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Performance of Automatic Sprinkler Systems for Extinguishing Incipient and Propagating Conveyor Belt Fires Under Ventilated Conditions

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UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	m/min	meter per minute
g/g	gram per gram	m/s	meter per second
g/s	gram per second	$(m \cdot s)^{1/2}$	meter second to 1/2 power
kg/m	kilogram per meter	m^2	square meter
kJ/g	kilojoule per gram	m^3/min	cubic meter per minute
kJ/(g•°C)	kilojoule per gram per degree Celsius	min	minute
kPa	kilopascal	mm	millimeter
kW	kilowatt	MW	megawatt
L	liter	pct	percent
L/min	liter per minute	ppm	part per million
$L/(min \cdot m^2)$	liter per minute per square meter	s	second
m	meter	vol pct	volume percent
		°C	degree Celsius

PERFORMANCE OF AUTOMATIC SPRINKLER SYSTEMS FOR EXTINGUISHING INCIPIENT AND PROPAGATING CONVEYOR BELT FIRES UNDER VENTILATED CONDITIONS

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

ABSTRACT

The U.S. Bureau of Mines evaluated the effectiveness of automatic water sprinkler systems on the suppression of incipient and propagating conveyor belt fires under ventilated conditions. Large-scale experiments were performed at airflows ranging from 1.1 to 4.6 m/s. In incipient fire experiments with 100 °C, standard-response sprinklers installed above and between the belts, the sprinklers activated later, the peak heat release rates were larger, and more belting was consumed at the higher airflow. In similar experiments with 74 °C, fast-response sprinklers, the sprinklers activated at the same heat release rate for both high and low airflows, but the peak heat release rate and amount of belting consumed was slightly higher at the lower airflow. In incipient fire experiments with sprinklers located only above the top belt, the heat release rate and amount of belting consumed was larger at the higher airflow. The propagating fire experiments showed that sprinklers located above and between the belts were effective in stopping flame propagation. Peak heat release rates and amount of belting consumed were larger at the higher airflows for both the 74 °C, fast-response and 100 °C, standard-response sprinklers. The sprinklers were equally effective at each airflow.

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INTRODUCTION

Underground mine fires are a serious threat to life, property, and the Nation's mineral resources. Between 1970 and 1992, the U.S. Mine Safety and Health Administration (MSHA) investigated 320 coal mine fires (*1-2*).[4] Timko found that 56 of the fires (18 pct) occurred in conveyor belt entries (*3*). In 1988, a conveyor belt fire that started in the drive area spread rapidly through the Marianna No. 58 Mine in Pennsylvania and the entire mine had to be sealed (*4*).

Federal regulations for underground coal mines require that either automatic sprinkler systems, deluge-type water spray systems, foam generators, or dry 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 45 m of nonfire-resistant belt along all conveyor (sprinkler) 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 (*5*).

The standards 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 recommendations set forth in National Fire Protection Association (NFPA) 1968-69 edition, Code 13, "Installation of Sprinkler Systems" (NFPA-13). NFPA-13 provides the minimum requirements for the design and installation of automatic sprinkler systems, including the selection and spacing of sprinklers, water supplies, and system testing and maintenance. However, NFPA-13 does not consider the effect of ventilation on the activation characteristics or water distribution patterns of the sprinklers.

Earlier U.S. Bureau of Mines (USBM) research on the extinguishment of conveyor belt fires using automatic sprinkler systems was conducted by Mitchell (*6*). In that study, a 30.5-m-long, double strand of rubber-cotton-rayon conveyor belting was ignited and the fire allowed to propagate before encountering the sprinkler system. The sprinklers were pendent-type heads with 0.68-cm orifices. The sprinklers were connected to 2-cm pipe and delivered 42 L/min of water at 414 kPa. No information was available on the activation temperatures of the sprinklers. In tests at 1.0-m/s airflow with sprinklers above the top belt on 9.1 or 18.3 m centers, the sprinklers were unable to extinguish the belt fire. In tests at the same airflow with sprinklers above the belting and between the belts on 9-, 15-, 21-, or 28-m centers, the sprinkler system extinguished the propagating belt fires in all cases. Mitchell states in a later publication (*7*) that these experiments formed the basis for the requirement in reference 5 for directing water onto both the upper and bottom surfaces of the top belt and to the upper surface of the bottom belt.

In a study funded by the USBM in 1974, Warner compared the effectiveness of different types of suppression systems, including automatic sprinkler systems, to extinguish conveyor belt fires originating in belt drive areas (*8*). In the tests with automatic sprinklers, 6.0-m lengths of single- and double-strand conveyor belts were ignited by a propane burner. Sprinklers were mounted above the top belt at various intervals upstream and downstream from the ignition point. The study examined the effects of sprinkler spacing, activation temperature, residual pressure, and number of sprinklers activated, at airflows of 0.6 and 1.8 m/s.

The results indicated that a single branch line sprinkler system above the top belt at a minimum residual pressure of 69 kPa, providing a minimum waterflow rate of 68 L/min, with sprinklers on 3.0-m centers and activation temperatures between 93 and 149 °C, provided adequate belt drive protection. Sprinkler spacing had the greatest influence on system performance, but the spacing was dependent on the activation temperature of the sprinklers. In tests with 138 °C sprinklers, suppression was achieved with 3.6-m sprinkler spacings at 0 m/s, with 3.0-m spacings at 0.6-m/s airflow and 2.4-m spacings at 1.8-m/s airflow. In tests using sprinklers with activation temperatures of 100 °C, the opposite effect was observed. At the 0.6-m/s airflow, 3.0-m spacings were able to suppress the fire, but at the 1.8-m/s airflow, 3.6-m spacings were required.

The results of the earlier work by Mitchell and Warner showed that sprinkler systems were effective in extinguishing incipient and propagating conveyor belt fires at airflows up to 1.8 m/s (*6, 8*). Recent research by the USBM showed that higher ventilation airflows can have a significant effect on the water discharge patterns of automatic sprinklers, rendering some types of sprinklers ineffective at extinguishing fires just upwind of the sprinkler (*9*). Another study (*10*) showed that as the airflows were increased, the time to activate the sprinklers for a given fire size increased. At higher airflows, the highest air temperatures were shifted downstream from the fire, so that a fire directly under a sprinkler might not activate the sprinkler above it. This study also showed that certain

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

environmental factors, such as coating of the sprinklers with rock dust, can increase the time for some sprinklers to activate. A third study showed that the use of directional, fast-response sprinklers decreased the time required to extinguish wood crib fires at the higher airflows (*11*).

In this report, the USBM evaluated the effectiveness of automatic sprinkler systems to extinguish incipient and propagating conveyor belts fires at different airflows. Experiments were conducted at airflows ranging from 1.1 to 1.3 m/s and from 4.2 to 4.6 m/s to examine the effects of ventilation, sprinkler type, and installation design on the extinguishment of incipient conveyor belt fires. Experiments were also conducted at airflows of 1.1 and 4.0 m/s to study the extinguishment of propagating conveyor belt fires. This study is part of a program to evaluate the performance of fire suppression systems in underground coal mines and supports the USBM's goal to improve safety in the mining industry.

MATERIALS

SPRINKLERS

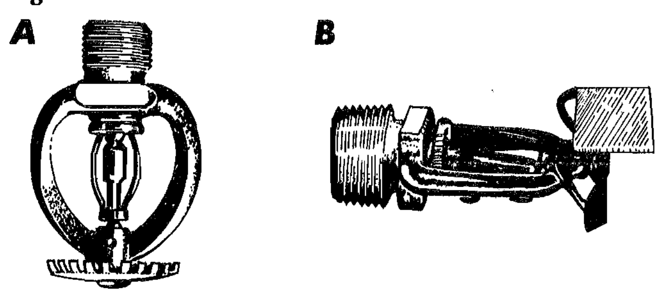
The sprinklers used in these experiments were 100 °C, standard-response, pendent type; 74 °C, fast-response, pendent type; and 74 °C fast-response, horizontal sidewall. All three sprinkler types are commercially available. The orifice diameter of the sprinklers was 1.27 cm. The activation mechanism for 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. The activation temperature of a sprinkler is controlled by varying the composition, thus the melting temperature, of the metal alloy that holds the fusible link together.

The response parameter of a sprinkler, or its thermal sensitivity, is defined by its response time index (RTI) value. Sprinklers with RTI values in the range of 100 to 400 $(m \bullet s)^{1/2}$ are referred to as "standard-response" sprinklers, while sprinklers with RTI values of 50 $(m \bullet s)^{1/2}$ or below are referred to as "fast-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 (*12*). Examples of pendent and horizontal sidewall sprinklers are shown in figure 1.

CONVEYOR BELTING

The conveyor belting was an 11-mm-thick by 1.07-m-wide, three-ply styrene-butadiene rubber (SBR) belt, obtained new from the manufacturer. The belting was considered to be fire resistant, based on the current small-scale Federal approval test for fire-resistant belting (*13*). The belt had a 5-mm top cover and a 2-mm bottom cover and weighed 14 kg/m. The belting had a carbon mass fraction of 0.5552 and a total heat of combustion of 23.8 kJ/g. This belting was selected because it met Federal standards for fire resistance, was typical of the type of belting used in many underground coal mines, and exhibited higher flame propagation and heat release rates than polyvinyl chloride (PVC) and neoprene belting in experiments conducted by Lazzara (*14*) at airflows up to 4.1 m/s.

Figure 1



Examples of pendent (A) and horizontal sidewall (B) sprinklers.

DESCRIPTION OF EXPERIMENTS

The experiments were conducted in the USBM's aboveground fire gallery located at the Lake Lynn Laboratory. The fire gallery is a 27.4-m-long tunnel constructed of masonry block walls, an arched metal roof, and a concrete floor. The interior walls are covered with a 6-cm-thick ceramic insulation blanket, while insulation on the arched roof is 9 cm thick. The height of the tunnel at the apex of the arched roof is 2.5 m, and the tunnel has a cross-sectional area of 7.5 m^2. The tunnel is coupled to a 1.8-m-diam, 3,500-m^3/min axivane fan by a 6-m-long tapered transition section. The ventilation flow can be varied by adjusting the pitch of the fan blades and/or by diverting the airflow from the tunnel by opening two steel doors located in the transition area. A schematic of the gallery is shown in figure 2.

