fire size-versus-time curve under nonventilated conditions (see figure 5) where changes in the fire size resulted in discernable changes in the activation times of the sprinklers. To conduct the experiments with the exposed sprinklers, the sprinklers were placed directly above the liquid fuel fires under nonventilated conditions, together with their corresponding new sprinklers, and their activation times compared. The results are shown in table 3.

The most significant effect was observed for the 57° C (135° F) sprinklers from mine 1. These sprinklers did not activate when exposed to a 145-kW fire, while a corresponding new sprinkler activated in 30 s. These sprinklers

Table 3.—Comparison of activation times of new and exposed sprinklers in large-scale tunnel experiments

Mine-manufacturer-sprinkler	Activation temp, °C (°F)	Fire size, kW	Activation time for exposed sprinkler, s	Activation time for new sprinkler, s	Comments for exposed sprinkler
1-B-1	57 (135)	145	DNA	30	Covered with rock dust.
1-B-2	57 (135)	145	DNA	30	Do.
2-B-1	100 (212)	220	42	[1]43	Slightly corroded.
2-B-2	100 (212)	220	48	[1]43	Do.
2-B-3	100 (212)	220	57	[1]43	Covered with rock dust.
3-B-1	100 (212)	220	24	[1]43	Severely corroded.
3-B-2	100 (212)	220	57	[1]43	Do.
3-B-3	100 (212)	220	52	[1]43	Slightly corroded.
4-C-1	74 (165)	180	3	[1]27	Covered with rock dust.
5-C-1	100 (212)	220	42	[2]57	Slightly corroded.
5-C-2	100 (212)	220	43	[2]57	Do.
5-C-3	100 (212)	220	47	[2]57	Do.
6-C-1	100 (212)	220	68	[2]57	Covered with rock dust.
6-C-2	100 (212)	220	72	[2]57	Do.
6-C-3	100 (212)	220	78	[2]57	Do.
7-C-1	100 (212)	220	36	[2]57	Do.
7-C-2	100 (212)	220	45	[2]57	Do.
7-C-3	100 (212)	220	50	[2]57	Do.

DNA Did not activate.

[1] Average of 2 sprinklers.

[2] Average of 5 sprinklers.

were covered with rock dust, but that factor did not appear to affect other sprinklers tested from mines 6 and 7, which were also covered with rock dust. The sprinklers from mines 6 and 7, however, were rated at 100° C (212° F). The 100° C (212° F) sprinklers from mines 2 and 3, which came from the same manufacturer as the sprinklers from mine 1, were generally unaffected by the condition of the sprinklers, with the exception of sprinkler 3-B-1. That sprinkler activated significantly faster than the new heads, 24 s compared to 43 s. Sprinkler 3-B-1 was significantly more corroded than the other exposed sprinklers, however, indicating that it was exposed to much harsher conditions than the other sprinklers, and may have been significantly older than the other sprinklers from that mine.

Sprinkler 4-C-1 was the only 74° C (165° F) rated sprinkler tested, and only one was available. The results showed a very large difference in the activation times between the exposed sprinkler and the average activation time of the new heads. The exposed sprinkler activated 3 s after the fuel tray was ignited, while the two new sprinklers of the same type activated in 25 and 30 s, respectively. This exposed sprinkler was also covered with rock dust, but no other discernable features were evident to account for this difference.

Nine 100° C (212° F) sprinklers from manufacturer C, from three different mines, and five corresponding new sprinklers were also evaluated under these test conditions at a fire size of 220 kW. The activation time of the five new heads ranged from 44 to 84 s, with an average activation time of 57 s. The results for the exposed sprinklers also showed a fairly wide range of activation times, from 36 to 78 s, but these were not significantly outside the range observed for the new sprinklers.

The overall results indicated that mine exposure has the potential to significantly affect the activation times of sprinklers, particularly as noted in the experiments with the sprinklers from mines 1 and 4. However, with the possible exception of sprinkler 3-B-1, the activation times for the 100° C (212° F) rated sprinklers did not appear to be adversely affected by the exposure to the mine environment. Whether these results are due to the particular mine environments to which the sprinklers were exposed, or are a function of the rated activation temperatures is not clear.

