

Fire Research Note

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THE PERFORMANCE OF AUTOMATIC SPRINKLER SYSTEMS

PART I - THE EFFECT OF CEILING HEIGHT, RATE OF FIRE DEVELOPMENT, AND SPRINKLER POSITION ON RESPONSE TO A GROWING FIRE

by

M. J. O'DOGHERTY and R. A. YOUNG

FIRE RESEARCH Station

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MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE JOINT FIRE RESEARCH ORGANIZATION

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SUMMARY

This report describes experiments in which wooden crib fires, developing at various rates, were burnt below a joisted ceiling. Sprinkler heads were mounted in a bay between joints and also below a joist. Continuous measurements were made of air temperature and sprinkler bulb temperature during the fire development. The size of fire at sprinkler operation was determined for a range of ceiling heights, horizontal distances of sprinklers from the fire axis, and depths of sprinkler mounting below the soffit of the ceiling or joist.

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1. Introduction

The work described in this Note forms part of an investigation into the operation of sprinkler systems against solid fuel fires. A sprinkler system has a dual role in that it has to detect the fire and also to control its spread. These functions must be considered jointly when examining the arrangement of sprinkler heads which will lead to an optimum design for the system, and the present work is aimed at establishing some general principles of system design.

The first part of the programme, which is described in this Note, was concerned with the function of a sprinkler system in detecting a fire. A number of factors which can influence the size of fire detected by a sprinkler head were examined. These factors were the height of ceiling, the horizontal distance of the sprinkler head from the source of the fire, the depth of the sprinkler beneath the ceiling, and the rate at which the fire develops from a small source. The effect of these factors was examined, with the heads mounted in a ceiling bay between two joists, and also with the heads mounted directly beneath a joist.

2. Experimental procedure

2.1. Preliminary experiments

The sprinklers used in the work were of the glass bulb type, which are generally used in this country. Preliminary experiments were made to determine the temperature recorded by a thermocouple, attached to the surface of a sprinkler bulb, at the moment at which the bulb burst. A sprinkler bulb, rated at 68°C (155°F) (the rating generally used in this country), was immersed in a water bath with the hot junction of a 40 s.w.g. chromel/alumel thermocouple attached to its The temperature of the bath was raised at a rate of 1°C per min. It surface. was found that the mean value of the surface temperature recorded at the instant of bursting of the bulb was approximately 72°C. (162°F). A similar experiment was performed in a wind tunnel, with rates of rise of air temperature of $1^{\circ}C$ per min. and 30°C per min., and it was found that the temperature recorded on bursting of the bulb did not differ significantly from 72°C. The most consistent results were obtained when the thermocouple hot junctions were attached to the sides of the bulb, in a plane of symmetry normal to the direction of the incident air stream.

Sprinklers having bulbs with a temperature rating of $260^{\circ}C$ ($500^{\circ}F$) were used in the main experiments, to avoid the inconvenience of bulbs bursting during the course of the work, after tests at similar rates of rise of air temperature had shown that there was no appreciable difference in the thermal properties of bulbs with ratings of $68^{\circ}C$ and $260^{\circ}C$.

2.2. Experimental variables

The variables examined in the experiments were the height of the ceiling, the distance of the sprinkler from the vertical axis of the fire, the depth of the sprinkler beneath the ceiling, and the rate of fire development. The experiments were conducted in a laboratory of plan area 150 ft. x 50 ft., and 40 ft., in height. The ceiling had joists (1 ft. in width, and $19\frac{1}{2}$ in. deep, situated at 15 ft. centres) across the width of the laboratory. Two series of experiments were made, the first with sprinklers mounted under a joist, and the second with sprinklers mounted directly under the ceiling along the centre line of a bay between adjacent joists. Figure (1) is a diagram of the general experimental arrangement, and details of the range of the variables are given below.

(i) Height of ceiling

Four heights were employed, measured from the base of the fire to the ceiling of the laboratory (between the joists); the nominal heights were 36, 28, 20 and 12 ft. Measurements at the three lower ceiling heights were made by supporting the fire on a platform at the appropriate heights.

(ii) Horizontal distance of sprinkler from fire axis

The top row of sprinklers was attached to a mounting member which was positioned either in the ceiling bay, or under a joist. The sprinkler heads were spaced at intervals of 5 ft, with the first sprinkler situated immediately above the point of origin of the fire; the other sprinklers were at 5, 10, and 15 ft from a vertical axis through the point of origin (the fire axis).

(iii) Depth of sprinkler beneath ceiling

Three levels of sprinklers were used, these being arranged so that the deflector plates were 8, 16 and 24 in below the ceiling or the underside of the joist. The yokes of the lower sprinklers were screwed to thin brass strips, which were themselves screwed to the yoke of the uppermost sprinkler, as shown in Plate (1).

(iv) Rate of fire development

Three designs of wooden crib were employed $\binom{(1)}{}$, to give three different rates of fire development. The wood used was saw-finished softwood (Pinus Sylvestrie) of square section, which had been conditioned for a period of four weeks prior to burning, at 65°F and relative humidity 65 per cent. The mean moisture content by weight of wood samples taken during the experiments was 10.9 per cent, with a standard error of 0.25 per cent. The cribs were built on a 3 ft square base, the details of construction being as follows:-

	Stick size (in)	Spacing ratio	Number of layers
Fire A	· 1	1.5:1	32
Fire B	1	3:1	42
Fire C	0.5	8:1	96

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The number of layers quoted refers to the size of fire used at the 36 ft ceiling height. At lower ceiling heights the crib height was reduced so as to limit the maximum fire size, but this had no significant effect on the rate of fire development. The spacing ratio is the ratio of the distance between adjacent sticks to the stick width. The cribs detailed above are shown in Plate (2).