In all the experiments, a double-strand conveyor belt configuration was used. The top strand of conveyor belting was supported by a conveyor belt frame. The frame is 21 m long and 1.5 m wide and centered in the tunnel. The frame consists of a 0.45-m-diam tail pulley and 0.13-m-diam troughed idler assemblies spaced at 1.2-m intervals. The distance from the center of the idler assemblies to the roof was 1.3 m. The center of the tail pulley is 2.6 m from the transition area and used as the reference point for all thermocouple and sprinkler locations. To support the bottom strand of conveyor belting, steel reinforcing rods were attached to the frame at 1-m intervals. The distance between the top and bottom strands of belting ranged from 0.4 m near the center of the idler assemblies to 0.5 m near the outside edge of the belting. This is shown in figure 2.

Initially, two experiments were conducted with no sprinklers installed, to study the ignition characteristics of the belting and to obtain baseline heat release data. In these experiments, the top and bottom belts extended 3.7 m downstream from the center of the tail pulley.

INCIPIENT FIRE EXPERIMENTS

For the incipient fire extinguishment experiments, two different sprinkler system designs and belting lengths were employed. In the first design, the top and bottom strands of belt extended 6.1 m downstream from the center of the tail pulley. Sprinklers were located directly above the center of the tail pulley and 2.4, 4.9, and 7.3 m downstream. The sprinklers were located 0.15 m from the roof of the tunnel and 1.15 m above the center of the top belt. Sprinklers were located between the belts, midway between the top and bottom belts at the outer edge of the belting, 2.4 and 4.9 m downstream from the center of the tail pulley. The belt configuration was designed to simulate the protected belting downstream from a drive roller. The sprinkler locations and spacings were in accordance with Federal regulations for water sprinkler systems in conveyor belt drive areas (*5*).

For the second design, the top and bottom strands of belt extended 7.6 m downstream from the center of the tail pulley. Sprinklers were located directly above the tail pulley and 3.0 and 6.1 m downstream. These sprinklers were also located 0.15 m from the roof and 1.15 m above the center of the top belt. No sprinklers were installed between the belts. In this design, the sprinkler locations and spacings were in accordance with NFPA-123 standards for sprinkler installation in underground bituminous coal mines (*15*).

PROPAGATING FIRE EXPERIMENTS

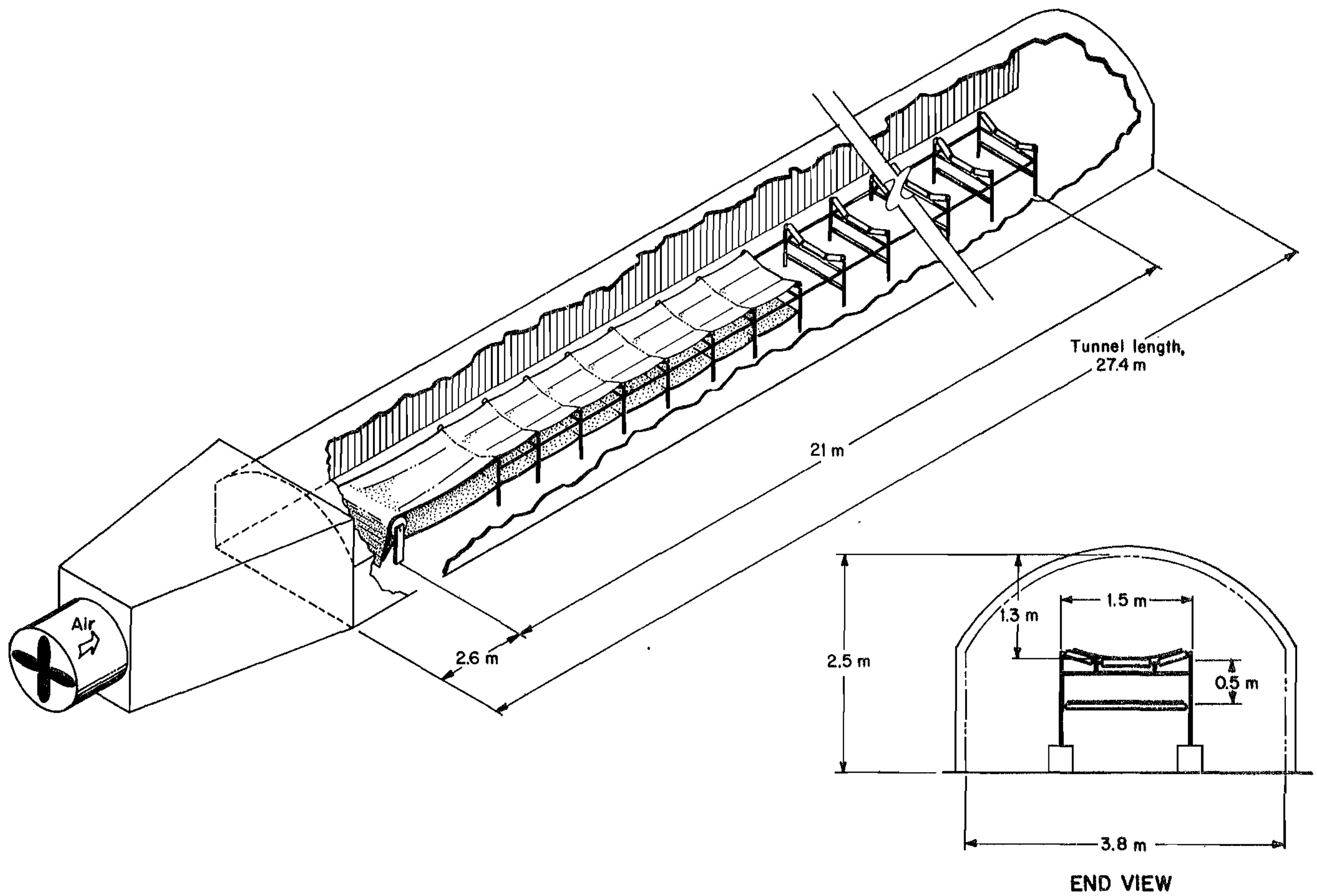
In the propagating conveyor belt fire extinguishment experiments, the top and bottom belts extended 15.2 m downstream from the center of the tail pulley. The sprinklers were located above the top belt and between the belts, 10.4, 12.8, and 15.2 m downstream. The top sprinklers were located on the belt centerline, 0.15 m from the roof of the tunnel and 1.15 m above the top belt. In experiments with pendent-type sprinklers between the belts, the sprinklers were located between the belts, midway between the top and bottom belts, at the outer edge of the belting. When directional sprinklers were used between the belts, these sprinklers were located between the belts, on the belt centerline, and oriented to discharge the water upstream into the airflow.

BELT IGNITION

In the ignition area, the bottom belt was positioned so that 0.7 m of the belting extended from the center point of the tail pulley over two gas burners used to ignite the belting. The end of the belting was approximately 15 cm from the floor. The top piece of belting was positioned so that 1.0 m of the belting hung over the tail pulley, extending to the end of the bottom strand of belting. The belting and the two gas burners were shielded from the airflow by low-density cement foam blocks, shown in figure 3. The block wall in front of the tail pulley was 1.2 m high and 2 m across and extended downstream approximately 2 m on each side of the conveyor structure.

Two jet-type burners were used to ignite the belting. The burners each had rated heat outputs of 64 to 128 kW, for a combined rating of 128 to 256 kW. To ignite the belts, a total methane gas flow of 0.20 m^3/min was supplied to the two burners to produce a 130-kW fire. The methane was left on until the burners ignited the bottom strand of belting. This was measured by the

Figure 2



Schematic of Lake Lynn aboveground fire gallery.

thermocouples embedded in the belting and by visual observation via a video camera. The flaming bottom belt then ignited the top belt. The time required to ignite the bottom belt varied from 6 to 10 min, depending on the airflow. A schematic of the tail pulley, gas burners, and belting arrangement near the burners is shown in figure 3.

AIRFLOW MEASUREMENT

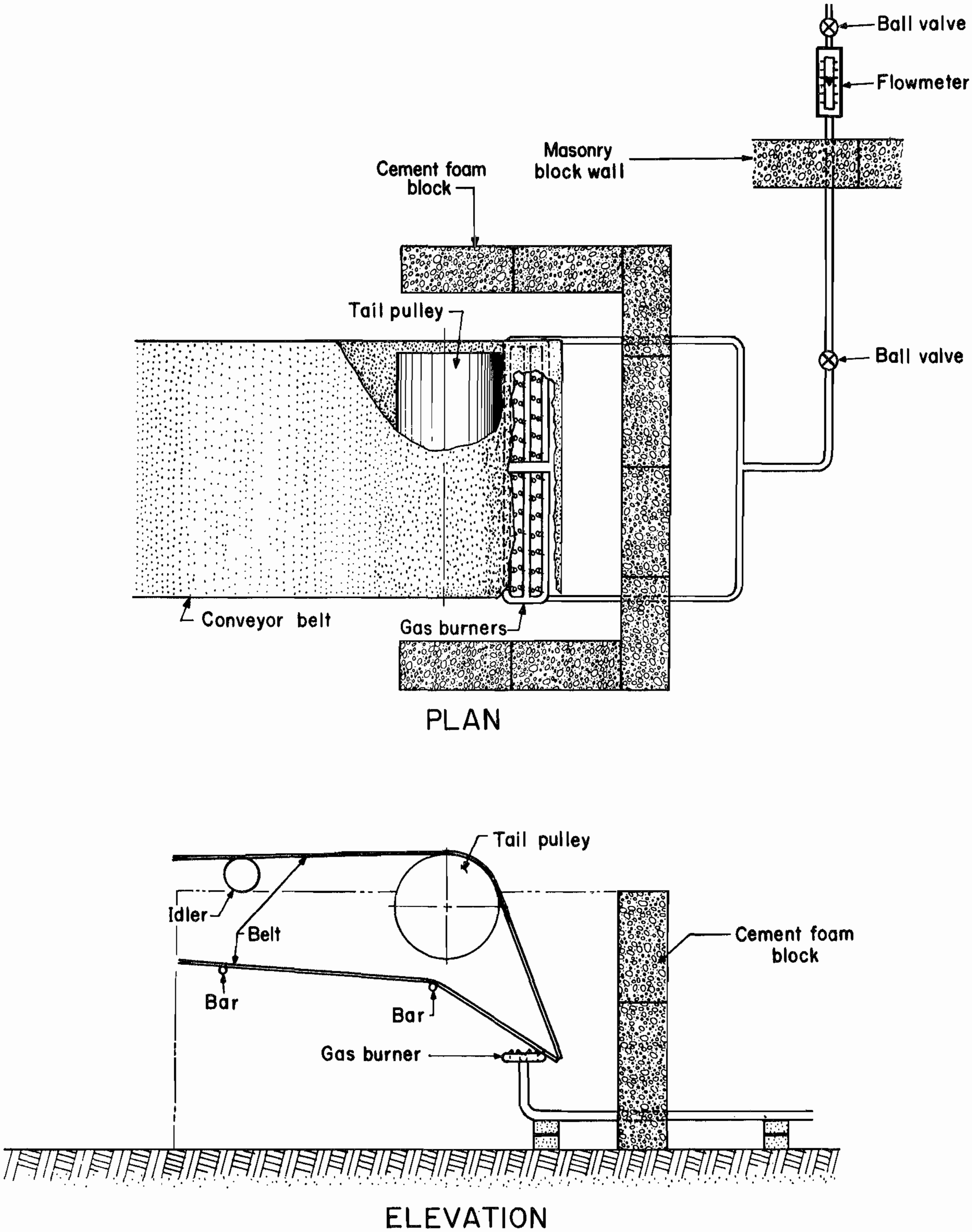
The airflow was measured using a vane anemometer at various locations throughout the fire tunnel. The reported airflow values for the incipient fire experiments are the average values of measurements made 5 cm above the top belt at the center and outside edges of the belt, 2.4 and 4.9 m downstream from the center of the tail pulley. Airflow measurements were also made 5 cm above the belt at the tail pulley. At the lower airflows, the values at the tail pulley were approximately double the reported value because of turbulence caused by the ignition area shielding. However, additional measurements showed that the airflows returned to the reported values 1 m downstream from the tail pulley.

