Fire Research Note

NO. 603

THE PERFORMANCE OF AUTOMATIC SPRINKLER SYSTEMS:

PART II - THE EFFECT OF WATER APPLICATION RATE AND FIRE SIZE ON THE EXTINCTION OF WOODEN CRIB FIRES

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SUMMARY

This report describes experiments on the extinction of wooden crib fires by water spray. A study was made of the effect of variations in water application rate, the rate of heat output of the fire, and crib construction. Measurements were made of fire spread, extinction time, quantity of water required for extinction, and air temperatures at ceiling level of the building used.

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

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1. Introduction

This Note describes the second part of an experimental programme, on the performance of sprinkler systems, in which the water requirements for adequate fire control were studied. Wood crib fires similar to those used in the first part of the experimental programme(1) were subjected to a range of water application rates, at various stages in their development, and the subsequent fire behaviour was studied, in order to obtain a measure of the optimum water requirements to control, and, if possible, extinguish, the developing fires.

2. Experimental procedure

Two factors which would be expected to affect the water requirements were examined in the experiments, these being:-

(a) The size of the fire when water was first applied to it; the fire sizes chosen were those with instantaneous rates of convective heat output of 250, 500, 1000, 1500, and 2500 Btu/s.

(b) The rate of water application over the crib plan area, those used being 0.049, 0.075, 0.10, 0.13, 0.18, 0.23 and 0.28 gal/ft^2/min, a range representative of the range of discharge rates for $\frac{1}{2}$ in. sprinkler heads at various pressures(2).

The cribs were built with base dimensions of 6 ft x 3 ft so that the longitudinal spread of fire could be studied; details of the crib constructions are given in the following table.

Crib reference	CRIB A	CRIB B	CRIB C
Stick size	1 in x 1 in	1 in x 1 in	$\frac{1}{2}$ in x $\frac{1}{2}$ in
Spacing between adjacent sticks	$1\frac{1}{2}$ in	3 in	4 in
Crib height	2 ft 8 in	3 ft 6 in	4 ft
Rate of fire development	Slowest	Intermediate	Most rapid

The cribs were ignited at the centre of the base of one half of the crib, by 50 ccs. of industrial methylated spirits contained in a small circular tray. The fires were allowed to develop until the selected burning rate was attained, and water was then applied. The rate of burning of the fire was obtained by measuring the air temperature rise beneath a joist at ceiling level (39 feet above the crib base), immediately above the fire, using a relationship derived in the first part of the programme[1]. Only crib B was examined in detail, but limited comparative experiments were conducted for crib A and crib C. The range of burning rates examined was chosen to cover the greater part of the burning rate - time characteristic of crib B.

Water was applied to the fires from an impinging jet nozzle, which gave a uniform rate of application over the crib plan area. The nozzle was situated $11\frac{1}{2}$ ft above the plane of the top of the crib, as shown in Figure (1). The rate of application of water to the top of the crib was calibrated with nozzle pressure. The drop size distribution of the spray was examined, and it was found that there was no significant change in the mass median diameter over the range of discharge rates and pressures (10-50 lbf/in^2) used in the experiment. The mean value of the mass median diameter was 1.15 mm., and that of the modal diameter was 0.44 mm.

During each experiment the fire behaviour was studied visually, and by taking time lapse photographs. Measurements were made of the rate of fire spread along the crib, the time required for extinction, and the maximum spread of fire after water application. In addition, continuous measurements were taken of the air temperature rise 8 in. below a ceiling joist, by 40 s.w.g. thermocouples situated at distances of 0, 5, 10, and 15 ft. from the fire axis (see Figure (1)).

3. Results for crib B (intermediate rate of fire development)

3.1. Maximum fire spread after water application

The flame front spread along the crib in discrete increments, equal to the stick spacing, the flames "flashing-over" suddenly to the next column of sticks.

A rate of water application of 0.075 $gal/ft^2/min$ was usually required to limit fire spread within the length of the crib, but in some cases a rate as low as 0.05 $gal/ft^2/min$ was adequate. As the rate of water application was increased above the minimum, the extent of fire spread was markedly reduced, falling from about 2-3 ft. at the minimum rate, to a value of 3-4 in. at the highest rates of water application used. There was a considerable degree of variability in the results, but the trends were consistent. A typical graph relating maximum fire spread and rate of water application is given in Figure (2), which represents an inverse power law. The following relationship was established:

$$S = 0.90R^{-1.24 \pm 0.081} \qquad \text{...... (1)}$$

where S is the maximum spread in inches, and R is the rate of water application in $gal/ft^2/min$. The constants are mean values for all sizes of fire on initial application of water.

There are two important points which are brought out by the curve shown in Figure (2). If the water application rate fell below about 0.10 $gal/ft^2/min$, ther was a marked increase in fire spread, accompanied by the possibility that some of the fires would not be controlled. At rates of application above about 0.23 $gal/ft^2/min$ the fire spread decreased very slowly with increasing application rate. There was no appreciable advantage to be gained, therefore, in increasing the rate of application above this value.

The maximum spread of fire following water application was not dependent on the initial fire size, for a particular rate of application, as shown in Figure (3). The total fire spread from ignition, which is a measure of the fire damage, is obviously larger the greater the initial fire size, since the fire is larger when the water is first applied (see Figure (3)).

Except for rates of application of 0.23 $gal/ft^2/min$ and above, the water appeared to have little effect on the burning zone where the fire was well established, but inhibited the spread until the centre of the fire zone was burned out, after which the radiation level fell markedly, and the spray was able to extingish the remainder of the burning material. The important mechanism in the extinction was the marked reduction in the rate of fire spread following water application (see Section 3.4). At rates of water application of 0.23 $gal/ft^2/min$ and above, there was a change in the mode of extinction. The flames were beaten down into the crib, because the downward thrust of the spray was greater than the upthrust of the flames. Extinction was relatively rapid, and fire damage was localised in the lower half of the crib.

3.2. Extinction time

The extinction time was taken as the time from the initial application of water until the cessation of all flaming. The relation between extinction time and rate of water application was similar to that observed for the maximum fire spread; a typical curve is given in Figure (4). In general, the extinction time fell rapidly with increasing rate of water application from about 40 min. at the lowest rates, to about 10 mins at the highest rate. The extinction time was independent of initial fire size and the relation between the extinction time, T (min), and the rate of water application, R ($gal/ft^2/min$), is given by:-

$$T = 4.8R^{-0.71 \pm 0.042} \qquad \ldots\ldots (2)$$

where the constants are mean values for the range of initial fire sizes which was used.