Each crib was ignited at the centre of the base from a small source, consisting of a shallow circular tray, containing approximately 30 cc of methylated spirits.

Figure (2) shows the rate of burning of each of the cribs, plotted against time from ignition. The rate of burning was obtained by weighing the crib continuously, and plotting its weight against time; the slope of the curve so obtained is the rate of weight loss, and represents the burning rate.

The slope of the curves shown in Figure (2) represents the rate of development of the fire, i.e. the rate at which the burning rate is changing. The fires develop relatively slowly in the early stages, the development then becoming much more rapid until a point of inflexion is reached, after which the rate of development falls off, at first slowly, and then more rapidly, until a maximum burning rate is reached. In the earlier stages when the rate of burning is between 45 per cent and 75 per cent of the maximum rate, the rate of development was found to be practically linear. The mean linear rates of development were 3.3, 8.7, and 25.8 Btu/s² for fires A, B, and C, respectively.

2.3. Temperature measurements

The air and bulb temperature measurements were made with 40 s.w.g. chromel/ alumel thermocouples, the cold junctions of which were maintained at O^oC in an The surface temperatures of all the sprinkler bulbs were measured, by ice bath. strapping the thermocouple hot junctions to the bulbs with fine copper wire. Air temperatures were measured adjacent to the sprinklers situated at 8 in below the ceiling and below the joist, at a position approximately $\frac{1}{2}$ in from the bulb, on the side of the sprinkler nearest to the fire. Compensating leads, using one common lead were brought to d.c. amplifiers, and the voltage outputs were recorded automatically on pen recorders. Switching units were used because of the large number of thermocouples (16), and one amplifier and recorder was used for each set of four thermocouples. A circuit diagram is given in Figure (3), and a typical temperature record is shown in Plate (3). Normally each thermocouple position was monitored at intervals of 36 s, but when temperatures were rising quickly, it was possible to record two out of each set of four thermocouples at intervals of 24 s.

3. Results

The air and bulb temperature rises were plotted against time directly from the temperature records. (Figs. 4 and 5). The form of the curves was identical to that of the burning rate of the fire plotted against time, as can be seen by comparing Figures (4) and (5) with Figure (2). The bulb temperature rise lags behind the air temperature rise because of the time constant of the bulb⁽²⁾.

The results were analysed by plotting the air temperature rise and the bulb temperature rise against the instantaneous rate of convective heat output of the fire, at various stages in its development.

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The rate of convective heat output of the fires was obtained by assuming that 75 per cent of the calorific value appeared as convected heat. This is an average figure for that generally assumed (70-80 per cent(3)), and was confirmed by some subsidiary measurements of the heat radiated from the burning cribs. Assuming a calorific value of 8000 Btu/lb for wood, a rate of burning of 1 lb/min produces a rate of convective heat output of 100 Btu/s (25.2 K cal/s).

3.1. Air temperature rise (8 in. below ceiling or joist)

3.1.1. Variation with rate of convective heat output

(a) Measurements on vertical fire axis

Typical results are shown in Figure (6). It was found that at a given rate of convective heat output, for all ceiling heights, the temperature rise was independent of the rate of fire development. This finding results from the small time lag required for the gaseous combustion products from the fire to rise to ceiling level.

The upward velocity of the hot gases, in a plume rising from a fire originating from a point source, is given approximately by \sqrt{gL} ⁽⁴⁾, where g is the acceleration due to gravity, and L is the flame height, and it was deduced that the velocity lay in the range 10-20 ft/s, except in the very early stages of fire development. Hence for practical purposes, the air temperature rise at any given time is dependent only on the burning rate of the fire, not on its rate of development. Any differences which do exist arise because of the inherent variability of the results, but they are not significant.

The relationship between the rise in air temperature, θ_a , and the rate of convective heat output of the fire, Q, was almost a linear one, and is represented by the equation:-

$$\theta_{a} = k_{1} Q^{0.89 \pm 0.021}$$
(1)

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where k₁ depends on ceiling height, and whether the sprinkler is mounted in the bay or under the joist.

The exponent of Q is a mean value for all ceiling heights, and for sprinklers mounted both in the bay and under the joist.

At ceiling heights of 12 ft. and 20 ft. there was a larger rise in air temperature under the joist than in the bay at any given rate of burning, but for the 28 ft. and 36 ft. ceilings there was no significant difference. This effect is largely due to the fact that the depth of the joist represents a relatively small proportion of ceiling heights of 28 ft. and 36 ft. but is a significant proportion of 12 ft and 20 ft.