The airflow was also measured 5 cm above the center and outside edges of the bottom belt, 2.4 and 4.9 m downstream from the center of the tail pulley, and 5 cm from the roof at each sprinkler location. Lastly, the airflow was measured at nine locations across the cross section of the tunnel, 22 m downstream from the tail pulley.

The reported values for the propagating fire experiments are the average of measurements made 5 cm above the top belt, 4.9, 10.4, 12.8, and 15.2 m downstream. As was the case for the incipient fires, the airflow at the tail pulley was approximately double the reported values at the lower airflows. Airflows were also measured near the roof and 5 cm above the bottom belt at each sprinkler location and across the cross section of the tunnel near the exit.

For both the incipient and propagating experiments, the airflows were fairly uniform throughout the tunnel, with the exception of the air velocities measured 5 cm above the tail pulley. The airflow velocities measured near the

Figure 3



Schematic of belt ignition area.

tunnel exit for the experiments at the higher airflows were about 20 pct lower than the reported airflow value, whereas at the lower airflows, the exit velocity was about 10 pct higher. The airflows at the sprinklers above the top belt were about 10 pct higher at both the high and low airflows. Airflows between the belts were generally 25 to 50 pct of the top belt values.

WATER SUPPLY

Water was supplied by a diesel fire pump from a 38,000-L storage tank located approximately 300 m from the fire gallery, through a 10-cm supply line, to a hydrant near the tunnel. The water entered the tunnel through 3.8-cm-inside diameter piping to the sprinklers. The water system was designed to supply at least 10 L/(min•m^2) of water over the top surface of the belt, as required by Federal regulations for automatic sprinkler systems in underground coal mines (*5*).

INSTRUMENTATION

Thermocouples were imbedded just below the surface of the belts to measure belt temperatures and flame propagation rates. The thermocouples were located at the center of the top and bottom belting, starting at the center of the tail pulley, and at 1.22-m-intervals downstream to the end of the belting. An array of 12 thermocouples, distributed over the cross-sectional area of the tunnel, was located 22 m downstream from the tail pulley to measure the average gas temperature of the exit gas stream. The average temperature was calculated by multiplying the temperatures of each thermocouple by the percentage of the cross-sectional area of the exit represented by that thermocouple and summing those values.

A gas sampling probe was located 23 m downstream from the tail pulley to measure the average CO, CO_2, and O_2 concentrations in the exit gas stream. The probe had four 3-mm-diam inlet ports spaced along the vertical height of the tunnel, 0.5, 1.0, 1.5, and 2.0 m from the tunnel floor. The reported CO_2 values are corrected for the ambient CO_2 concentration of 330 ppm.

The outputs of the thermocouples and gas analyzers were connected to a 96-channel data acquisition system that transmitted the data to a computer for storage and analysis. The data were logged at 10-s intervals and displayed in real time on a computer terminal. The experiments were also recorded on videotape.

SUPPRESSION CRITERION

The conveyor belting fire was considered extinguished when there were no visible flames as a result of belt burning on the conveyor structure or floor and all thermocouple readings were less than 100 °C. At that time, any smoldering belting on the conveyor structure or the floor was extinguished with a handheld hose.

RESULTS AND DISCUSSION

INITIAL CONVEYOR BELT FIRES

Initial experiments were conducted at airflows of 0.8 and 4.0 m/s, with no sprinklers installed, to study the ignition characteristics of the belting and to obtain baseline heat release and flame propagation data.

In the experiment at the 0.8-m/s airflow, the burner was turned off at 10 min. The heat release rate at that time, based on the exit gas temperatures, was 0.2 MW. (See appendix A for methods to calculate heat release rates.) No CO, CO_2, or O_2 data were available for this experiment. By 17.5 min, the fire in the ignition area was fully developed and began to propagate along the belting. (See appendix B for the method used to calculate flame propagation rates.)

The flame front propagated along the top belt, from 1.2 to 3.7 m, at a rate of 2.1 m/min, reaching the end of the belting at 19 min. The flame propagated along the bottom belt, from 1.2 to 3.7 m, at a rate of 0.7 m/min, reaching the end of the belting at 21.5 min. The heat release rate, shown in figure 4, leveled off at about 1.2 MW at 20 min, with a peak level of 1.4 MW observed at 28.5 min. The heat release rate then fell rapidly. The flame propagation rate and peak heat release rate are shown in table 1.

Table 1.—Flame propagation rates and peak heat release rates for initial belt fires[1]

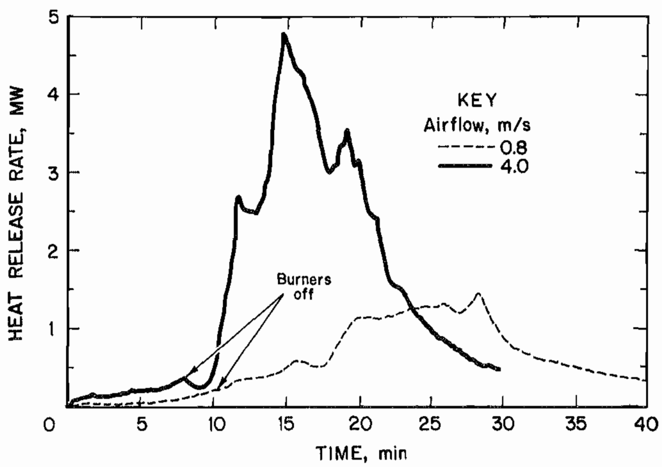
Airflow, m/s	Flame propagation rate, m/min		Peak heat release rate, MW
	Top belt	Bottom belt	
0.8	2.1	0.7	1.4
4.0	1.0	0.5	4.8

[1]Top and bottom belting length = 3.7 m.

In the experiment at the 4.0-m/s airflow, the burners were turned off at 8 min. The heat release rate at that time, based on the exit gas temperatures, was 0.3 MW. Within 2 min the flame began propagating along the top and bottom belts, at rates of 1.0 and 0.5 m/min, respectively. At 16 min, just 8 min after the burners were turned off, both the top and bottom belts were fully enveloped in flames. A peak heat release rate of 4.8 MW was observed at 14.7 min. These results are also in figure 4 and table 1.

The results indicate that a relatively small ignition source, 0.13 MW, was able to ignite a double strand of fire-resistant SBR conveyor belting, in this configuration, in under 10 min. At both airflows, the fire was able to propagate out of the ignition area within 10 min after the burner was turned off. The flame propagation rate along the top belt was about twice as fast at the 0.8-m/s airflow than the rate observed at the 4.0-m/s airflow, and about 40 pct faster along the bottom belt at the lower airflow. The heat release data indicated that the peak heat release rate at the 4.0-m/s airflow, 4.8 MW, was about 3.5 times higher than that measured at the 0.8-m/s airflow, 1.4 MW. The lengths of belting used in these experiments were not long enough to generate steady-state flame propagation and heat release rates.

Figure 4



Heat release rates for initial conveyor belt fires.

INCIPIENT CONVEYOR BELT FIRES

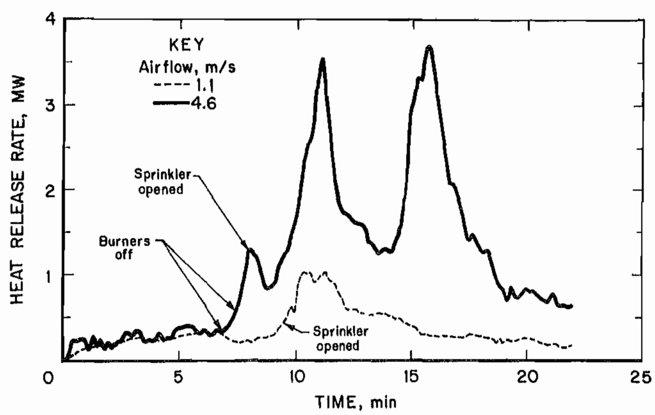
Sprinklers Installed in Accordance With Federal Standards

Experiments were conducted to evaluate the effectiveness of sprinklers to extinguish incipient belt fires. The first experiments used 100 °C, standard-response, pendent sprinklers, installed in accordance with Federal regulations (5), at airflows of 1.1 and 4.6 m/s. Experiments were then conducted using 74 °C, fast-response, pendent sprinklers above the belt and 74 °C, fast-response, directional sprinklers between the belts at an airflow of 1.1 m/s. Lastly, an experiment was conducted using 74 °C, fast-response, directional sprinklers above and between the belts at an airflow of 4.6 m/s.