A secondary finding from equations (1) and (2) is the relationship between extinction time and maximum fire spread after water application:-

$$T = 5.1S^{0.57} \qquad \ldots\ldots (3)$$

where T is expressed in min. and S in inches.

Figure (5) shows this relation plotted together with the experimental results. The extinction times for the largest spreads are generally rather high; this is probably because in these circumstances there was often an isolated region of the fire which burned feebly for a considerable time after the fire was effectively out. The results can be effectively represented by a linear relationship over the range of fire spreads observed (see dashed line in Figure (5)).

3.3. Quantity of water for extinction

The total quantity of water required to extinguish the fire is given by the product of the extinction time and the rate of water application. From equation (2) it would be expected that there would be a slow increase in the total quantity of water required as the rate of application was increased over the experimental range. Although the results appear to support this deduction, the variability of the total water quantities is such that there was no statistically significant dependence on the rate of water application. A typical set of results is shown graphically in Figure (6). The overall mean quantity required was found to be 2.7 gal/ft^2 of the crib plan area; this figure is independent of the initial fire size, because for a particular application rate the extinction time was independent of initial fire size.

3.4. Rate of fire spread

A comparison was made between the rate at which fire spread along the crib when it was burning freely, and the rate of spread with various rates of water application. Even at the smallest rates of application, when the fire was not controlled within the crib length, the rate of fire spread was markedly reduced by the application of water. Figure (7) shows fire spread plotted against time, for different rates of water application together with the maximum spread attained by the fires. The curves show clearly the effect of water application on rate of spread, which becomes progressively less with increasing rate of application, and with time from the initial water application.

Over the first two divisions of the crib, the effect of water application was so small as to appear independent of rate of application, presumably because of the time delay before water begins to penetrate to the lower levels of the crib, so that fire spread at the bottom levels was not inhibited in the early stages of water application. In general, the application of water began to have a pronounced effect on the rate of spread after a time of 4-5 min.

4. Comparison of crib fires

The results discussed above for crib B were compared with similar results for cribs A and C, which were the cribs with the slowest and most rapid rates of fire development, respectively. Crib A was examined for an initial rate of convective heat output of 1500 Btu/s, and crib C for initial rates of convective heat output of 250 and 1500 Btu/s. The results are summarised in the following table, which gives mean values of fire spread, extinction time, and quantity of water required for extinction.

Crib reference	Fire spread after water application (in) — Rate of water application		Extinction time (min) — Rate of water application		Quantity of water required for extinction (gal ft^{-2})
	0.1 gal ft^{-2}min^{-1}	0.25 gal ft^{-2}min^{-1}	0.1 gal ft^{-2}min^{-1}	0.25 gal ft^{-2}min^{-1}	
A	8.0	1.4	23.8	16.2	3.2
B	15.3	4.9	24.0	13.0	2.7
C	18.9	5.1	9.8	5.2	1.3

The same general trends were observed for crib C as for crib B, but the results differed quantitatively. It was found that the fire was not as easily controlled as that in crib B, and in no case was the fire arrested within the crib length with a rate of application less than 0.1 gal/ft^2/min. At low rates of water application the maximum fire spread after water application was significantly larger for crib C than for crib B (about 25 per cent more at 0.1 gal/ft^2/min), but at high rates of application there was little difference. The extinction times recorded for crib C were markedly lower than those for crib B, being about 40 per cent of the latter times. The shorter extinction time is probably due to a combination of three factors: (a) the smaller degree of obscuration to water flow because of the more open crib structure, (b) the shorter duration of the fire before collapse of the centre of the burning zone, and (c) the smaller volume of burning material to be extinguished. As a direct result of the shorter extinction time, the quantity of water required for extinction was less than that required for crib B, the mean quantity being 1.3 gal/ft^2. This quantity was again independent of the rate of application.

The limited experiments performed with crib A indicate a maximum spread markedly less than the values observed for crib B. The extinction times, however, were not appreciably different from those for crib B, and as a result the total water quantities required for extinction were also similar.

5. Air temperature rise measurements

The air temperature rise was recorded immediately above the fire, and at horizontal distances of 5, 10 and 15 ft from the vertical axis of the fire. The thermocouples were situated at 8 in below the ceiling joists of the laboratory, which were 19½ in deep at their centre.

Except for rates of water application above 0.23 gal/ft^2/min, the air temperature continued to rise after water was applied to the fire, until a maximum value was reached. Typical air temperature records are represented diagrammatically in Figures (8)(a) and (8)(b). The maximum air temperature rise recorded was plotted against the rate of water application, for all the initial fire sizes. Typical results are shown in Figure (9). The scatter of results is considerable, but over the range of water application rates considered the relationship is practically a linear one, with the maximum air temperature rise falling continuously until an application rate of 0.23 gal/ft^2/min is reached when the rise is equal to that attained before the water is applied (see Figure 8(b)). From Figure (9), it can be seen that for a particular rate of water application, the maximum air temperature rise becomes greater as the initial fire size becomes larger.

In order to examine what rate of water application is required to prevent the operation of sprinklers at a specified distance from the fire, it is necessary to examine the relationship between the maximum air temperature rise and the maximum bulb temperature rise. The results of Part I of the programme were used[1] to plot the maximum temperature rise against the maximum bulb temperature rise, for ceiling heights of 36 ft and 28 ft. A linear relationship was obtained for all three rates of fire development, and no marked difference was found between the two ceiling heights. It was assumed that the results could be applied to the ceiling height of 39 ft used in the extinction experiments without appreciable error. The relationships are shown graphically in Figure (10).

From Figure (10) it is possible to obtain the maximum air temperature rise which can be permitted if the sprinkler bulb is not to burst. If we take a 60°C maximum rise in bulb temperature as representing sprinkler operation, then the air temperature rise must have a maximum of less than 75°C, for the intermediate rate of fire development (crib B). From this maximum permissible air temperature it is possible to obtain the rate of water application required to keep within this limit, from the graphs relating maximum air temperature rise and water discharge rate (see Figure (9)).