(b) <u>Measurements at 5, 10, and 15 ft from vertical fire axis</u>

For the measurements made in the bay, the temperature rise, at a given_rate of convective heat output, was independent of the rate of fire development. A similar result was found for the measurement below the joist at ceiling heights of 28 ft. and 36 ft. but at heights of 12 ft and 20 ft. the rise in temperature was smaller, the more rapidly the fire developed, the effect being more pronounced for the 12 ft. ceiling. Typical results are given in Figure (7). The latter effect probably arises because of the way in which the layer of hot gases builds up at ceiling level. On high ceilings a thick layer is established quickly for all three rates of fire development, because of the large volume flow rate of hot gas arriving at ceiling level(3) and the temperature gradient near the ceiling is not very dependent on development rate at a particular rate of convective heat output. Under low ceilings, however, the hot gas layer is much thinner, at a given rate of convective heat output, because of the smaller volume flow rate of hot gas The more rapid the rate of fire development, the arriving at the oeiling. smaller is the total volume of hot gas produced in the time taken to attain The result is a thinner layer of hot gas and a a given heat output. greater temperature gradient near the ceiling for more rapidly developing fires, with a consequently lower temperature rise at a given point below This effect was absent for the measurements in the bay, the ceiling. presumably because of the more rapid establishment of the hot gas layer, due to its conservation between the joists.

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The following relationship was established between air temperature rise and rate of convective heat output:-

$$\theta_a = k_2 Q^{0.90 \pm 0.015}$$
 (2)

This equation holds for all the measurements made in the bay, and for those made under the joist at ceiling heights of 28 ft. and 36 ft; the exponent of Q is a mean value for distances of 5, 10, and 15 ft. from the fire axis. The value of k_2 depends on ceiling height, distance from the fire axis, and whether the sprinklers are in the bay or under the joist.

The measurements taken under the joist, at ceiling heights of 12 ft. and 20 ft. show that the temperature rises recorded early in the fire were very small, because of the relatively low position of the thermocouples in the hot gas layer. The result of the low temperature rises early in the fire history, was that the rate of increase of temperature rise with rate of convective heat output was apparently more rapid at these ceiling heights. The effect was given emphasis by the smaller range of heat outputs employed at these heights. The following relationships were found:-

20 ft. ceiling (under joist) $\theta_a = k_3 Q^{1.04 \pm 0.049}$ (3) 12 ft. ceiling (under joist) $\theta_a = k_4 Q^{1.20 \pm 0.026}$ (4)

The exponents of Q are mean values for all rates of fire development, and for 5, 10, and 15 ft. from the fire axis. The constants of proportionality, k_3 and k_4 depend on distance from the fire axis and rate of fire development.

A comparison of the results in the bay with those under the joist, shows that there was a greater temperature rise in the bay, for a given rate of convective heat output. The difference was greatest at low ceiling heights for the most rapidly developing fire, and arises because the hot gas layer builds up rapidly in the bay formed between the joists.

3.1.2. Variation with ceiling height

(a) Measurements on vertical fire axis

At a given rate of convective heat output, the air temperature rise decreased rapidly as the ceiling height was increased. Figure (8) shows the relationship graphically, for measurements in the bay and under the joist. The following relationships were established:-

In b ay:	$\theta_a = k_5 H^{-1.93 \pm 0.017}$	(5)
Under joist:	$\theta_{\rm m} = kc {\rm H}^{-2.78} \pm 0.044$	(6)

where H represents the ceiling height.

The constants of proportionality are dependent on the instantaneous rate of convective heat output.

The more rapid reduction in temperature rise with increasing ceiling height observed for the measurements taken under the joist, is due to the higher temperatures recorded under the joist at the lower ceiling heights (see Section 3.1.1.).

(b) Measurements at 5, 10, and 15 ft. from vertical fire axis

For measurements taken in the bay there was a continuous decrease in the temperature rise with increasing ceiling height, following the relationship:-

$$\Theta_{a} = k_{7} H^{-1.21} \pm 0.039 \tag{7}$$

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The value of k_7 depends on the rate of convective heat output of the fire, and distance from the fire axis.

The temperature rise under the joist was related to the ceiling height in a more complex manner. Typical curves illustrating the relationships are given in Figure (9), for a particular rate of convective heat output. As the ceiling height was reduced, all the fires showed the same increase in temperature rise down to a height of 28 ft. but below this height the temperature rise was smaller the more rapid the rate of fire In addition, only the fire with the slowest development rate development. showed a progressive increase in temperature rise with a reduction in ceiling height below 28 ft. The more rapidly developing fires showed a maximum temperature rise in some cases, with a fall in temperature rise as the ceiling height approached 12 ft. These effects were observed for relatively low convective heat outputs, (applicable to operation of sprinklers on or near the fire axis at low ceiling heights) when the layer of hot gas at ceiling level was comparatively thin. The evidence available, however, suggests that at greater rates of convective heat output (circa 1500 Btu/s and above) there was an increase in temperature rise with decreasing ceiling height, irrespective of rate of fire development.

The air temperature rise under the joist for the slowest rate of fire development (fire A), is related to the rate of convective heat output, between ceiling heights of 20 ft. and 36 ft. by the equation:-

$$\theta_{a} = k_{8} H^{-1.53 \pm 0.021}$$
 (8)

The more rapidly developing fires follow this law down to a ceiling height of 28 ft. but below this height the temperature rise is less than that given by the equation, the discrepancy becoming greater the lower the ceiling height. The value of kg depends on the rate of convective heat output of the fire and distance from the fire axis.

3.1.3. Variation with distance from vertical fire axis

In the bay there was a continuous reduction in temperature rise with distance from the fire axis. At low ceiling heights there was a relatively large reduction in temperature rise up to 5 ft. from the fire axis, with a more gradual fall at greater distances. For large ceiling heights the rate of fall of temperature rise with distance was more uniform. Some typical graphs are shown in Figure (10).