In the experiment at the 1.1-m/s airflow with 100 °C, standard-response, pendent sprinklers, the burners were turned off at 6.5 min. At that time, the heat release rate was about 0.35 MW, as shown in figure 5. The highest measured belt temperatures were 60 °C at 1.2 m on the top belt and 157 °C at the center of the tail pulley on the bottom belt.

The heat release rate fell briefly and then increased. The sprinkler directly above the center of the tail pulley opened at 9.5 min, at a heat release rate of 0.45 MW. At the time that the sprinkler activated, the temperature of the bottom belt at 0 m had reached 600 °C and the flames had not yet reached the thermocouple at 1.2 m. The maximum temperature of the top belt was 125 °C at 1.2 m. Temperatures continued to climb at those positions for about 1.5 min, reaching maximums of 900 and 170 °C, respectively, before cooling. The maximum CO and CO_2 concentrations and minimum O_2 concentration were also observed at 9.5 min, 625 and 6,200 ppm, and 19.9 vol pct,

Figure 5



Heat release rates for incipient fires with 100 °C, standard-response sprinklers above and between belts.

respectively. The ambient O_2 concentration is 20.9 vol pct. These data are shown in table 2. The heat release rate continued to climb, reaching a maximum or 1.0 MW at 11.5 min. The water discharge from the one opened sprinkler above the tail pulley prevented the flame from propagating out of the ignition area, with just 0.9 m of the top belt and 1.5 m of the bottom belt consumed, as measured downstream from the centerline of the tail pulley. No other sprinklers activated.

In the experiment at the 4.6-m/s airflow, the gas burners were turned off at 7.5 min. The heat release rate at that time, shown in figure 5, was 0.6 MW. The top belt temperatures were all below 30 °C, while the bottom belt temperature at the tail pulley had reached 600 °C. The temperature of the bottom belt 1.2 m downstream was 200 °C and increasing rapidly. At 8.0 min, the sprinkler located between the belts, 2.8 m downstream, activated.

Table 2.—Experimental data for incipient belt fires using sprinklers above and between belts

Sprinkler type and airflow, m/s	Heat release rate, MW		Peak conc, ppm		Minimum O_2 conc, vol pct	Belt consumed, m	
	When first sprinkler opened	Peak	CO	CO_2		Top	Bottom
100 °C, standard response:							
1.1	0.4	1.0	625	6,200	19.9	0.9	1.5
4.6	1.3	3.7	540	5,000	19.9	2.5	1.2
74 °C, fast response:							
1.1	0.4	1.5	550	6,100	19.8	0.9	1.2
4.6	0.4	0.4	90	750	20.6	0	0

Conc Concentration.

The heat release rate observed at that time was 1.3 MW, downstream CO and CO_2 concentrations were 190 and 1,700 ppm, respectively, and the O_2 concentration was 20.4 vol pct.

The heat release rate continued to rise, reaching 3.6 MW at 11 min. At that time, the water spray effectively stopped flame propagation along the bottom belt at 1.2 m. The bottom belting near the tail pulley continued to burn for about 3 min after the flame propagation was stopped, before being consumed. During that time, the burning bottom belt ignited the top belting. The top belt fire then propagated approximately 2.5 m, at a rate of 1.2 m/min. Flame propagation along the top belt was stopped by the water spray from the opened sprinkler between the belts. Before the top belt propagation was stopped, the heat release rate reached a peak of 3.7 MW and a minimum O_2 concentration of 19.85 vol pct was observed at 16 min. The peak CO and CO_2 concentrations, 540 and 5,000 ppm, respectively, occurred during the propagation of the bottom belt, at 11 min. None of the sprinklers above the top belt opened in this experiment.

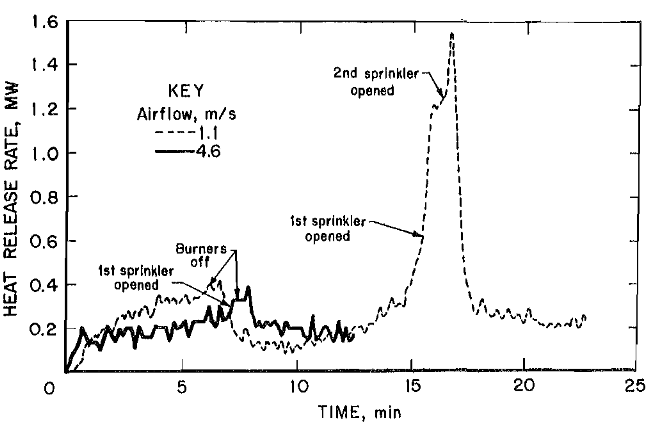
The data indicate that the heat produced by the ignition of the bottom belting was sufficient to activate the sprinkler between the belts, limiting flame propagation along the bottom belt. However, the higher airflow had a cooling effect on the sprinklers located above the belt, preventing the sprinklers above the top belt from opening. Temperature data from the thermocouples located near the top sprinklers indicated that had the top belt propagated past 2.4 m, the sprinkler located 7.3 m downstream would have activated, probably preventing flame propagation past that point.

An experiment was conducted at an airflow of 1.1 m/s using 74 °C, fast-response, pendent sprinklers above the top belt and 74 °C, fast-response, horizontal sidewall (directional) sprinklers between the belts. In the experiment at the 1.1-m/s airflow, the bottom belting was ignited in 6 min. The heat release rate at that time, shown in figure 6, was 0.4 MW, and temperatures of the top and bottom belt at the tail pulley were 24 and 350 °C, respectively.

Temperature data indicated that the fire did not begin to propagate from the ignition area until about 16 min, when the temperature of the bottom belt at 1.2 m reached 300 °C. The sprinkler located above the top belt, 4.9 m downstream, opened just before that time, at 15.5 min. The heat release rate at 15.5 min, shown in figure 6, was 0.6 MW. The sprinkler located between the belts, 2.4 m downstream, activated at 16.5 min, at a heat release rate of 1.2 MW. The heat release rate continued to rise until 17.0 min, reaching a maximum of 1.5 MW. Peak CO and CO_2 concentrations of 550 and 6,100 ppm, respectively, and a minimum O_2 concentration of 19.8 vol pct were also observed at that time. In this experiment, 0.9 m of the top belting and 1.2 m of the bottom belting were consumed. These data are shown in table 2.

In the experiment at the 4.6-m/s airflow with the 74 °C, fast-response, horizontal sidewall sprinklers, the sprinkler between the belts, 2.4 m downstream, activated at 7.0 min. The methane burners were still on, and the heat release rate from the burner and burning belt was just 0.25 MW. The temperature of the bottom belt at 0 m when the sprinkler activated was 250 °C, and at 1.2 m, the temperature was 150 °C. The highest observed top belt

Figure 6



Heat release rates for incipient fires with 74 °C, fast-response sprinklers above and between belts.

temperature at that time was 48 °C, 1.2 m downstream. Carbon monoxide and carbon dioxide concentrations had reached 90 and 750 ppm, respectively, while the O_2 concentration had dipped to 20.6 vol pct. When the sprinkler activated, belt temperatures immediately fell and by 9 min, there were no visible flames. Only minor damage to the first 1.2 m of the top and bottom conveyor belting was observed.

Effect of Ventilation on Extinguishment

In the experiments using the 100 °C, standard-response sprinklers, the sprinkler system effectively controlled and extinguished the incipient conveyor belt fires at both the 1.1- and 4.6-m/s airflows. In the experiment at the lower airflow, the sprinkler located above the tail pulley was the first to activate. This sprinkler was able to prevent flames from propagating out of the ignition area. As a result, just 0.9 m of the bottom belt and 1.5 m of the top belt were consumed.

At the higher airflow, the sprinkler located between the belts, 2.8 m downstream, was the first to open. This resulted in 2.5 m of the top belt being consumed before the water spray from the bottom sprinkler was able to extinguish the fire along the top belt. Bottom belt damage was limited to 1.2 m, slightly less than at the lower airflow.

The peak heat-release rate was significantly higher at the higher airflow, 3.7 MW, compared to 1.0 MW at the lower airflow, as a result of the increased amount of belt burning at the higher airflow. Peak CO and CO_2 values were comparable because of the dilution effect at the higher airflow.

The results with the 74 °C, fast-response sprinklers showed that the heat release rate, belt damage, and downstream CO and CO_2 concentrations were significantly lower at the 4.6-m/s airflow compared to the results at the 1.1-m/s airflow. At the lower airflow, the sprinkler above the belt 4.9 m downstream activated first, followed by the sprinkler between the belts, 2.4 m downstream from the tail pulley. The sprinklers effectively controlled the fires, limiting flame propagation to 0.9 m along the top belt and 1.2 m along the bottom belt, and the peak heat release rate to 1.6 MW.

In the experiment at the 4.6-m/s airflow, the sprinkler between the belts, 2.4 m downstream, activated before the belt fire was fully developed, resulting in only minor damage to the belting in the ignition area. The heat release rate was limited to 0.4 MW, and the combustion gas concentrations were significantly lower than those observed at the 1.1-m/s airflow. These results indicated that there was a significant improvement in extinguishing effectiveness of the sprinkler system using the 74 °C, fast-response, directional sprinklers at the higher airflow compared to the lower airflow.

Effect of Sprinkler Type on Extinguishment

The results of the experiments at the 1.1-m/s airflow using either 100 °C, standard-response or 74 °C, fast-response sprinklers showed no apparent difference between the sprinkler types in the extinguishing effectiveness on incipient conveyor belt fires under these experimental conditions. The sprinkler systems activated at the same heat release rate, 0.4 MW, and effectively extinguished the fires. Peak downstream heat release rates were limited to less than 2 MW, and the amount of top and bottom belt consumed was less than 1.5 m using both types of sprinklers. The use of low-temperature, fast-response sprinklers did not appear to significantly improve sprinkler system performance, either in the time to activate or in limiting the peak heat release rate or flame propagation.