Laboratory Oven Experiments

Additional experiments to examine the effect of the mine environment on the activation times of the sprinklers were carried out in a laboratory oven under more controlled conditions. In these experiments, the exposed sprinkler and corresponding new sprinklers of the same type from the same manufacturer were placed in the oven, and the oven temperature was increased from room temperature to 300° C (572° F). Initially, the oven temperature reached 50° C (122° F) in about 5 min and then increased at a linear rate of 3.5° C/min (6° F) to 300° C (572° F). The times to activation and temperatures at activation were measured and compared. Experiments were conducted on one sprinkler type from three different mines and two sprinklers from a fourth mine. The number of experiments was limited to the availability of the exposed sprinklers. The results are shown in table 4. The exposed sprinkler identification corresponds to the identification code used in table 3.

Table 4.—Comparison of activation times of new and exposed sprinklers in laboratory oven experiments

Mine-manufacturer-sprinkler	Activation temp, °C (°F)	Activation time, min	Temperature at activation, °C (°F)
1-B-3	57 (135)	13.1	84 (183)
1-B-4	57 (135)	14.8	86 (187)
B (new)	57 (135)	12.2	81 (178)
B (new)	57 (135)	12.3	78 (172)
B (new)	57 (135)	13.3	78 (173)
3-B-4	100 (212)	25.9	123 (253)
B (new)	100 (212)	25.3	123 (253)
B (new)	100 (212)	25.8	123 (253)
6-C-4	74 (165)	18.4	104 (219)
C (new)	74 (165)	18.8	102 (216)
C (new)	74 (165)	18.4	101 (214)
7-C-4	100 (212)	26.5	118 (244)
C (new)	100 (212)	25.5	115 (239)
C (new)	100 (212)	25.7	113 (235)

The largest observed temperature deviation was an increase of 6° C (11° F) in the average temperature at activation for the exposed sprinklers from mine 1 compared to average value for the new sprinklers. However, in general, these results showed no significant difference in the activation times and temperature at activation between the exposed and new sprinklers.

IMPLICATIONS OF RESULTS

The results of this study showed that ventilation and fire size can have a significant effect on the activation times of automatic sprinklers typically used in underground coal mines. In addition, the ventilation and fire size also greatly influence the temperatures downstream from a fire, which determine which sprinklers will activate in a given fire situation and installation design.

In these experiments, at airflows of 45 m/min or under nonventilated conditions, a sprinkler directly above the fire activated, and probably would have controlled or extinguished a fire directly under it. However, at airflows of

90 m/min and greater, 900-kW fires were not large enough to activate sprinklers directly above the fire before a sprinkler 5 m downstream activated. Temperature profiles near the tunnel roof showed that the highest temperatures were shifted downstream as far as 3.7 and 5 m at the 150- and 250-m/min airflows, respectively. Therefore, at airflows of 90 m/min and greater, even if a fire started directly under a sprinkler head, it is likely that a downstream sprinkler would activate first.

Previous studies by the USBM in the same tunnel on the water coverage characteristics of automatic sprinklers showed that airflows of 90 m/min or greater can also significantly affect the spray patterns of pendent-type sprinklers typically used in underground coal mines (*11*). At 90 m/min airflow, the water discharge density from a pendent-type sprinkler that activated 2.4 m downstream from a fire was less than 4 $L/(min \cdot m^2)$ at the fire location, while the largest water discharge was observed downstream of the sprinkler. Federal regulations for sprinkler systems on conveyor belts require a minimum average discharge density of 10 $L/(min \cdot m^2)$ over the top surface of the belt, with a minimum sprinkler spacing of 2.4 m. A minimum of 10 $L/(min \cdot m^2)$ is required over the top surface of unattended underground equipment (*7-8*). In the sprinkler activation experiments at an airflow of 250 m/min, the tunnel roof temperature profile indicated that the first sprinkler to activate under these conditions would be 3.7 m downstream from the fire. At that airflow, the water discharge pattern from a pendent-type sprinkler 3.7 m downstream of a fire location would not reach the fire. Although the data on activation and water discharge patterns are directly applicable only to the experimental conditions in these studies, this information clearly demonstrates that improper design of a sprinkler system can render the system ineffective. Specifically, where ventilation flows are necessary, such as in a coal mine, an improperly designed system can lead to a situation where a fire might activate a sprinkler downstream from the fire and the water is discharged from the opened sprinkler downstream and away from the fire.

Current Federal regulations for underground coal mines do not consider the effect of ventilation on sprinkler spacing. The results of these experiments show that in an underground mining environment, ventilation can have a significant effect on the activation characteristics of an automatic sprinkler system and is important in the design and installation of automatic sprinkler systems in these types of environments.