The temperature rise under the joist showed, in general, a rapid reduction in the first 5 ft. from the fire axis, a relatively small reduction between 5 ft. and 10 ft. and no measurable fall beyond 10 ft.; typical curves are shown in Figure (10). The reduction in temperature rise in the first 5 ft. became markedly greater at lower ceiling heights.

The difference in temperature rise between a point immediately above the fire, and a point 15 ft. from its axis, was greater under the joist than in the bay, particularly for the lower ceilings (see Figure (10)). This is because the central temperature rise under a joist is equal to, or greater than that in the bay, but temperature rises away from the axis are lower under the joist (see Section 3.1.1.).

3.1.4. Measurements across ceiling bay

Some subsidiary measurements were made of the air temperature rise across the bay formed between adjacent joists, in experiments with sprinklers mounted directly under the ceiling. Thermocouples were placed at 8 in. below the ceiling in a plane normal to the centre line of the bay, and at 4 ft. from the fire axis. Additional thermocouples were situated in the same plane, 8 in. under a joist, and also in the adjacent bay. The siting of the thermocouples is shown in Figure (11).

The results show clearly that at a given rate of convective heat output of the fire, the air temperature rise across the bay is almost uniform. This is shown in Figure (11), which is a typical temperature profile. The difference in temperature rise under the joist, and in the adjacent bay, was found to become relatively greater as the ceiling height was reduced.

3.2. Bulb_temperature rise

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The results for bulb temperature rise follow the same general trends as those observed for air temperature rise. The only sprinklers for which there were both air and bulb temperature rise measurements were those situated at 8 in. below the ceiling in the bay, or 8 in. below the joist. These measurements show that an approximately linear relationship exists between the rise in bulb temperature and the rise in air temperature. Typical graphs showing the form of the relationship are given in Figure (12). The form of the curves can be predicted on simple theoretical grounds, and this aspect of the work will be discussed in a further Note.

An important feature of the results is that the bulb temperature rise is dependent on the rate of fire development in all circumstances, whereas the air temperature rise was generally independent of development rate.

In general, for a given rate of convective heat output, the bulb temperature rises measured in the bay were larger than those measured under the joist (c.f. Section 3.1.1.(b)).

3.2.1. Variation with rate of convective heat output

In general, the bulb temperature rise was linearly related to the rate of convective heat output of the fire, as shown by typical curves in Figure (13). There is usually a small intercept on the heat output axis, because there was no measurable rise in bulb temperature at very low rates of heat output. The relationship begins to depart from linearity towards the maximum of the burning rate curve, because the bulb temperature continues to rise, due to the time constant of the bulb, but the burning rate of the fire approaches and passes through its maximum value.

3.2.2. Variation with rate of fire development

At a particular rate of convective heat output the bulb temperature rise decreased with increasing rate of fire development. Figure (14) shows typical results in which the rise in bulb temperature has been plotted against the "linear" rate of fire development (see Section 2.2). In general, the rate of decrease in temperature rise becomes progressively less rapid as the rate of development increases.

The results arise because of the finite time constant of the sprinkler bulb. The more rapidly the air temperature rises the lower is the bulb temperature rise at a particular air temperature, as can be seen from Figure (12).

This aspect of the results will be discussed in greater detail in a subsequent Note.

3.2.3. Variation with ceiling height

(a) Sprinklers on vertical fire axis.

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The bulb temperature rise, at a given rate of convective heat output, decreased rapidly as the ceiling height was increased. Typical curves are shown in Figure (15). The relationships between the rise in bulb temperature, Θ_b , and ceiling height, H, were found to be:-

In bay: $\theta_b = k_9 H^{-1.95 \pm 0.036}$ (9)

Under joist:
$$\theta_{b} = k_{10} H^{-2.33 \pm 0.043}$$
 (10)

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The values of k_9 and k_{10} depend on the rate of convective heat output of the fire, the rate of fire development, and on the depth of the sprinkler below the ceiling or joist.

There were limited results for the 12 ft. and 20 ft. ceiling heights, because the bulbs burst frequently during the experiments, and it was impracticable to replace them continuously.

The more rapid reduction of bulb temperature rise with increasing ceiling height for the measurements taken under the joist is a reflection of the results observed for the air temperature rise (see Section 3.1.2.).

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(b) Sprinklers at 5, 10 and 15 ft. from vertical fire axis

The rise in bulb temperature in the bay showed a decrease with increasing ceiling height, for a given rate of convective heat output, following the relationship:-

 $\theta_{\rm b} = k_{11} \, H^{-1.10 \pm 0.054} \tag{11}$

The value of k_{11} depends on the rate of convective heat output of the fire, the rate of fire development, the distance from the fire axis, and the depth below the ceiling or jois:

Measurements under the joist show similar trends to those observed for air temperature rise (see Section 3.1.2.). In general, there was an increase in temperature rise at a given rate of heat output with decreasing ceiling height, down to approximately 20 ft. Below this height the temperature rise with further reduction in height was relatively small, and in a number of cases a maximum was reached at a particular height, followed by a decrease at smaller heights. The latter effect was generally more evident for the more rapidly developing fires, and at the lower levels below the joist.

Some typical curves illustrating the results are given in Figure (16).

3.2.4. Variation with depth below ceiling or joist

(a) Sprinklers on vertical fire axis

The bulb temperature rise under the joist increased with the depth of the sprinkler beneath the joist. This result is expected, since the temperature rise in the plume of hot gases increases with proximity to the fire. For sprinklers situated in the bay, however, there was no significant change in temperature rise with increasing depth between 8 in. and 24 in.