It was found that the larger the initial fire size the greater was the rate of water application required to prevent sprinkler operation beyond a given distance; Figure (11) shows the relationship between fire size and water application rate required to prevent sprinkler operation beyond a horizontal distance of 15 ft from the fire axis. For a particular ceiling height there will be a minimum and maximum fire size at sprinkler operation, corresponding to a fire immediately below a sprinkler head, and at the maximum horizontal distance of 7 ft from the nearest head, assuming a 10 ft spacing. These limits for a ceiling height of 28 ft are given in figure (11), for sprinklers mounted 8 in below a ceiling joist (taken from the results of Part I of the programme(1)). It can be seen that to prevent sprinklers operating beyond a radius of 15 ft, a rate of application of about 0.23 gal/ft^2/min over the fire area is required, for the maximum fire size. For higher ceilings the discharge rate required to prevent operation beyond 15 ft will be higher because the maximum fire size will be larger; for example, for a 36 ft ceiling, extrapolation of the graph shown in Figure (11), indicates a rate of discharge of approximately 0.28 gal/ft^2/min. It was observed, however, that if the water application rate was 0.23 gal/ft^2/min or more, the air temperature rise did not exceed that at first application of water. Hence it may not be necessary to use rates of application much in excess of 0.23 gal/ft^2/min even on large fires; it is not certain, however, whether this rate would apply for fires much larger than the maximum of the range used in the experiments (2500 Btu/s convective heat output).

For the most rapidly developing fire (crib C), it was found that the application rates required to prevent sprinkler operation beyond a certain distance, were similar to those deduced for crib B. Although the rate for a given initial fire size was smaller for crib C, because of the larger permissible maximum air temperature rise (90°C), the fire was larger at sprinkler operation (for a given set of conditions), because of its greater development rate. The overall result was that the rates of water application required were similar for the two fires. For example, at a ceiling height of 28 ft, an extrapolation of the results shows that the most rapidly developing fire required a rate of application of approximately 0.23 gal/ft^2/min, in order to prevent sprinkler operation beyond a radius of 15 ft.

The measurements of air temperature rise indicate the technique which can be adopted for determining the water discharge rate required to prevent sprinkler operation beyond a specified distance from the fire axis. Further work is required on this problem, however, particularly on the effect of having water discharging at ceiling level, rather than at some distance below the ceiling, as in the present work. The effect on air temperatures of a number of sprinkler heads discharging progressively in the vicinity of the fire should also be examined.

6. Conclusions

Consideration of the results enables the following conclusions to be drawn:-

(1) A minimum rate of water application of 0.075 gal $ft^2\ min^{-1}$ was required to arrest the spread of fire within the crib length for crib B. The corresponding minimum rate for crib C was 0.1 gal $ft^2\ min^{-1}$.

(2) As the rate of water application was increased above the minimum necessary for control, the fire spread was observed to decrease rapidly, from about 2-3 ft at the control rate to a value of 3-4 in at the highest rates used (0.28 gal $ft^2\ min^{-1}$).

(3) The rate of water application required to limit fire spread to a specific distance was not dependent on the size of fire when water was first applied.

(4) The extinction time was positively correlated with the fire spread after water was applied; in nearly all cases, when control was established, the fire was extinguished within 5 to 40 minutes of water application.

(5) For water application rates in excess of about 0.23 gal/ft^2/min the reduction in fire spread and extinction time with increasing rate of application was relatively small. The flames were beaten down into the crib and damage was localised in its lower half.

(6) The total quantity of water required for extinction did not vary significantly with rate of water application. For crib B (intermediate fire development rate) the mean quantity was 2.7 gal/ft^2, referred to the crib plan area; the corresponding figure for crib C (the most rapidly developing fire), was 1.3 gal/ft^2.

(7) The application of water, even at a low rate, resulted in a marked reduction in the rate of fire spread, except in the first few minutes before the water had penetrated sufficiently into the crib, when there was only a small effect.

(8) A limited comparison of the three cribs with different fire development rates showed similar trends for all the fires, but the results differed quantitatively. The fire spread was generally larger the more rapid the rate of fire development. The extinction time was least for the most rapidly developing fire (crib C), but there was a little difference in the times for the intermediate (crib B) and slowest development rates (crib A).

References

(1) O'DOGHERTY, M. J., and YOUNG, R. A. 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". F.R. Note No. 601/1965.

(2) Manual of Firemanship - Part 4, Home Office (Fire Service Dept.) H.M.S.O. 1961.