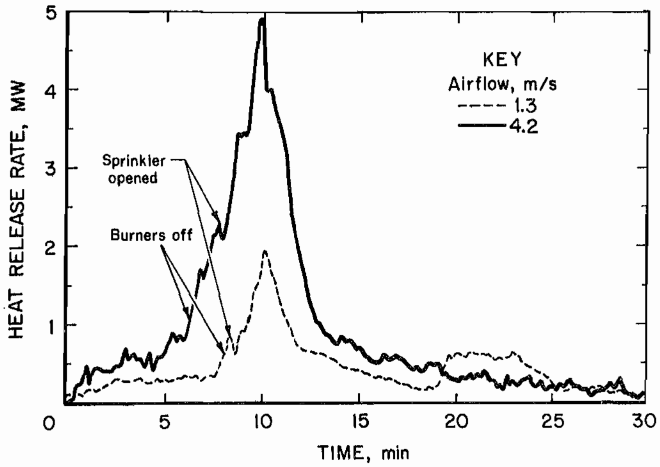
The results of the experiments at the 4.6-m/s airflow, however, did show a significant increase in effectiveness when the low-temperature, fast-response, directional sprinklers were used. The system with the 74 °C, fast-response sprinklers activated at a heat release rate of 0.4 MW, compared to 1.3 MW for the system with the 100 °C, standard-response, pendent sprinklers. In addition, a peak heat release rate of 0.4 MW was observed in the test with the 74 °C, fast-response sprinklers, compared to 3.7 MW for the 100 °C, standard-response sprinklers. The amount of belting consumed during the experiment with the standard-response, pendent sprinklers, 2.5 m of top belt and 1.5 m of bottom belt, was considerably more than in the experiment with the fast-response, directional sprinklers, which resulted in just minor damage to the belting.

Sprinklers Installed in Accordance With NFPA Standards

Experiments were conducted at airflows of 1.3 and 4.2 m/s to evaluate the effectiveness of sprinklers installed above the top belt, with no sprinklers between the belts, to extinguish incipient belt fires. Standard-response, pendent sprinklers with activation temperatures of 100 °C were installed directly above the tail pulley, 3.0 and 6.0 m downstream. These sprinklers were installed in accordance with current NFPA-123 standards for sprinkler installations in underground bituminous coal mines (*15*).

In the experiment conducted at the 1.3-m/s airflow, the burners were turned off at 8 min. The heat release rate at that time, shown in figure 7, was 0.6 MW. The highest temperatures observed were 500 °C at 0 m of the top belt and 800 °C at 0 m of the bottom belt, indicating that the fire had not yet propagated out of the ignition area. The sprinkler directly above the center of the tail pulley activated at 8.25 min, at a heat release rate of 0.8 MW, and quickly extinguished the flames on the top belt. No other sprinklers activated. Flames on the bottom belt were able

Figure 7



Heat release rates for incipient fires using 100 °C, standard-response sprinklers above belts.

to propagate 1.8 m over the next 2 to 3 min, before water running off from the top belt stopped flame propagation. The peak heat release rate, 1.9 MW; maximum CO and CO_2 concentrations, 1,200 ppm and 1.0 vol pct, respectively; and minimum O_2 concentration, 19.4 vol pct, were observed at 10 min. The 1.8 m of bottom belting continued to burn until consumed, as indicated by the decreasing heat release rate over the next 15 to 20 min.

Three experiments were conducted at the 4.2-m/s airflow. In the first experiment, the burners were turned off at 6.3 min, at a heat release rate of about 1.0 MW. At that time, the flames had reached 1.2 m along the bottom belt, and the temperature had reached 800 °C at 0 m of the bottom belt. The top belt was not fully ignited, as temperatures were still below 50 °C.

At 8.5 min, the sprinkler located above the belt, 3.0 m downstream, activated. At that time, the flame had propagated 2.7 m along the bottom belt, but had not yet propagated out of the ignition area on the top belt. The heat release rate when the sprinkler activated was 3 MW. A second sprinkler, 6.1 m downstream, activated at 9.3 min, at a heat release rate of 3.4 MW. The top belt in the ignition area was fully engulfed in flames at 10 min and propagated 1.2 m before encountering water from the sprinklers at 12 min. A peak heat release rate of 6 MW was observed at that time. The flame had propagated 3.7 m along the bottom belt, at a flame propagation rate of 0.4 m/min. Peak CO_2 and CO concentrations and the minimum O_2 concentration of 0.9 vol pct, 775 ppm, and 19.6 vol pct, respectively, were also observed at 12 min. These results are shown in table 3.

From the 14th to 16th minute, water pressure was lost in the sprinkler supply line. During this time, no appreciable change in the flame propagation rates or heat release rates was observed. However, when the waterflow was restored, flames continued to propagate along the bottom belt, at a rate of 0.36 m/min, eventually consuming 7 m of the 7.6-m length of belting. The water spray prevented the flames from further propagating along the top belting. The underside of the top belt was charred from the bottom belt flames along its entire remaining length. The results indicate that the top belt shielded the bottom belt from the water spray, allowing the flame to propagate along the bottom belt. It was unknown what effect the water stoppage had on the test results.

A second experiment was conducted at 4.2-m/s airflow using the same belting and sprinkler configuration to determine if the water stoppage during the previous experiment affected the results. In this experiment, the gas burners were turned off at 6.2 min. However, the bottom belting failed to ignite. The burners were reignited at 10.8 min and allowed to burn until 12.5 min. During this time period, both the bottom and top belts were ignited by the burner.

The sprinklers 3.0 and 6.1 m downstream from the tail pulley activated at 16.0 min. The flames along the top and bottom belts had propagated 2.4 m, and the heat release rate at the time the sprinklers activated was 2.7 MW. The heat release rate continued to increase, reaching a peak of 4.8 MW at 18 min. Peak CO and CO_2 concentrations of 525 ppm and 0.7 vol pct, respectively, were observed at that time, as was the minimum O_2 concentration, 19.9 vol pct. The water spray was able to reach both belts, stopping the flame propagation along both belts at that time.

Table 3.—Experimental data for incipient belt fires using sprinklers above top belt

Airflow, m/s	Heat release rate, MW: When first sprinkler opened	Heat release rate, MW: Peak	Peak conc, ppm: CO	Peak conc, ppm: CO_2	Minimum O_2 conc, vol pct	Belt consumed, m: Top	Belt consumed, m: Bottom
1.3	0.8	1.9	1,200	10,000	19.4	0	1.8
4.2	3.0	6.0	775	9,000	19.6	1.2	[1]7.0
	2.7	4.8	525	7,000	19.9	2.4	2.4
	2.3	4.9	500	7,400	19.9	2.0	2.4

Conc Concentration.
[1]Waterflow stopped from 14 to 16 min because of pressure loss.

In this experiment, it appeared that the belts ignited differently during the second attempt to ignite the belts than in previous experiments. The top belt appeared to be ignited directly by the burners, whereas in the previous experiments, the bottom belt was ignited first, which in turn ignited the top belt. This may have allowed the flame propagation along the top belt to occur ahead of the flame propagation along the bottom belt, exposing the flaming bottom belt to the water spray from the sprinklers.

A third experiment was conducted with the same belting and sprinkler configuration at an airflow of 4.2 m/s. In this experiment, the burners were turned off at 6.5 min, at a heat release rate of 1 MW, as shown in figure 7. At that time, the flames had not yet reached the thermocouples located at 1.2 m on the top and bottom belts. At 7.8 min, the sprinkler 3.0 m downstream opened. The heat release rate was 2.3 MW and the flames had propagated past the thermocouples located at 1.2 m on the top belt. The flames had not yet reached the thermocouple located 1.2 m downstream on the bottom belt.

The water spray effectively stopped the flame propagation along the top belt at 2.0 m and at 2.4 m along the bottom belt. At 10.5 min, the heat release rate peaked at 4.9 MW, the CO and CO_2 concentrations peaked at 500 and 7,400 ppm, respectively, and the O_2 concentration dropped to a minimum of 19.9 vol pct. The heat release rate then dropped steadily as the belt continued to burn until consumed.

The results of this experiment compare very well with those obtained in the second experiment in terms of maximum heat release and gas concentrations. Slightly more bottom belt was consumed in the latter experiment, although it appears that this sprinkler configuration can effectively prevent flame from propagating out of the ignition area at this airflow. However, the results from the first experiment at this airflow indicated that even a short interruption in waterflow could result in catastrophic consequences as the fire spread beyond the sprinklered zone.

Comparing the results of the experiments using the 100 °C, standard-response sprinklers installed above the tail pulley and 3.0 and 6.0 m downstream above the belting, the sprinkler system effectively controlled and extinguished the incipient conveyor belt fires at both 1.3- and 4.2-m/s airflows. This analysis excludes the results of the experiment at 4.2 m/s in which the waterflow to the sprinkler system was interrupted during the extinguishment phase of the experiment.

Although the sprinkler system was able to control and extinguish the fires at both airflows, there were significant differences in the heat release rate required to activate the system, peak heat release rates, combustion gas concentrations, and amount of belting consumed. Probably the most significant difference observed at the two airflows was in the location of the sprinkler(s) that opened. In the experiment at 1.3-m/s airflow, the sprinkler located directly above the tail pulley opened, at a heat release rate of just 0.8 MW. This limited fire damage to the top belt to just that belting that extended over the tail pulley into the ignition area. Approximately 1.8 m of the bottom belt was consumed before the fire on the bottom belt was extinguished.

In the experiments at the 4.2-m/s airflow, the first sprinkler to open in both tests was the sprinkler located 3.0 m downstream from the tail pulley, at an average heat release rate of 2.5 MW. By that time, flames had begun to propagate along both the top and bottom belts. The fire propagated 2.0 to 2.4 m along the top belt and 2.4 m along the bottom belt before being stopped by the water spray from the sprinkler at 3.0 m.

Because of the increased amount of belting involved in the fires at the higher airflow, significantly higher peak heat release rates were observed, 4.8 and 4.9 MW, compared to 1.9 MW at the lower airflow. Peak CO and CO_2 concentrations were higher, and minimum O_2 concentrations were lower at the 1.3-m/s airflow, since the higher airflow at 4.2 m/s acted to dilute the CO and CO_2 concentrations and increase the O_2 concentration.

Comparison of Sprinkler Configurations

Experiments were conducted using 100 °C, standard-response, pendent sprinklers installed according to Federal regulations for sprinkler installations in belt drive areas, where the sprinklers were installed above and between the belts on 2.4-m centers, and according to NFPA guidelines for sprinkler installations in underground bituminous coal mines, where the sprinklers were installed only above the top belt, on 3.0-m centers. The experiments were conducted at airflows of 1.1 and 4.6 m/s and 1.3 and 4.2 m/s, respectively. (See tables 2 and 3.)

In the experiments at the lower airflows, the sprinkler located directly above the tail pulley was the only sprinkler to activate in both design installations (Federal regulations and NFPA-123 guidelines). As shown in tables 2 and 3, the sprinkler was able to control and extinguish the fires, with limited belt damage.