(b) Sprinklers at 5, 10, and 15 ft. from vertical fire axis

In general, the bulb temperature rise at a given rate of heat output decreased as the depth below the ceiling (in the bay) or joist was increased. The rate of decrease of temperature rise became greater at low ceiling heights, indicating a greater temperature gradient in the layer of hot gas adjacent to the ceiling. The increase in temperature gradient with decreasing ceiling height was not very marked for sprinklers mounted under the ceiling, but was pronounced for the sprinklers under the joist. Some typical results are shown graphically in Figure (17), for sprinklers mounted under the joist.

For ceiling heights of 36 ft. and 28 ft. there was little difference between the rate of fall of temperature rise with depth for sprinklers in the bay and under the joist. At lower ceiling heights however, the temperature gradient was greater under the joist, particularly for the 12 ft. ceiling where the effect of depth was generally marked; typical graphs are shown in Figure (18).

3.2.5. Variation with distance from vertical fire axis

The bulb temperature rise showed the same general trends as were observed for the air temperature rise. Some typical results are given in Figure (19).

For sprinklers under the joist there was a rapid fall in temperature rise in the first 5 ft. from the fire axis, which became more pronounced at low ceiling heights. This reduction in temperature rise was greatest at the lower sprinkler levels, because bulbs immediately over the fire were hotter than those above them, whereas sprinklers off the fire axis were cooler than those above them. Beyond a distance of 10 ft. there was no appreciable reduction in temperature rise at a given rate of heat output.

Sprinklers sited in the bay showed a continuous reduction in bulb temperature rise with increasing distance from the fire axis, with the exception of the sprinklers at 24 in. below the ceiling (below the level of the undersides of the joists), where there was no appreciable change beyond 10 ft. as for the sprinklers mounted directly under the joist.

The sprinklers situated under the joist showed the larger difference in bulb temperature rise between a sprinkler immediately above the fire, and one at 15 ft. from the fire axis.

4. Size of fire at sprinkler operation

From a practical point of view it is important to know the size of fire at the moment of operation of a sprinkler head. In this section the relationship of the fire size at sprinkler operation to the experimental variables is The actual size of fire which has to be tackled is considered a more considered. useful criterion than the operating time, which is only indicative of fire size for a known rate of development. If the rates of development of two fires differ, a given time of operation may represent widely differing fire sizes when the sprinklers operate. For example, a response time of 6 min. would correspond to a rate of convective heat output of 320 Btu/s for the least rapidly developing fire, and 3040 Btu/s for the most rapidly developing. A rapidly developing fire may operate a sprinkler on a high ceiling in the same time as a more slowly developing fire on a lower ceiling, but the fire size at operation would be considerably larger in the former case.

A sprinkler bulb temperature rise of 60° C was adopted as the criterion for sprinkler operation, and the size to which the fire had grown at operation was determined from the graphs relating bulb temperature rise and convective heat output (see Figure (13)). The bulb temperature rise is typical of normal conditions and represents operation of a sprinkler head (rated at 68° C) at a bulb surface temperature of 72° C, from an ambient temperature of 12° C. Obviously if the ambient temperature has some other value, the fire size may be either larger or smaller than that considered in the following sections. Its size, however, can be easily determined from the appropriate graphs. In some cases it was necessary to extrapolate, to obtain the size of the fire at sprinkler operation, particularly for the measurements under the joist at the lowest ceiling heights, where the bulb temperature rise was insufficient for sprinkler operation.

The size of fire at sprinkler operation is subject to variation, because of variations in the burning rate-time characteristic of the fires, and also in the bulb bursting temperature. The range of variation is not shown on the illustrative graphs, but it can be determined from the basic data, for any given set of circumstances.

4.1. Variation with rate of fire development

It was generally true that the size of fire at sprinkler operation was larger the more rapid the rate of fire development. Typical results are shown plotted in Figure (20), which shows that the rate at which the operating fire size increases becomes less at high rates of fire development.

4.2. Variation with ceiling height

(a) Sprinklers on vertical fire axis

The size of fire at sprinkler operation, Q_0 , increased rapidly with ceiling height, H, following the relationship:-

 $Q_0 = k_{12} H^{2.18 \pm 0.045}$ (12)

This equation is applicable to measurements made in the bay and under the joist; a typical curve is given in Figure (21). The value of k_{12} depends on the rate of fire development, depth of sprinkler below ceiling or joist, and whether the sprinkler is mounted below the ceiling (in bay) or joist.

The exponent of H is based on a limited number of curves because there were relatively few results at low ceiling heights, because of bursting of the bulbs. The form of the relationship follows from that observed for bulb temperature rise (Section 3.2.3.).

(b) Sprinklers at 5, 10, and 15 ft. from vertical fire axis

For sprinklers mounted in the bay the size of fire at sprinkler operation showed, in general, a linear increase with increasing ceiling height. The linear relationship is expected from the measurements of bulb temperature rise, which is almost inversely proportional to ceiling height (see Section 3.2.3.). Some typical graphs are shown in Figure (22). From this figure it can be seen that the operating fire size increases more rapidly with ceiling height as the rate of development becomes greater. This finding can be deduced on simple theoretical grounds, and will be considered in a later Note.