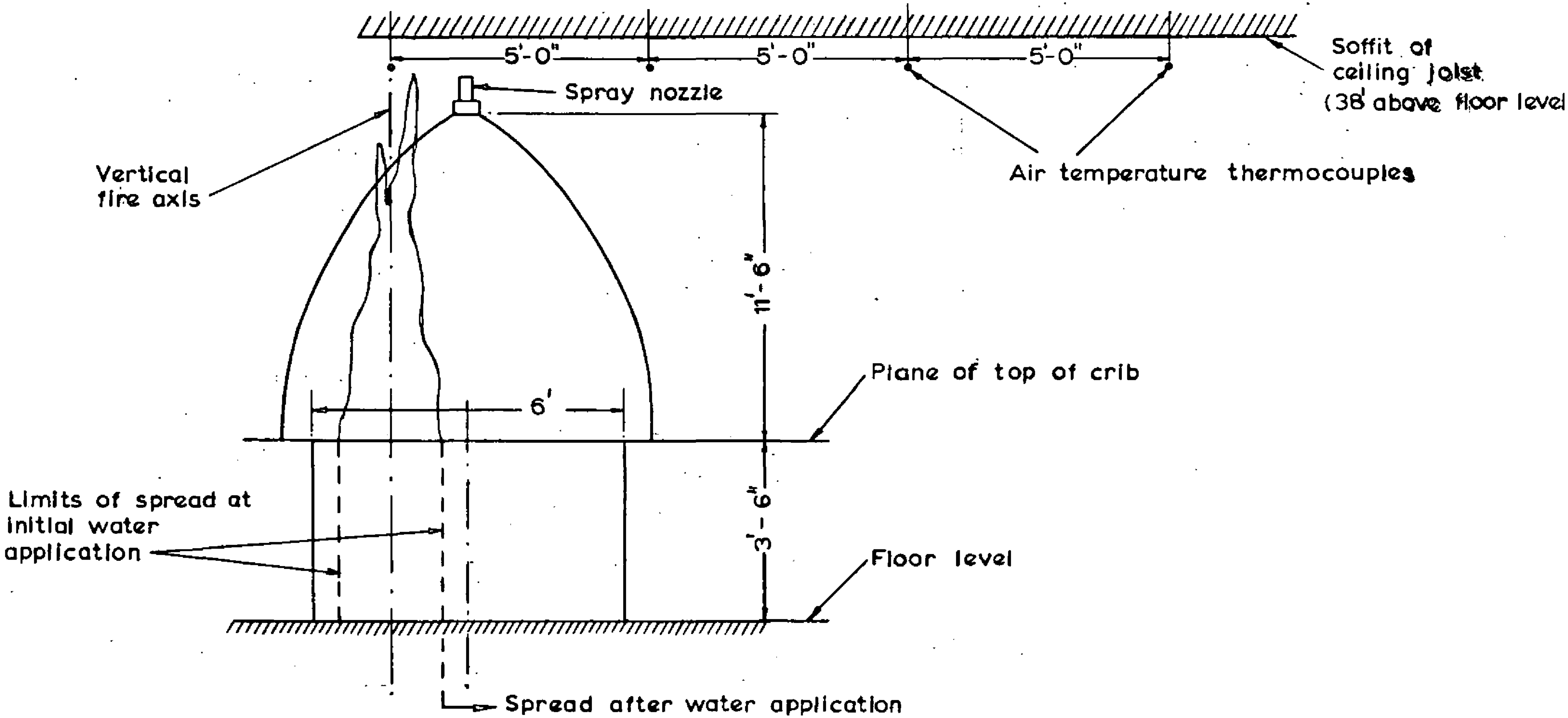
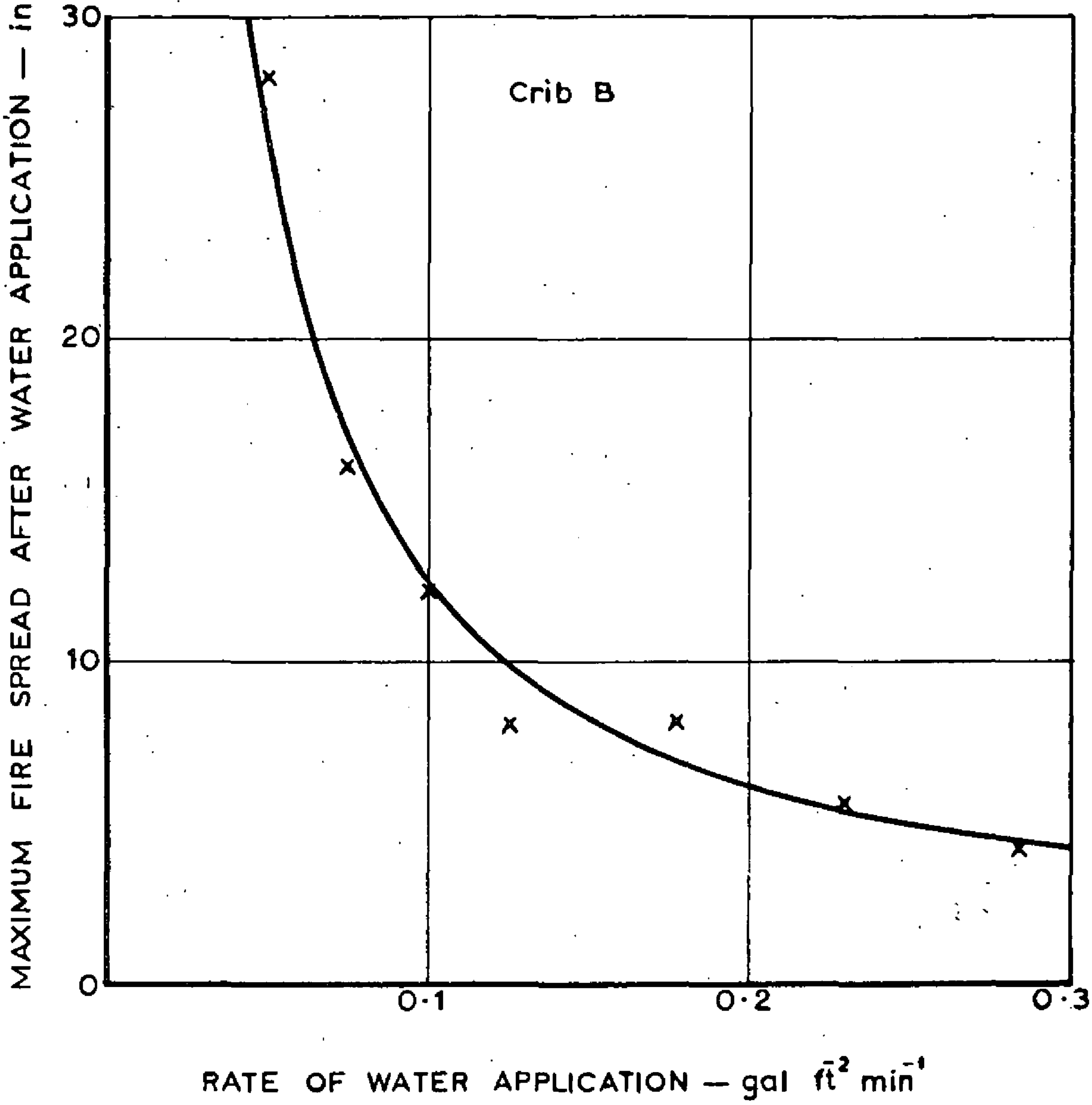