In the experiment at the higher airflows using the design with sprinklers located above and between the belts, the sprinkler located between the belts, 2.4 m downstream, activated at a heat release rate of 1.3 MW. This sprinkler alone was able to control and extinguish both the top and bottom belt fires. The fire had a peak heat release rate of 3.7 MW, with 2.5 m of the top belt and 1.2 m of the bottom belt consumed by the fire. In the experiments at the higher airflow, excluding the test where the waterflow was interrupted, with sprinklers located only above the top belt, the sprinkler located 3.0 m downstream activated at a much higher average heat release rate, 2.5 MW. An average peak heat release rate of 4.9 MW was observed, and an average of 2.2 m of the top belt and 2.4 m of the bottom belt were consumed.

The results at the higher airflows indicate that both sprinkler installations were effective in extinguishing this type of incipient conveyor belt fire under these conditions. However, in the experiments using the NFPA-type installation, the sprinkler activated at a significantly higher heat release rate, allowing a larger peak heat release rate and slightly more belting to be consumed. The design with sprinklers above the top belt and between the top and bottom belt provides a higher degree of protection.

PROPAGATING CONVEYOR BELT FIRES

100 °C, Standard-Response Sprinklers

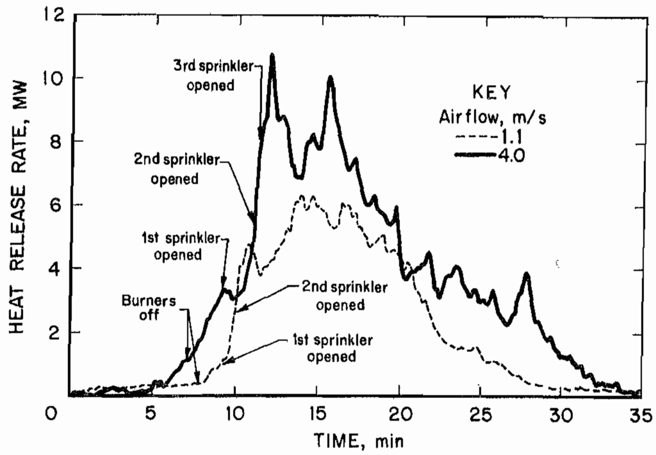
In the experiment at the 1.1-m/s airflow using standard-response, pendent-type sprinklers, the belting was ignited in 8.0 min. The heat release rate, shown in figure 8, when the burners were turned off was 0.4 MW. The sprinkler located above the top belt, 10.4 m downstream, activated at 9.3 min, just 1.3 min after the burners were turned off. At that time, the heat release rate was 1.1 MW and the fire had propagated 1.2 m along the bottom belt. The fire had not yet propagated out of the ignition area along the top belt.

The fire propagated very quickly along the top belt, reaching the belt thermocouple 4.9 m downstream at 10 min, a rate of 4.5 m/min. At the same time, the flame front had propagated to between the thermocouples located 1.2 and 2.4 m downstream on the bottom belt, a rate of 0.5 m/min. At 10 min, the sprinkler located above the top belt 12.8 m downstream opened. At that time, the heat release rate was 3 MW.

The flames continued to propagate along the top and bottom belts, both at a rate of 0.5 m/min. The flame front on the top belt reached the water spray 7.9 m from the ignition area at 16 min, and further propagation along that belt was stopped. The bottom belt flame propagation lagged behind the top belt, so that water from the top sprinkler ran off the top belt onto the bottom belt. The bottom belt flame front reached the water 7.6 m from the ignition area at 19.5 min, and flame propagation was stopped along the bottom belt.

The heat release rate climbed to 6 MW at 14 min, where it remained until the flame propagation was halted by the water discharge. The CO and CO_2 concentrations peaked at 2,000 ppm and 2.9 vol pct, respectively, and the O_2 concentration dropped to 16.6 vol pct at 14 min. These data are shown in table 4. The heat release rate and CO

Figure 8



Heat release rates for propagating fires using 100 °C, standard-response sprinklers.

and CO and CO_2 concentrations then fell, as the O_2 concentration rose, over the next 10 min, when the experiment was stopped. The belting that had been involved in the fire continued to burn during that time. In total, 7.9 m of the top belt and 7.6 m of the bottom belt were consumed.

In the experiment at the 4.0-m/s airflow using standard-response, pendent sprinklers, the burners were turned off at 7.5 min. The flames had propagated 1.8 m along the bottom belt, while the top belt flames had not yet propagated out of the ignition area. The heat release rate at that time, shown in figure 8, was 1.8 MW. At 9.5 min, the sprinkler, located above the top belt, 10.4 m downstream, activated. The heat release rate was 3.0 MW, and the flame front along both the top and bottom belt had reached 2.4 m. The sprinkler above the belt, 12.8 m downstream, activated at 11.0 min, followed by the top sprinkler 14.2 m downstream at 11.7 min.

A total of 8.8 m of the top belt and 10.7 m of the bottom belt were consumed in the fire. The flame propagation rate along the bottom belt was 0.7 m/min over the first 8.5 m. The flame continued to propagate to 10.7 m over the next 8 min. The flame propagation rate along the top belt averaged 1.4 m/min, twice that of the bottom belt. The heat release rate peaked at 10.8 MW at 12.2 min, when 5.0 m of the bottom belt and 6.1 m of the top belt were involved in the fire. Maximum CO and CO_2 concentrations of 1,300 ppm and 1.7 vol pct, respectively, and a minimum O_2 concentration of 18.4 vol pct, shown in table 4, were also observed at that time. At 15.5 min, the heat release rate began to fall steadily. At 35 min, all visible flames were extinguished and the experiment was terminated.

Table 4.—Experimental data for propagating belt fires

Sprinkler type and airflow, m/s	Flame spread rate, m/min		Heat release rate, MW		Peak conc,		Minimum O_2 conc, vol pct	Belt consumed, m	
	Top belt	Bottom belt	When first sprinkler opened	Peak	CO, ppm	CO_2, vol pct		Top	Bottom
100 °C, standard response:									
1.1	[1]4.5	0.5	1.1	6.0	2,000	2.9	16.6	7.9	7.6
	[2]0.5	—	—	—	—	—	—	—	—
4.0	1.4	0.7	3.0	10.8	1,300	1.7	18.4	8.8	10.7
74 °C, fast response:									
1.1	0.7	0.3	0.6	5.3	2,200	2.8	16.9	7.6	6.7
4.0	[1]2.1	[3]1.4	1.9	8.1	970	1.4	18.9	7.6	8.8
	[2]0.1	[4]0.3	—	—	—	—	—	—	—

Conc Concentration.
[1]Between thermocouples located at 1.2 and 4.9 m.
[2]Between thermocouples located at 4.9 and 7.3 m.
[3]Between thermocouples located at 1.2 and 7.3 m.
[4]Between thermocouples located at 7.3 and 8.6 m.

NOTE.—Dashes indicate no data.

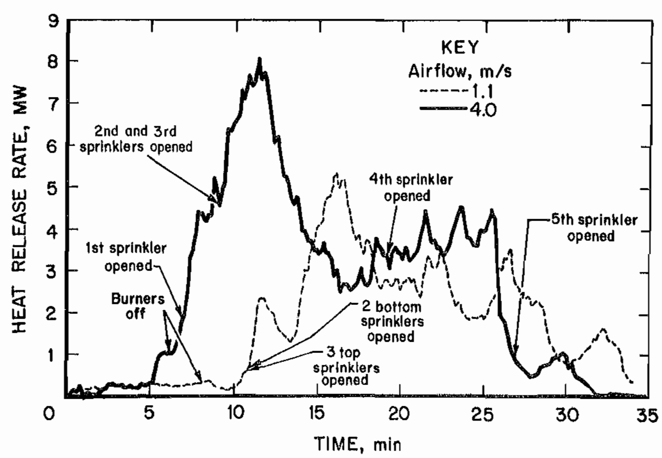
The water spray from the top sprinkler 10.4 m downstream from the tail pulley extended to 2.2 m upstream, indicating that the fire burned just 0.6 m past where the water spray reached on the top belt. The fire along the bottom belt was able to burn 1.9 m past the top belt and was eventually extinguished by the water from the top sprinklers. No sprinklers between the belts opened in this experiment, even though the bottom belt fire burned a total of 10.7 m and a sprinkler was located between the belts at 10.4 m. The thermocouple located next to the sprinkler reached a maximum temperature of just 80 °C at 26 min. The thermocouple located near the sprinkler between the belts at 12.8 m reached a maximum temperature of 180 °C at 26 min, but that sprinkler did not open either. It is likely that the sprinkler did not reach temperatures high enough to activate it because of water runoff from the top belt onto that sprinkler, even though the air near the sprinkler reached a temperature well above the activation temperature of the sprinkler.

74 °C, Fast-Response Sprinklers

In the experiment at the 1.1-m/s airflow using the 74 °C, fast-response, horizontal sidewall sprinklers, the belting was ignited at 8.1 min. The heat release rate at that time, shown in figure 9, was 0.3 MW. At 10.8 min, the three sprinklers located above the top belt, 10.4, 12.8, and 15.2 m downstream activated, at a heat release rate of 0.6 MW. At 10.9 min, two sprinklers located 10.4 and 12.8 m downstream between the belts opened. The heat release rate of the burning belts when the bottom sprinklers opened was 0.8 MW.

The belt thermocouples indicated that the flame front was just beginning to propagate along the top belt when the sprinklers opened, but had not reached the thermocouple at 1.2 m. The flame had propagated to the thermocouple located 1.2 m from the ignition area on the bottom belt. The heat release rate increased to 2.5 MW just after the sprinklers opened and then fell to 1.2 MW. There was a delay in the flame propagation along the top and bottom belts until about 13.5 min. At that time, the flame front moved down the top belt at a rate of 0.7 m/min until the flame reached 4.8 m and then slowed to about 0.1 m/min over the next 2.4 m. The flame propagation rate along the bottom belt was 0.3 m/min. A total of 7.6 m of top belting and 6.7 m of bottom belting were consumed.

Figure 9



Heat release rates for propagating fires using 74 °C, fast-response sprinklers.

Water discharge measurements showed that the sprinklers wetted the top belting to 6.7 m from the tail pulley and the bottom belting to 8.8 m from the tail pulley. A peak heat release rate of 5.3 MW was observed at 16.2 min. At that time, the flames had propagated 4.8 m along the top belt and 3.0 m along the bottom belt. Peak CO and CO_2 concentrations of 2,200 ppm and 2.8 vol pct, respectively, and a minimum O_2 concentration of 16.9 vol pct, shown in table 4, were also observed at that time.