The relationship of operating fire size to ceiling height for sprinklers mounted under the joist is more complex than for those in the bay, because the operating fire size is greater than expected at low ceiling heights, and is often larger than that recorded at greater heights of ceiling. The latter effect arises from the low bulb temperature rises observed at low ceiling heights, because of the location of the sprinklers at a low level in the hot gas layer; this point has been discussed earlier in the Note. Some typical curves are shown in Figure (23) and also in Figure (24); the upward turn of the curves becomes more marked for rapidly developing fires, and at greater depths of the sprinkler below the joist.

The size of fire at sprinkler operation was generally smaller for sprinklers mounted in the bay than that for sprinklers under the joist. This is because of the more rapid build up of a hot gas layer in the bay, resulting in earlier sprinkler operation. The difference between the two mounting positions is proportionately greater the more rapid the rate of fire development, as can be seen from Figure (24). This is because the constraining effect of the joists has a relatively greater effect when the rate of fire development is rapid, because of the smaller total volume of hot gas produced by the fire when a given rate of heat output has been attained (see Section 3.2.).

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4.3. Variation with depth below ceiling or joist

(a) <u>Sprinklers</u> on vertical fire axis

For sprinklers mounted in the bay there was no significant change in the operating fire size as the depth of mounting below the ceiling was increased. For the sprinklers under the joist, however, there was a reduction in the operating fire size with increasing depth, which would be expected because of greater proximity to the fire.

(b) Sprinklers at 5, 10, and 15 ft. from vertical fire axis

In general, the operating fire size became larger as the depth of the sprinkler below the ceiling (in the bay) or joist was increased. Under the joist the rate of increase with depth became more rapid as the ceiling height was reduced, until for the 12 ft. ceiling it was often very large, because of the steep temperature gradient under the level of the joists. For sprinklers mounted in the bay, there was no marked effect of ceiling height on the rate of increase of operating fire size with increasing depth, because the temperature gradient below the ceiling was not appreciably affected by ceiling height. Some representative graphs are given in Figure (25).

4.4. Variation with distance from vertical fire axis

For sprinklers in the bay, the size of fire at sprinkler operation increased continuously with distance from the fire axis, with the exception of those mounted at the 24 in. level, for which there was no further increase beyond 10 ft. The rate of increase of operating fire size was relatively uniform with distance from the fire axis at the 8 in. level, at large ceiling heights, but tended to become less rapid beyond 5 ft. at the 16 in. level. The "flattening out" beyond 5 ft. was also evident at low ceiling heights, for which the greatest increase took place in the first 5 ft. Some typical graphs of the results are given in Figure (26).

For sprinklers mounted under the joist, the size of fire at sprinkler operation increased up to a distance of 10 ft. but beyond this distance there was no change. In some cases no further increase was observed beyond 5 ft. but in view of the results for air temperature rise (Section 3.1.3.), the evidence points to 10 ft. as the limiting distance. The greatest increase in operating fire size generally occurs in the first 5 ft. the increase becoming progressively greater as the ceiling height becomes smaller.

5. Discussion

The results show clearly the danger of rapidly developing fires, in that the more rapid the development rate, the larger the fire will be when sprinklers operate. For example, a sprinkler situated in the bay at 5 ft. from the fire axis, 8 in. below the ceiling, will operate at a rate of convective heat output of 1640 Btu/s, for a 36 ft. ceiling, with the slowest rate of fire development used in the experiments; for the most rapidly developing fire the rate of heat output at operation was 2600 Btu/s, an increase of 59 per cent.

The further the sprinkler is mounted below the ceiling (in the bay) or joist, the larger is the fire when it operates, with the exception of the rare case of a fire starting immediately below a sprinkler head. For sprinklers mounted under the joist, on low ceilings, the rate of increase in operating fire size with depth was very rapid. The general conclusion is, therefore, that the sprinklers should be mounted as close to the ceiling or joist as is practicable. This is particularly important for low ceilings, which have a large and undivided area, and the rate of fire development is expected to be high. Under these conditions the layer of hot gases adjacent to the ceiling will be relatively thin. On high ceilings, or when the ceiling area is comparatively small (as in the bays formed between the joists in the present work), the mounting of sprinklers in close proximity to the ceiling assumes less importance.

For sprinklers mounted in the ceiling bay it was found that immediately above the fire the size of fire required for sprinkler operation increased approximately in proportion to the ceiling height squared. At a distance of 5 ft. from the fire axis it was found that the relationship between fire size at sprinkler operation and ceiling height had become a linear one, and this relationship was found to hold up to 15 ft. from the fire axis.

There was no simple relationship between operating fire size and ceiling height for sprinklers mounted under the joist, because the size of fire which operated a sprinkler at the lowest ceiling height (12 ft.) was often larger than that required for operation at greater heights of ceiling. This is because of the considerable depth of joist $(19\frac{1}{2} \text{ in.})$ which resulted in a slow rate of rise of bulb temperature with increasing fire size, particularly for rapid rates of fire development. A general conclusion from the results is that mounting a sprinkler below a joist results in a larger size of fire when it operates, than for a sprinkler mounted in a similar position relative to the fire below the ceiling in the bay formed between joists. The difference between the respective fire sizes becomes more serious the lower the ceiling, the lower the mounting position, and the more rapidly the fire developes.