FIG.1. GENERAL EXPERIMENTAL ARRANGEMENT



Rate of convective heat output at water application — 2500 Btu/s

FIG.2. VARIATION OF MAXIMUM FIRE SPREAD WITH RATE OF WATER APPLICATION

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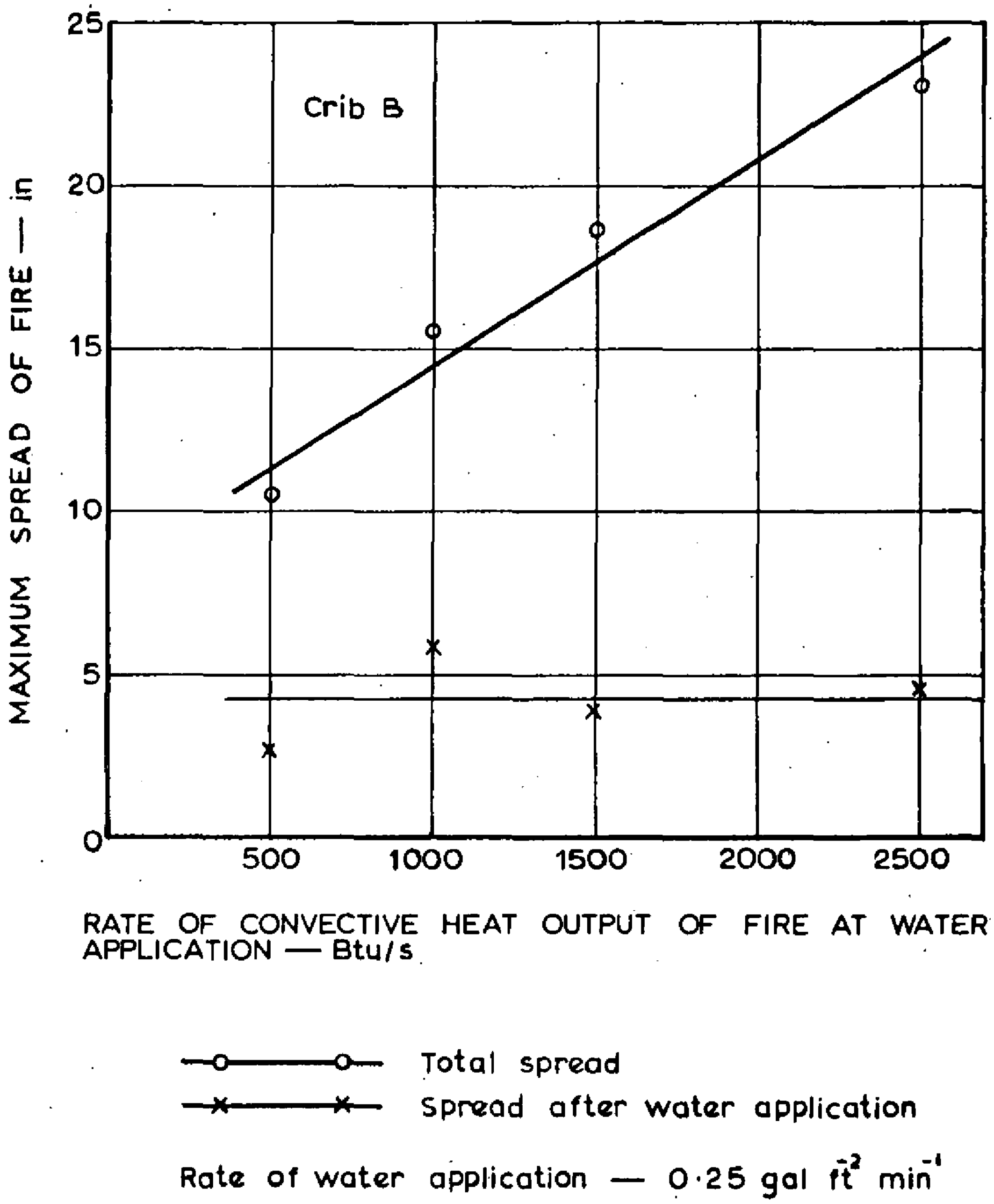

FIG.3. VARIATION OF FIRE SPREAD WITH FIRE SIZE AT WATER APPLICATION

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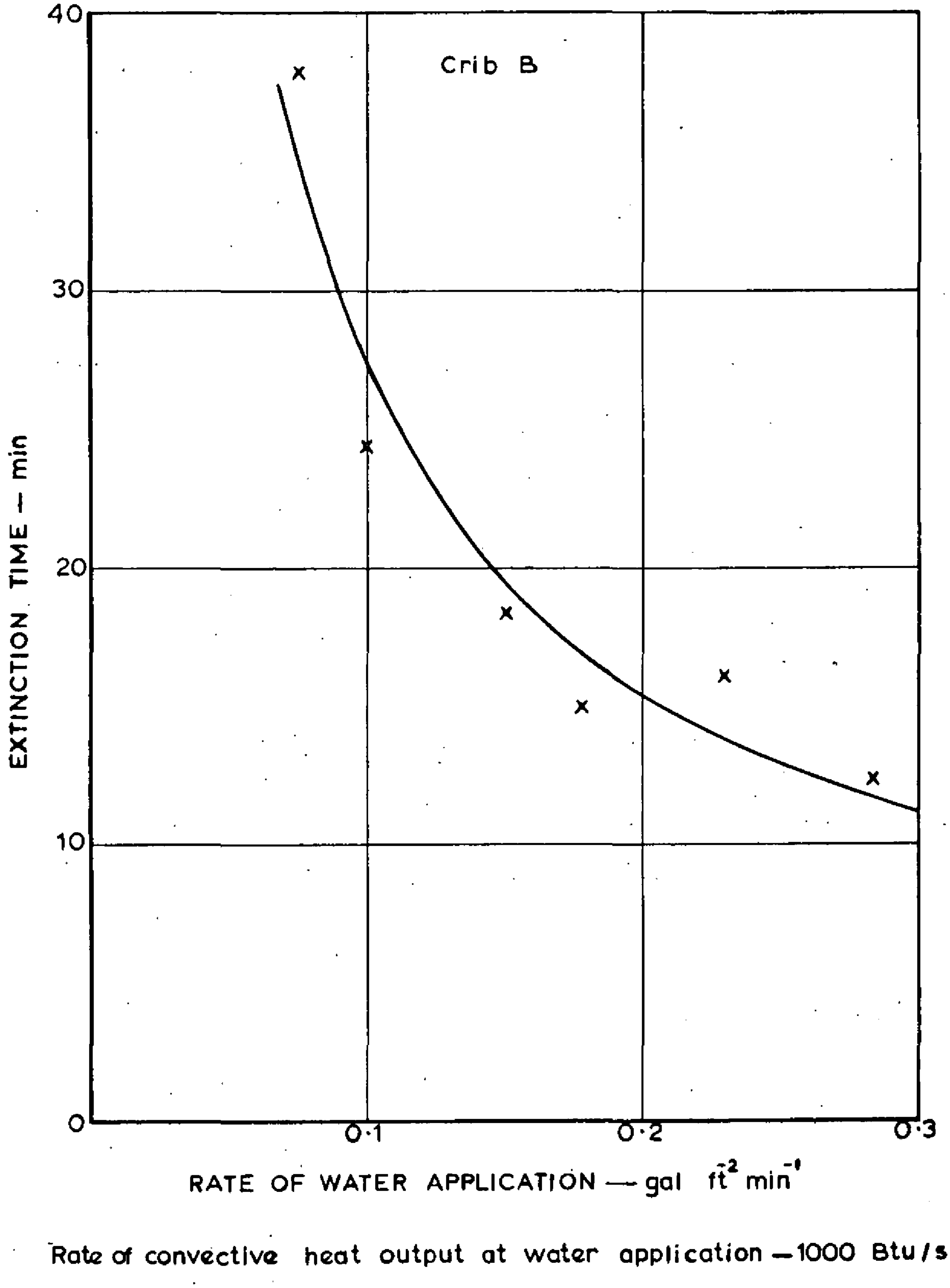