As was the case in the experiment with the 100 °C, standard-response sprinklers, the top belting was consumed faster than the bottom belting, resulting in water runoff from the top belt onto the bottom belt. Thus, even though the top sprinklers wetted more belting upstream from the sprinklers, less bottom belting was consumed. The data on flame propagation rates and the amount of belting consumed indicate that the water spray slowed the flame propagation rates, but the flame was able to propagate through at least 1 m of wetted belting.

In the experiment at the 4.0-m/s airflow using the 74 °C, fast-response, horizontal sidewall sprinklers, the bottom belting was ignited at 6.0 min. At that time, the heat release rate, shown in figure 9, was 1.0 MW and the fire had reached the thermocouple at 1.2 m on the bottom belt. The top belt was not yet ignited. The sprinkler located above the top belt, 10.4 m downstream, activated at 7.0 min, 1 min after the burners were turned off. The heat release rate at that time was 1.9 MW. The sprinklers 12.8 and 15.2 m downstream opened 2.1 min later, at 9.1 min. Two sprinklers located between the belts also opened in this experiment. The sprinkler located 10.4 m downstream opened at 19.4 min, and the sprinkler 12.8 m downstream opened at 27 min.

The flame propagation rate along the top belt was 2.1 m/min over the first 4.9 m of belting. The rate then slowed to 0.1 m/min from 4.9 to 7.3 m. The flame front reached the thermocouple at 7.3 m at 24 min. The flame propagation along the bottom belt averaged 1.4 m/min over the first 7.3 m, decreasing to 0.3 m/min from 7.3 to 8.6 m.

The heat release rate peaked at 8.1 MW at 11.5 min, then fell to about 2.4 MW from 16 to 18 min. The heat release rate then rose gradually to 4.7 MW over the next 10 min before falling to zero. Peak CO_2 and CO concentrations of 1.4 vol pct and 970 ppm at 11.7 and 10.5 min, respectively, were observed. A minimum O_2 concentration of 18.9 vol pct was observed at 11.8 min. These data are shown in table 4. A total of 7.6 m of the top belt and 8.8 m of the bottom belt were consumed in this experiment. Water discharge measurements showed that the water spray from the sprinkler reached to 7.3 and 8.8 m on the top and bottom belts, respectively.

Effect of Ventilation on Extinguishment

The results showed that the sprinkler system was able to stop flames from propagating past the system at both 1.1- and 4.0-m/s airflows, at these test conditions, using both the 100 °C, standard-response sprinklers and the 74 °C, fast-response sprinklers. In all the experiments, the propagating flame front was extinguished when the flames reached the water spray from the sprinklers. However, the belting preceding the water sprays burned until the belting was consumed.

In the experiments using the 100 °C, standard-response sprinklers, the most significant effect of ventilation was seen in the heat release rate at which the first sprinkler activated. At 1.1 m/s, the first sprinkler opened at a heat release rate of 1.1 MW, compared to a 3.0-MW fire before the first sprinkler opened at 4.0 m/s. This difference was likely due to the cooling effect of the ventilating air on the combustion gases.

The effect of the ventilation on the upstream water distribution pattern from the top sprinklers was minimal. Measurements made under nonfire conditions showed that the water spray at 1.1 m/s, with two top sprinklers open, extended 2.5 m upstream from the sprinkler located at the 10.4 m location, reaching the top belting 7.9 m from the center of the tail pulley. At 4.0 m/s, the water spray from the three top sprinklers opened extended 2.2 m upstream, or 8.2 m from the center of the tail pulley, a difference of only 0.3 m compared to the water spray at the 1.1-m/s airflow. Water coverage data for pendent-type sprinklers from reference 10 showed an upstream coverage distance of 3.6 m at 0.7-m/s airflow compared to an upstream coverage distance of 2.4 m at the 4.0-m/s airflow. However, in those experiments, the surface above the sprinkler was a flat plywood roof, whereas in these experiments, the sprinkler was located below an arched ceramic fiber insulation covered roof. The ceramic blanket may have acted to reduce water deflection, limiting the coverage distance somewhat at the lower airflow.

The difference in the amount of top belting consumed in the experiments was also small. At the 1.1-m/s airflow, 7.9 m of the top belt was consumed, compared to 8.8 m of the top belt at 4.0 m/s. At the lower airflow, the amount of top belt consumed coincided with the upstream water coverage from the top sprinkler on the top belt under nonfire conditions. At the higher airflow, however, 0.6 m of belt that was wetted in the water distribution test at this airflow was consumed. In reference 9, it was reported that airflows greater than 2.5 m/s were capable of affecting water droplet size, producing smaller diameter water droplets. Thus, the droplets at the edge of the upstream water spray may have been small enough to be vaporized by the heat from the fire before hitting the belting.

There was a more significant difference in the amount of bottom belting consumed at each airflow, 7.6 m at 1.1 m/s compared to 10.7 m at 4.0 m/s. In both experiments, the flame propagation rate of the top belt exceeded that of the bottom belt. At 1.1 m/s, the bottom belt flame propagation was stopped when the bottom belt flame front reached the water runoff from the top belt. At 4.0 m/s, however, the flames along the bottom belt were able to burn past the top belt an additional 1.9 m.

The airflow also affected the peak heat release rate, maximum CO_2 and CO concentrations, and minimum O_2 concentrations observed during the experiments. A significantly larger peak heat release rate was observed at the higher airflow, 10.8 MW compared to 6.0 MW, while peak CO_2 and CO concentrations were lower and the minimum O_2 concentration was higher at the higher airflow.

Similar results were observed in the experiments with the 74 °C, fast-response sprinklers. At the 1.1-m/s airflow, the first sprinkler opened at a heat release rate 0.6 MW, compared to 1.9 MW at the 4.0-m/s airflow. Again, the effect of ventilation on the upstream water coverage was small. At the 1.1-m/s airflow, the top sprinkler water coverage extended 3.7 m upstream, 6.7 m from the tail pulley, compared to 3.4 m, or 7.0 m from the tail pulley at the 4.0-m/s airflow. This is in poor agreement with the results from reference 9, which showed a difference in coverage distance of 2.4 m at similar airflows for the directional sprinklers. In these experiments, the two sprinklers between the belts at 10.4 and 12.8 m opened. The water coverage extended just 1.5 m upstream at both airflows because of water deflection by the idler arms on the belt structure.

The amount of top belting consumed by the fire was the same at both airflows, 7.6 m, apparently since the water coverage was nearly the same at both airflows. At 1.1- and 4.0-m/s airflows, 0.6 and 0.9 m, respectively, of belting that was wetted in the coverage tests were consumed by fire. The amount of bottom belting consumed was significantly more at the higher airflow, 8.8 m, compared to 6.7 m at the lower airflow. At the higher airflow, the bottom belt damage coincided with the water coverage from the bottom sprinklers. However, at the lower airflow, about 2 m less of belting was consumed, even though the water coverage from the bottom sprinklers did not extend that far upstream. Therefore, it appears that the bottom belting was extinguished by water spray or runoff from the top sprinklers.

The airflow also affected the peak heat release rate, maximum CO and CO_2 concentrations, and minimum O_2 concentrations observed during these experiments. The peak heat release rate at 1.1 m/s was 5.3 MW, compared to 8.1 MW at 4.0 m/s, while peak CO and CO_2 concentrations were lower and the minimum O_2 concentration was higher at the higher airflow.

These results show that the sprinkler system was effective in stopping propagating conveyor belt fires at airflows up to 4.0 m/s with this belting configuration. The data indicated that at the higher airflow, significantly higher heat release rates were required to open the sprinklers compared to the lower airflows. In the experiments at the higher airflow, higher peak heat release rates were observed and more belting was consumed than at the lower airflows. However, the peak concentrations of CO and CO_2 were lower because of dilution, and the minimum O_2 concentration was higher because of the higher air volume, at the higher airflow.

Effect of Sprinkler Type on Extinguishment

The most significant effects of sprinkler type on extinguishing effectiveness were seen in the smaller heat release rate required to activate the sprinklers with the lower activation temperature and RTI value, and the number of sprinklers that opened. In addition, the directional sprinklers provided a slightly larger water coverage area upstream of the sprinklers.

At the 1.1-m/s airflow, five of the 74 °C, fast-response sprinklers opened, three above the top belt and two between the top and bottom belts, compared to two of the 100 °C, standard-response sprinklers. The first 74 °C, fast-response sprinkler opened at a heat release rate of 0.6 MW, compared to 1.1 MW in the experiment using the 100 °C, standard-response sprinklers. However, since the belting burned until it reached the water spray from the sprinklers, the peak heat release rate, CO and CO_2 values, and minimum O_2 concentrations were essentially the same in each experiment at this airflow.

At the 1.1-m/s airflow, the use of the fast-response, directional sprinklers resulted in slightly less belting being consumed, 7.3 and 6.7 m for the top and bottom belts, respectively, compared to the results with the standard-response, pendent-type sprinklers, where 7.9 and 7.6 m, respectively, of top and bottom belts were consumed. The water coverage of the directional sprinklers along the top belt extended 1.2 m further upstream than the pendent sprinklers, resulting in 0.6 m less belt being consumed. The pendent sprinklers along the bottom belt did not open, whereas two of the directional sprinklers opened in the experiments at 1.0 m/s. This resulted in 0.9 m less belting being consumed in the test with the directional sprinklers.

In the experiments at the 4.0-m/s airflow, it appeared that the most significant difference was in the heat release rate required to open the sprinklers. The first fast-response sprinkler opened at a heat release rate of 1.9 MW, compared to 3.0 MW in the experiment with the standard-response sprinkler.

The earlier activation of the fast-response sprinklers was not significant in the extinguishment of the fires, however, again because the flame front must reach the water discharge before it can be extinguished. The limiting factor was the belt coverage of the water discharge. The horizontal sidewall sprinklers discharged their water 1.2 m further upstream on the top belt compared to the pendent-type sprinkler, thus stopping the flame propagation of the top belt 1.2 m sooner. As was the case in the tests at 1.1 m/s, no 100 °C, standard-response sprinkler opened between the belts at 4.0 m/s, whereas two of the fast-response, directional sprinklers opened at this airflow. This resulted in 1.9 m less belt being consumed in the experiment with the fast-response sprinklers.