The measurements of the effect of the horizontal distance of the sprinkler from the fire give an indication of the possible circumstances in which a large number of sprinklers might be caused to operate. If there is a time delay in the application of water to the fire (as in a dry pipe system), or if the rate of water application is such as not to appreciably inhibit the rate of development of the fire, (and hence the air temperature rise at ceiling level), then sprinklers will operate at progressively greater distances from the fire. Under such circumstances there is a danger of a large number of sprinklers operating, particularly when the ceiling height is low, and/or when the sprinklers are mounted well below the ceiling. A similar effect may arise for high ceilings, although at a much larger fire size, when the air temperature rise curve has "flattened out" to a relatively constant value at a particular distance from There is evidence that this flattening out takes $place_{(2)}(5)$ but at the fire. distances outside the range of the present experiments (probably at a distance of 30 ft. or more).

The effect of the horizontal distance from the fire axis is also relevant to changes in sprinkler spacing in their effect on the maximum size of fire which can be encountered in given circumstances. For example, for crib B, and sprinklers mounted 8 in. below the ceiling (in bay), an increase in sprinkler spacing from 10 ft. x 10 ft. to 12 ft. x 12 ft. increased the maximum size of fire at sprinkler operation by 3 per cent for a 28 ft. ceiling, and 7 per cent for a 12 ft. ceiling, the horizontal distance of the nearest sprinkler from the fire axis being the maximum possible in each case, i.e. 7 ft. and $8\frac{1}{2}$ ft. respectively. Figure (27) shows how the effects of the experimental variables can be demonstrated in a simple graphical manner. The rate of convective heat output is plotted against ceiling height for sprinklers 8 in below the ceiling, in the bay, and situated immediately above the fire, at 7 ft. and at 10 ft. from the fire axis; the slowest and fastest rates of development are plotted on the graph. Similar curves can be drawn for any chosen distance from the fire axis, or for any other depth of sprinkler mounting below the ceiling or joist.

The usefulness of the graph lies in the fact that the effect of several parameters can be easily seen. For example, at a given ceiling height, the range of fire sizes which will be required to cause sprinkler operation must lie between the curve applicable to sprinklers immediately above the fire, and that at 7 ft. from the fire axis (assuming a 10 ft. square spacing). At a ceiling height of 20 ft. for example, the fire size at sprinkler operation may range from 430 Btu/s to 1070 Btu/s for the slowest rate of fire development, and up to 1650 Btu/s for the most rapid development rate.

The effect of increasing the sprinkler spacing on the maximum size of fire likely to be encountered can also be assessed from the graph. The line corresponding to a distance of 10 ft. from the fire axis is applicable to a sprinkler spacing on an approximately 14 ft. square grid.

6. Conclusions

(1) The air temperature rise was related to the instantaneous rate of convective heat output of the fires by simple power laws, which were close to linear relationships.

(2) The sprinkler bulb temperature rise was linearly related to the instantaneous rate of convective heat output of the fire, while the fire was continuing to develop. This fact enables the size of fire at sprinkler operation to be simply determined, for any rise in bulb temperature above ambient.

(3) The bulb temperature rise was almost linearly related to the air temperature rise, in accord with elementary theoretical considerations.

(4) The more rapidly the fire developed, the larger was the fire when sprinklers operated.

(5) (a) In the rare event of a fire starting immediately below a sprinkler, the size of the fire at sprinkler operation increased approximately in proportion to the square of the ceiling height.

(b) For sprinklers in the ceiling bay, not immediately above the fire, there was a linear increase in the size of fire at sprinkler operation with increasing ceiling height. The rate of increase was more rapid the greater the fire development rate.

(c) For sprinklers mounted below the joist, not immediately above the fire, the relationship of operating fire size to ceiling height was complicated by the slow rise in sprinkler bulb temperature at low ceiling heights (20 ft. and less). The result was that the operating fire size was often as large at low ceiling heights as that applicable to higher ceilings. The effect was most marked for rapid rates of fire development, and at the lower levels of mounting below the joist.

- (6) With the exception of sprinklers immediately above the fire, there was an increase in the size of fire at sprinkler operation as the depth of mounting below the ceiling (in the bay) or joist was increased. The rate of increase became much more rapid at low ceiling heights for sprinklers under the joist, but for those mounted in the bay, the ceiling height had little effect. On high ceilings the rate of increase was practically independent of whether the sprinklers were mounted in the bay or below the joist.
 - (7) (a) For sprinklers in the bay, above the level of the soffit of the joists, there was a continuous increase in the operating fire size with increasing horizontal distance from the fire axis. At low ceiling heights, however, the rate of increase became relatively small beyond 10 ft. distance.

(b) For sprinklers mounted under the level of the soffit of the joists (including those in the bay), there was, in general, an increase in operating fire size up to 10 ft. from the fire axis. Beyond this distance, however, there was no further change in the size of fire at sprinkler operation. The largest increase in operating fire size occurs in the first 5 ft. the increase becoming relatively greater the lower the height of ceiling.

(8) With the exception of sprinklers immediately above the fire, mounting sprinklers below the joist resulted in a slower sprinkler response, and therefore a larger fire at sprinkler operation than for sprinklers mounted in the bay, in a similar position relative to the fire. The difference became more serious for rapid rates of fire development, low ceiling heights, and with greater depth of mounting below the ceiling or joist.