FIG. 4. VARIATION OF EXTINCTION TIME WITH RATE OF WATER APPLICATION

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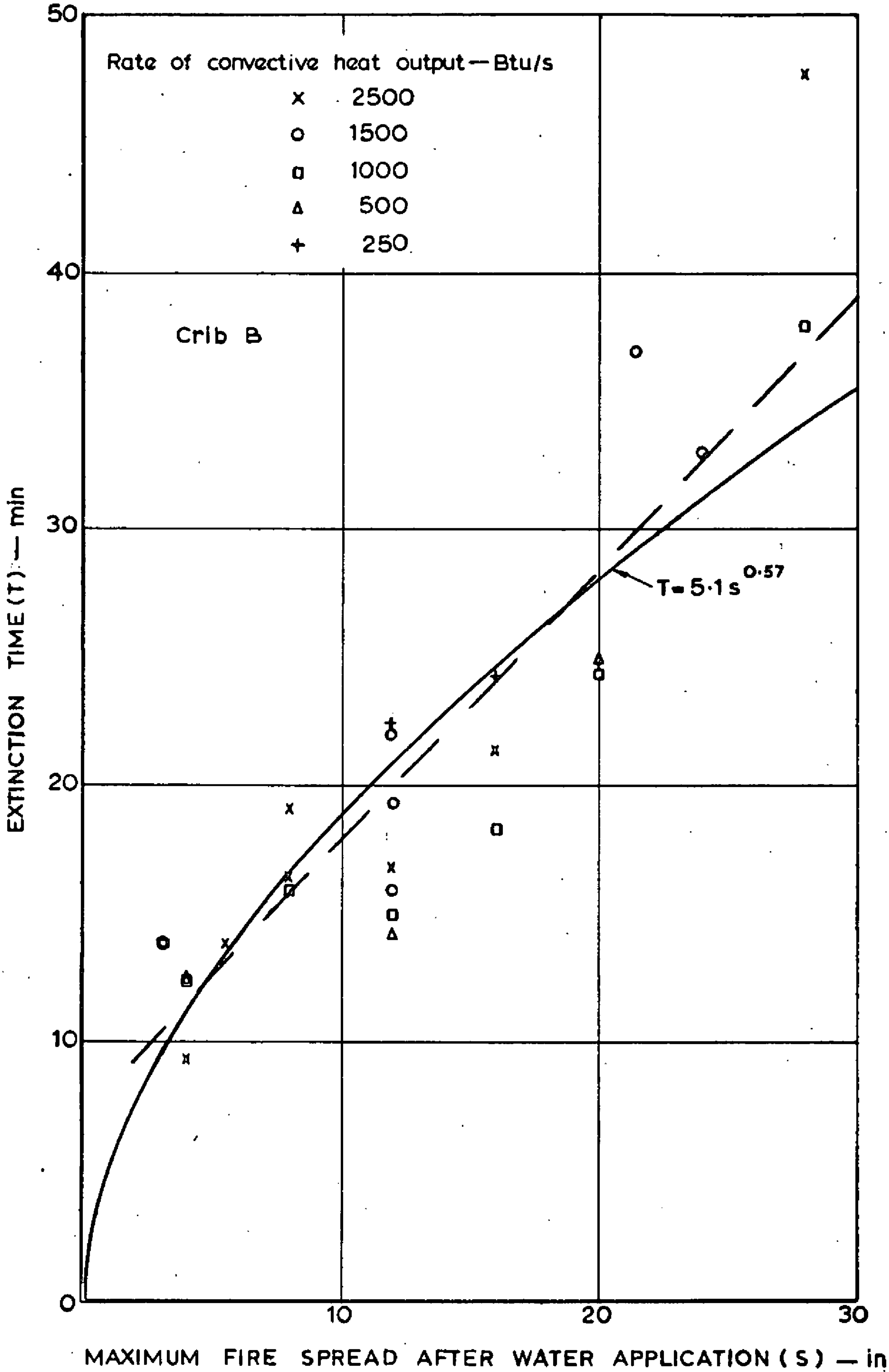

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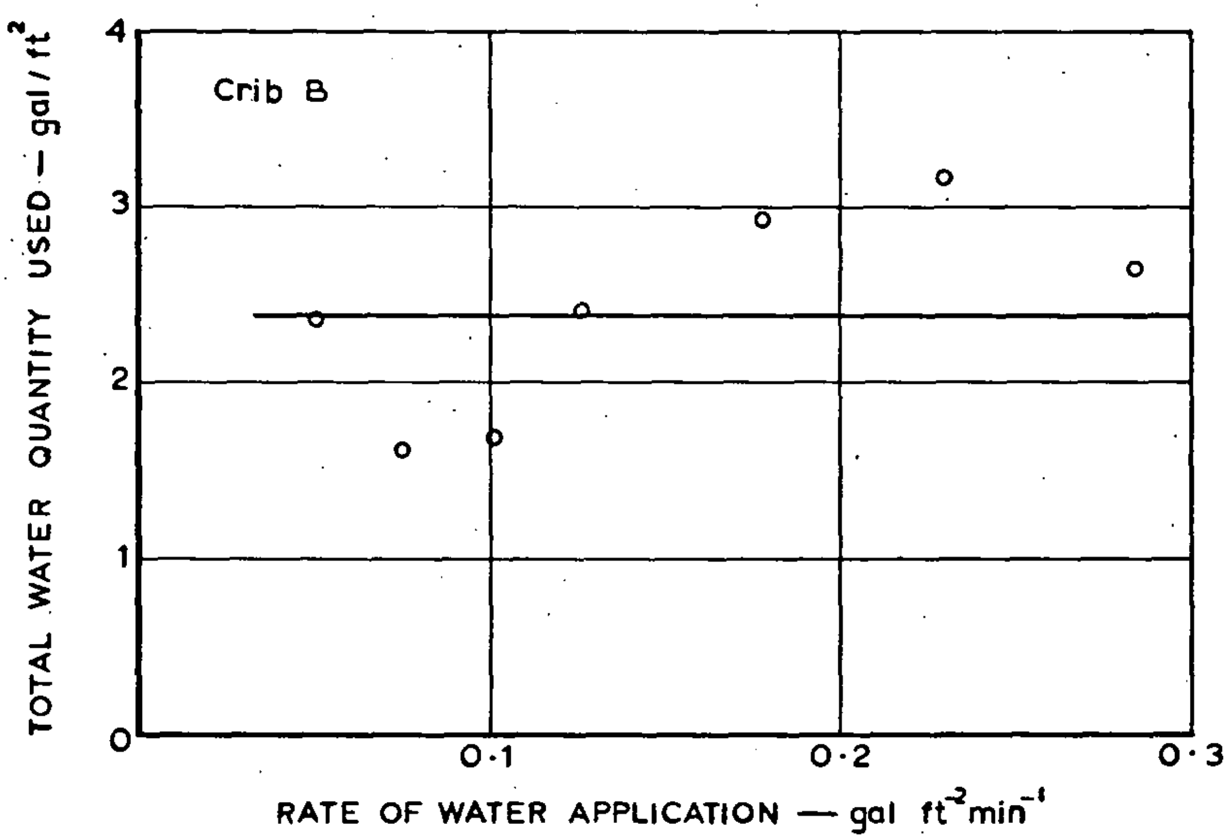
FIG. 5. RELATIONSHIP BETWEEN EXTINCTION TIME AND FIRE SPREAD AFTER WATER APPLICATION