These experiments were conducted with contained liquid fuel fires in which the fire reached its peak size quickly and did not propagate. Further experiments would be needed to evaluate the activation characteristics of automatic sprinklers under ventilated conditions when exposed to slowly developing and propagating fires, such as in belt drive areas. The implications of the results from these experiments are that for slowly developing fires, the relative effects of ventilation on the activation times would be similar. Under propagating fire conditions, the activation times of the sprinklers would depend on how large the fire was and how fast the fire was propagating.

These experiments also evaluated the effects of the sprinkler activation temperatures and RTI values. The results indicated that the relative effects of ventilation and fire size would be similar for sprinklers with higher activation temperatures and RTI values. However, as the activation temperature and RTI value increased, the response times of the sprinklers would increase. In terms of sprinkler performance, the increased activation times and RTI values would decrease the likelihood of a sprinkler system activating for small fires.

The results of the experiments to evaluate the effect of the mine environment on the activation times of the sprinklers indicated that, in general, the mine environment has little effect on their activation times as measured under these experimental conditions. However, the data showed that the potential for malfunction exists; routine inspection and sprinkler replacement schedules are recommended to ensure activation and to replace damaged or badly corroded sprinklers.

SUMMARY

This study was conducted to examine the effect of mining conditions on the activation of automatic sprinkler heads. In large-scale experiments, 57° C (135° F) fast-response sprinklers were exposed to liquid fuel fires in a rectangular-shaped tunnel, at airflows ranging from 0 to 250 m/min, to determine the effect of ventilation and fire size on commercial sprinklers. At 0- and 45-m/min airflows, fires ranging from 20 to 555 kW activated a sprinkler directly above the fire. The time to activation ranged from 6 to 111 s, with the time decreasing with increasing fire intensity. At airflows of 90, 150, and 250 m/min, a sprinkler installed 5 m downstream was the first to activate, at fire sizes ranging from 215 to 945 kW. Again, the time to activation decreased with increasing fire size.

Temperature profiles near the roof of the tunnel indicated that the highest temperature was located directly above the fire under nonventilated conditions, but was shifted downstream to 1.8, 2.4, 3.7, and 5 m at 45-, 90-, 150-, and 250-m/min airflows, respectively, under this tunnel geometry.

Analysis of the data indicated that at 90 m/min airflow or higher, a fire larger than 200 kW was required to

activate the sprinkler system, and the time to activate increased as airflow was increased, for a given fire size greater than 200 kW.

Experiments were also conducted using 57°, 74°, and 100° C (135°, 165°, and 212° F) standard- and fast-response sprinklers to determine the effect of rated activation temperature and RTI value on the activation times of the sprinklers at airflows ranging from 0 to 250 m/min. The results showed that there was no significant difference in the time to activate between the 57° and 74° C (135° and 165° F) fast-response sprinklers under these conditions. The 100° C (212° F) standard-response sprinklers took from 12 to 94 pct longer to activate than the 74° C (165° F) sprinklers at these airflows. The largest difference in activation times was observed between the 74° C (165° F) standard- and 74° C (165° F) fast-response sprinklers. The activation times for the standard-response sprinklers were from 86 to 280 pct longer than those for the corresponding fast-response sprinklers at airflows ranging from 0 to 250 m/min.

Large-scale and laboratory oven experiments were conducted on sprinklers obtained from seven underground coal mines to evaluate the effect of exposure to the mining environment on the activation times of sprinklers. In the large-scale experiments, the exposed sprinklers and corresponding new sprinklers were exposed to liquid fuel fires under nonventilated conditions. The results indicated that the mine environment had little effect on the activation times, with the exception of two 57° C (135° F) sprinklers, heavily coated with rock dust, which did not activate, and one 100° C (212° F) severely corroded sprinkler, which activated in a much shorter time than the new sprinklers. The laboratory oven experiments showed no significant differences in the activation times of the exposed sprinklers compared to new sprinklers.

This study showed that airflow can have a significant effect on the activation characteristics of automatic sprinklers. Consideration of this parameter is important in the design of a reliable and effective sprinkler system. In addition, sprinkler parameters, such as rated activation temperature and RTI value, can significantly change the response characteristics of sprinklers and should be considered in sprinkler system design.

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