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FIG.1. DIAGRAM SHOWING GENERAL EXPERIMENTAL ARRANGEMENT

Internal note 212 F.R.601

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FIG.2. TYPICAL CURVES SHOWING VARIATION OF RATE OF BURNING OF FIRES WITH TIME FROM IGNITION







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FIG.3. ARRANGEMENT OF CIRCUIT FOR TEMPERATURE MEASUREMENTS

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FIG.6. VARIATION OF AIR TEMPERATURE RISE WITH RATE OF CONVECTIVE HEAT OUTPUT OF FIRE

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Internal note 212. F.R. 601

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RATE OF CONVECTIVE HEAT OUTPUT --- Btu/s



12 ft ceiling. 10 ft from fire axis 8 in below joist

FIG.7. VARIATION OF AIR TEMPERATURE RISE WITH RATE OF CONVECTIVE HEAT OUTPUT OF FIRE

Internal note 212

1/5976

F.R. bot



CEILING HEIGHT-ft

x Under joist

o in bay

RATE OF CONVECTIVE HEAT OUTPUT - 750 Btu/s

FIG.8. VARIATION OF AIR TEMPERATURE RISE WITH CEILING HEIGHT FOR MEASUREMENTS ON FIRE AXIS

Internal note 212

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F.R. bol



CEILING HEIGHT FOR MEASUREMENTS AT 10FT FROM FIRE AXIS

178 Internal note 212

F.R. bol

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FIG.10 VARIATION OF AIR TEMPERATURE RISE WITH DISTANCE FROM FIRE AXIS, AT RATE OF CONVECTIVE HEAT OUTPUT OF 1000 Btu/s

1/5979 Internal note 212 F.R. 60



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FIG.11. VARIATION OF AIR TEMPERATURE RISE WITH DISTANCE ACROSS CEILING BAY



FIG.12 VARIATION OF SPRINKLER BULB TEMPERATURE RISE WITH AIR TEMPERATURE RISE .

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RATE OF CONVECTIVE HEAT OUTPUT - Btu / s 28ft celling Sprinkler on fire axis at 8in below ceiling joist

FIG.13. VARIATION OF BULB TEMPERATURE RISE WITH RATE OF CONVECTIVE HEAT OUTPUT OF FIRE

1/5982 Internal note 212

F.R. bol



-× × 5ft from fire axis

Sprinklers at 8in below ceiling (in bay) Rate of convective heat output --- 1000 Btu/s

FIG.14 VARIATION OF SPRINKLER BULB TEMPERATURE RISE WITH RATE OF FIRE DEVELOPMENT FOR 20 FT CEILING HEIGHT

1/5983 Internal note 212 F.R. toi





FIG 15 VARIATION OF BULB TEMPERATURE RISE WITH CEILING HEIGHT FOR SPRINKLERS SITUATED ON FIRE AXIS

1/5984 Internal note 212 F.R.to



CEILING HEIGHT - ft



FIG.16 VARIATION OF BULB TEMPERATURE RISE WITH CEILING HEIGHT FOR SPRINKLERS AT 5FT FROM FIRE AXIS

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FIG.17 VARIATION OF BULB TEMPERATURE RISE WITH DEPTH OF SPRINKLER BELOW CEILING JOIST, FOR DIFFERENT CEILING HEIGHTS, AT 5FT FROM FIRE AXIS

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FIG.18. VARIATION OF BULB TEMPERATURE RISE WITH DEPTH OF SPRINKLER BELOW CEILING OR JOIST, FOR 12 FT CEILING HEIGHT, AT 5FT FROM FIRE AXIS

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F.R. bol

Internal note 212

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28 FT CEILING HEIGHT



FIG.20. VARIATION OF RATE OF CONVECTIVE HEAT OUTPUT OF FIRE AT SPRINKLER OPERATION WITH RATE OF FIRE DEVELOPMENT

1/5989 Internal note 212 F.R 601



OUTPUT OF FIRE WITH CEILING HEIGHT FOR SPRINKLERS IMMEDIATELY ABOVE FIRE

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CEILING HEIGHT - ft

Sprinklers 16 in below celling (in bay)

FIG.22. VARIATION OF RATE OF CONVECTIVE HEAT OUTPUT OF FIRE AT SPRINKLER OPERATION WITH CEILING HEIGHT FOR SPRINKLERS AT 5FT FROM FIRE AXIS

1/5991 Internal note 212 F.R. bol



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FIG.23. VARIATION OF RATE OF CONVECTIVE HEAT OUTPUT OF FIRE AT SPRINKLER OPERATION WITH CEILING HEIGHT FOR SPRINKLERS AT 10 FT FROM FIRE AXIS

1 / 5992 Internal note 212

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FIG. 24. VARIATION OF RATE OF CONVECTIVE HEAT OUTPUT OF FIRE AT SPRINKLER OPERATION WITH CEILING HEIGHT FOR SPRINKLERS AT 5 FT FROM FIRE AXIS

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Internal note 212 F.R. 601



FIG 25. VARIATION OF RATE OF CONVECTIVE HEAT OUTPUT OF FIRE AT SPRINKLER OPERATION WITH DEPTH BELOW CEILING OR JOIST AT 5FT FROM FIRE AXIS



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FIG.26 VARIATION OF RATE OF CONVECTIVE HEAT OUTPUT OF FIRE AT SPRINKLER OPERATION WITH DISTANCE FROM FIRE AXIS

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FIG 27. GRAPH SHOWING RANGE OF RATE OF CONVECTIVE HEAT OUTPUT AT SPRINKLER OPERATION FOR VARIOUS PRACTICAL CIRCUMSTANCES

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F.R. 601

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EXPERIMENTS Z USED FIRES CRIB PLATE.2. CONSTRUCTION OF



PLATE. 3. TYPICAL TEMPERATURE RECORD

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