Rate of convective heat output at water application — 2500 Btu/s

FIG. 6. RELATIONSHIP BETWEEN QUANTITY OF WATER USED AND RATE OF APPLICATION

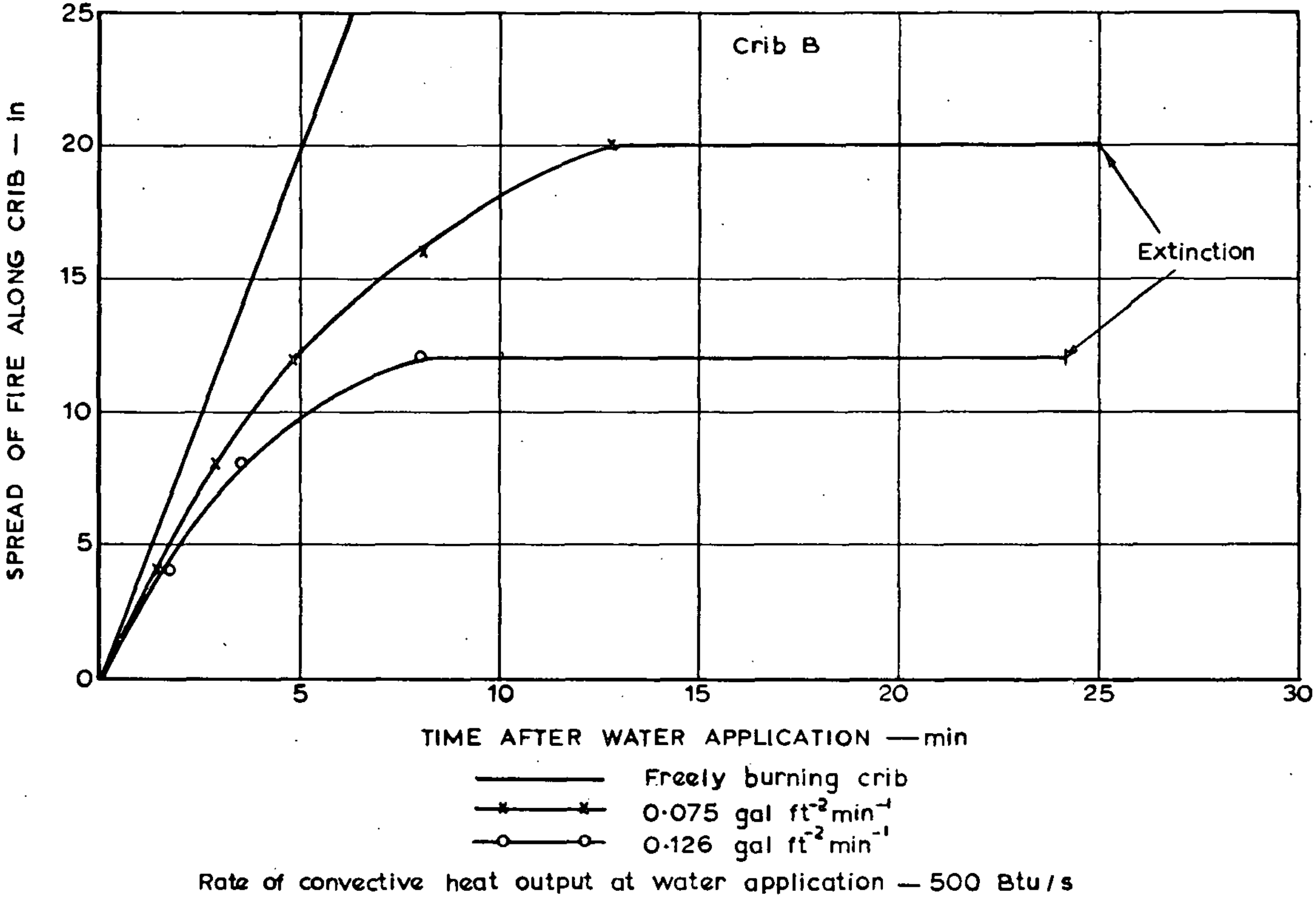
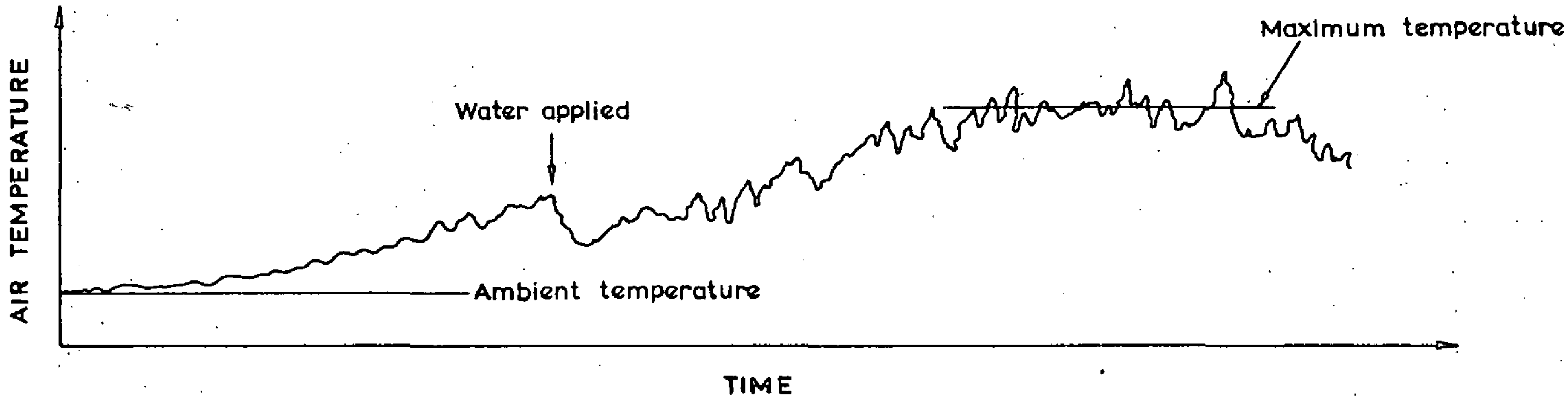
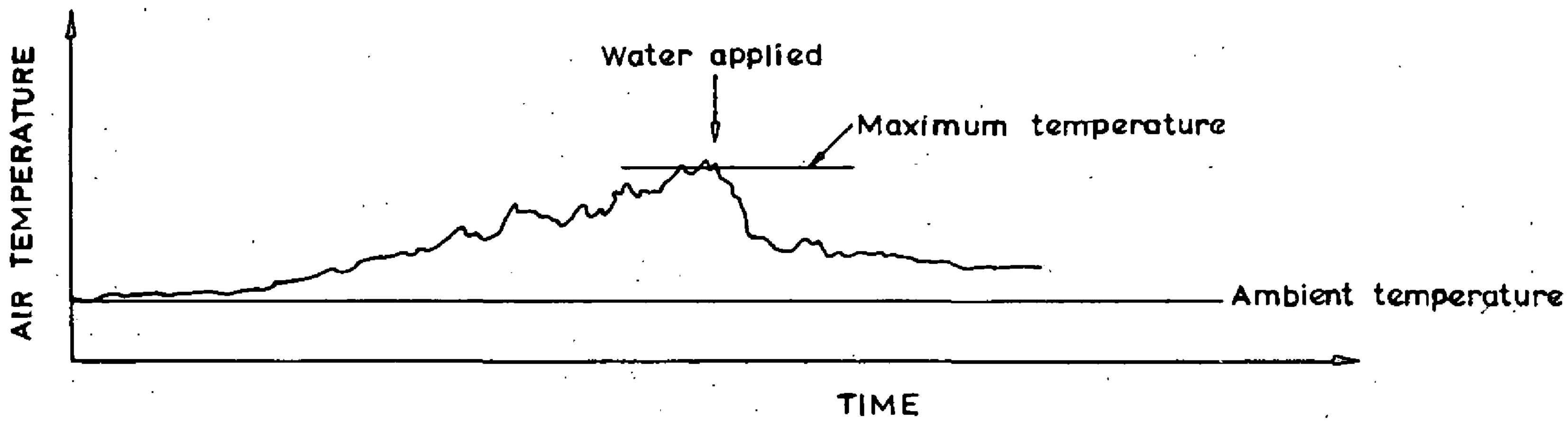