In summary, it appeared that the most significant differences in these experiments were the activation of the two 74 °C, fast-response sprinklers between the belts at both airflows and the smaller heat release rate required to activate the sprinklers in the experiments with the 74 °C, fast-response sprinklers. The 100 °C, standard-response, pendent sprinklers that activated above the top belt were able to stop the propagating belt fires in this belt and sprinkler system configuration. However, the ability of the top sprinklers to extinguish the fires propagating along both the top and bottom belts appeared to be dependent on the faster flame propagation rates of the top belts, which allowed water from the top sprinklers to contact the bottom belt prior to the flame front reaching that point. The lower activation temperature and response characteristics of the directional sprinklers provide a somewhat greater safety margin.

COMPARISON WITH PREVIOUS STUDIES

In Warner's study (*8*), 6.1-m single and double strands of PVC and nonfire-resistant rubber conveyor belting were ignited by a propane burner, with sprinklers installed above the top belt at various intervals upstream and downstream from the ignition point. The experiments were conducted at airflows of 0, 0.6, and 1.8 m/s. The results indicated that a single branch line sprinkler system using 100 °C, pendent-type sprinklers above the top belt provided adequate belt drive protection at those airflows. Warner also concluded that at air velocities greater than 1.3 m/s, only sprinklers with activation temperatures less than 107 °C should be used and sprinklers should be spaced no greater than 1.2 m apart.

The incipient fire experiments with sprinklers mounted above the top belt, in accordance with NFPA standards for sprinkler installation in underground bituminous coal mines (*15*), most closely approximated the tests conducted by Warner (*8*). In this study, double strands of conveyor belting extending 7.6 m downstream from the ignition point were used. Sprinklers were installed above the ignition point and at 3.0-m intervals downstream. The experiments were conducted at 1.3- and 4.2-m/s airflows, compared to 0, 0.6, and 1.8 m/s in Warner's study. The results of the test at the 1.3-m/s airflow showed that the sprinklers mounted above the top belt were able to extinguish the incipient conveyor belt fire, in agreement with Warner.

The experiments in this study at the 4.2-m/s airflow also showed that a single branch line system using 100 °C, pendent-type sprinklers above the top belt at 3.0-m intervals was effective in extinguishing incipient conveyor belt fires. However, the results of the experiments with sprinklers above the top belt compared to those with sprinklers between the top and bottom belt indicated that the configuration with sprinklers between the belts provided a higher degree of safety.

The propagating belt fire experiments in this study at 1.1 m/s most closely resembled those conducted by Mitchell (*6*). In Mitchell's tests, 30.5-m lengths of conveyor belting in a double-strand configuration were ignited at an airflow of 1.0 m/s and allowed to propagate. Sprinklers were located at various intervals above the top belt and between the top and bottom belts. Information on the activation temperatures of the sprinklers was not available. The results showed that the sprinklers were able to stop flame propagation at that airflow. However, there was no data to indicate what effect higher airflows would have on the sprinkler system's effectiveness.

The results from this study at the lower airflows were in agreement with Mitchell's (*6*). At a 1.1-m/s airflow, both the 100 °C, standard-response, pendent-type sprinklers and the 74 °C, fast-response, directional sprinklers located above the top belt and between the top and bottom belt effectively stopped flame propagation when the flames reached the water spray. This study also evaluated the effectiveness of these sprinklers to control a propagating belt fire at a 4.0-m/s airflow. The results showed that they were also effective in stopping the flame propagation along the conveyor belts for the lengths of belting used in this study.

CONCLUSIONS

This study was conducted to evaluate the effectiveness of automatic water sprinkler systems to control and extinguish incipient and propagating conveyor belt fires under ventilated conditions. Experiments were conducted to simulate incipient belt fires originating in a conveyor drive area at airflows of 1.1 and 4.0 m/s. Sprinklers were installed in accordance with Federal standards, where sprinklers are installed above and between the belts at 2.4-m intervals, and in accordance with NFPA standards, where sprinklers are located only above the top belt at 3.0-m intervals. Experiments were also conducted to simulate a propagating conveyor belt fire that runs into a sprinkler system installed downstream from the fire's origin. In these tests, sprinklers were installed above and between the belts at 2.4-m intervals and at airflows of 1.1 and 4.6 m/s.

The results indicated that each type of sprinkler installation was able to control and extinguish the incipient fires under these experimental conditions. In tests using 100 °C, standard-response sprinklers in both system configurations, the results showed an increased effectiveness at the lower airflows in terms of when the first sprinkler was activated and the peak heat release rate was observed. When the 74 °C, fast-response, directional sprinklers were installed according to the Federal standards, the sprinkler system showed a slightly improved performance at the lower airflow.

In the propagating conveyor belt experiments, the results indicated that the sprinkler system could stop flame propagation along the belts under these experimental conditions, for fires up to 10.8 MW. However, at the higher airflow, 4.0 m/s, the sprinklers activated at significantly higher heat release rates than at the lower airflow. This resulted in larger peak heat release rates and more belting consumed at the higher airflow.

Experiments to compare the effectiveness of sprinkler type in extinguishing propagating belt fires showed an increased effectiveness for the directional sprinklers compared to the pendent sprinklers because of the increased upstream coverage area of the water discharge. Activation temperature and response time appeared to have little effect in the extinguishment of the belts since both the 74 °C, fast-response and the 100 °C, standard-response sprinklers activated well in advance of the flame front reaching the sprinkler discharge.

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APPENDIX A.—HEAT RELEASE RATES

The heat release rates used in this report were calculated by three different methods. The first two methods used measurements of (1) the CO and CO_2 produced, and (2) the O_2 consumed. The average of these two methods is reported as the heat release rate in all the extinguishment experiments. The third method was based on the average change in temperature of the exit gases. This method was used to determine the heat release rate of the initial fires where there was no attempted extinguishment, and CO, CO_2, and O_2 data were not available.

TOTAL HEAT RELEASED USING COMBUSTION GASES CO AND CO_2

The first method requires the total heat of combustion and the mass fraction of carbon in the fuel, as well as the mass of CO and CO_2 generated per second. The total heat release rate, Q_{TOTAL}, in kilowatts, using the CO and CO_2 produced can be calculated from:

$$Q_{TOTAL} = \left[\frac{H_C}{k_{CO_2}}\right] \times \dot{M}_{CO_2} + \left[\frac{H_C - k_{CO}H_{CO}}{k_{CO}}\right] \times \dot{M}_{CO}, \qquad \text{(A-1)}$$

where H_C = total (net) heat of combustion of fuel, 23.8 kJ/g;

k_{CO_2} = stoichiometric yield of CO_2, g/g, = $3.67 \times X_c$, where X_c = carbon mass fraction of belt, 0.5552;

$\dot{M}_{CO_2}$ = generation rate of CO_2 from fire, g/s, = $1.97 \times 10^{-3}\ v_eA_o\ \Delta CO_2$, where v_e = exit air velocity, m/s; A_o = entry cross-sectional area, 7.53 m^2; and ΔCO_2 = CO_2 produced by fire, ppm;

k_{CO} = stoichiometric yield of CO, g/g, $2.33 \times X_c$;

H_{CO} = heat of combustion of CO, 10.1 kJ/g;

and $\dot{M}_{CO}$ = generation rate of CO from fire, g/s, = $1.25 \times 10^{-3}\ v_eA_o\ \Delta CO$, where ΔCO = CO produced by fire, ppm.

Substitution of the above parameters into equation A-1 gives:

$$Q_{TOTAL} = \left[1.48 \times 10^{-2} \left(\frac{H_C}{k_{CO_2}}\right) \Delta CO_2 + 9.41 \times 10^{-3} \left(\frac{H_C - k_{CO}H_{CO}}{k_{CO}}\right) \Delta CO\right] \times v_e. \qquad \text{(A-2)}$$

TOTAL HEAT RELEASED USING O_2 CONSUMED

The second method assumes a constant heat release of 13.1 kJ/g of O_2 consumed. This value is an average based on the combustion of various polymeric and natural carbonaceous materials in sufficient O_2, at least 12 to 16 pct in air (*16-17*). The total heat release rate in kilowatts can be calculated from:

$$Q_{TOTAL} = 13.1\ \frac{kJ}{g} \times \dot{M}_{O_2}, \qquad \text{(A-3)}$$

where $\dot{M}_{O_2}$ = O_2 consumption rate from fire, g/s.

The O_2 consumption rate is given by:

$$\dot{M}_{O_2} = 1.43 \times 10^{-3} v_e\ A_o\ \Delta O_2, \qquad \text{(A-4)}$$

where ΔO_2 = O_2 used, ppm.

Equation A-3 becomes, upon substitution of the fixed parameters,

$$Q_{TOTAL} = 0.141\ v_e\ \Delta O_2,\ \text{kW}. \qquad \text{(A-5)}$$

TOTAL HEAT RELEASED USING EXIT GAS TEMPERATURES

The third method assumes that the heat produced by combustion is used to heat the tunnel exit air temperature, T_{EXIT}, above ambient temperature, T_0, and that energy losses to the surrounding walls or steel belt support structure can be neglected. This heat release rate can be calculated from:

$$Q_{TOTAL} = C_P\,\rho_0\,v_e\,A_o\,\Delta T, \qquad \text{(A-6)}$$

where C_P = heat capacity of air, 1.088×10^{-3} kJ/(g•°C),

$\rho_0 = 1{,}200\ \frac{g}{m^3}$,

and $\Delta T = T_{EXIT} - T_0$, °C.

Substitution of these values into equation A-6 for the fixed parameters gives:

$$Q_{TOTAL} = 9.83\ v_e\,\Delta T. \qquad \text{(A-7)}$$

APPENDIX B.—FLAME PROPAGATION RATE

The flame propagation rates for the propagating conveyor belt fires were determined using the method described in reference 17. The rate was calculated from the time-temperature traces obtained from the thermocouples along the centerline of the top and bottom belts. The advancing flame front was considered to have reached a thermocouple position when the thermocouple temperature reached 310 °C and continued to rise. The flame propagation rates were measured from the time the flame front reached the thermocouple at 1.2 m until the flame front reached the last thermocouple that was not wetted by the water spray. The rates were determined by plotting the flame position versus time and drawing the best straight line through the points. The slope of the line is the flame propagation rate in meters per minute.

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