FIG.7. VARIATION OF FIRE SPREAD WITH TIME



(a) Rate of water application less than 0·23 gal ft^{-2} min^{-1}



(b) Rate of water application of 0·23 gal ft^{-2} min^{-1} or more

FIG.8. DIAGRAMMATIC REPRESENTATION OF VARIATION OF AIR TEMPERATURE AT CEILING LEVEL WITH TIME

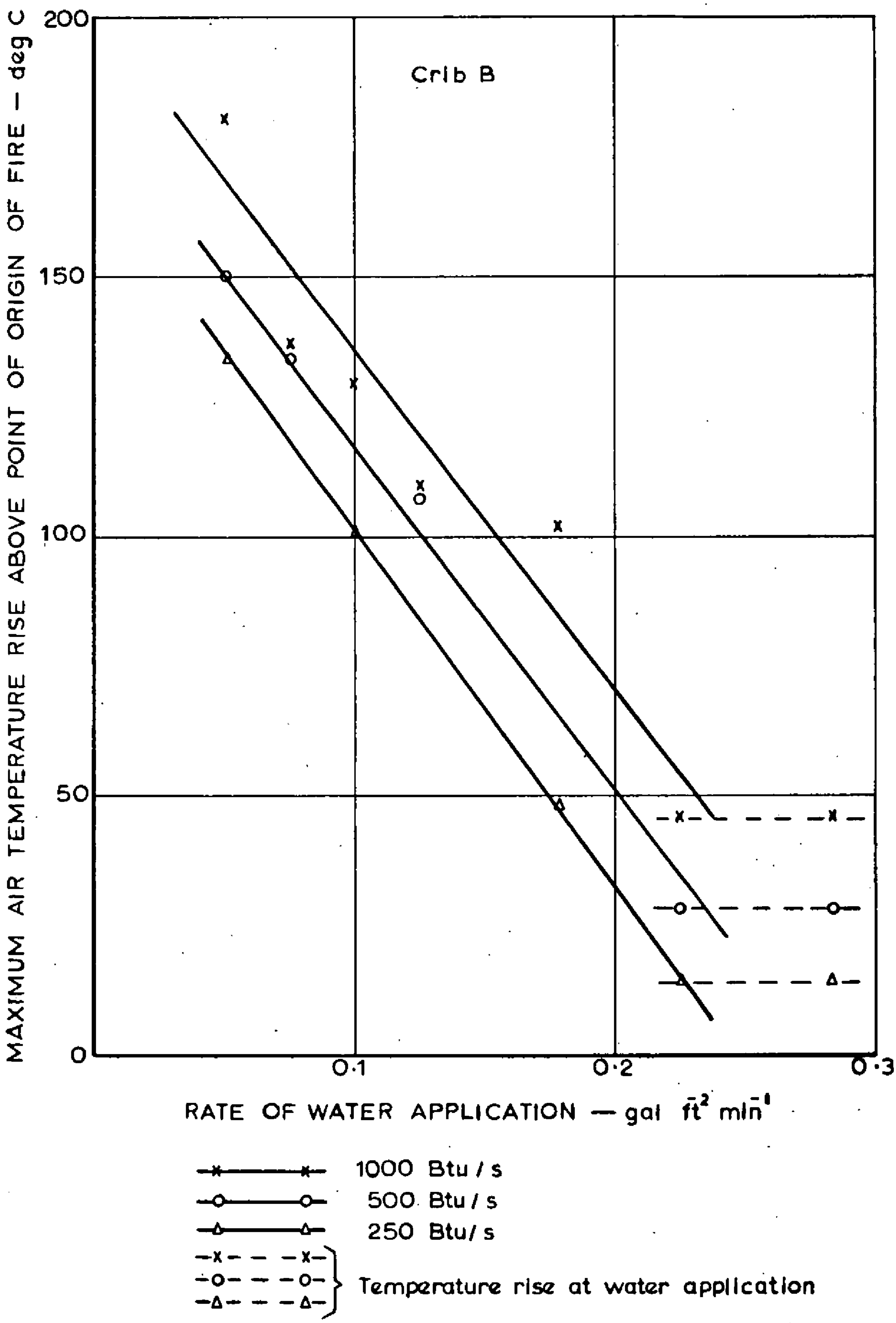


FIG. 9. VARIATION OF MAXIMUM AIR TEMPERATURE RISE WITH RATE OF WATER APPLICATION

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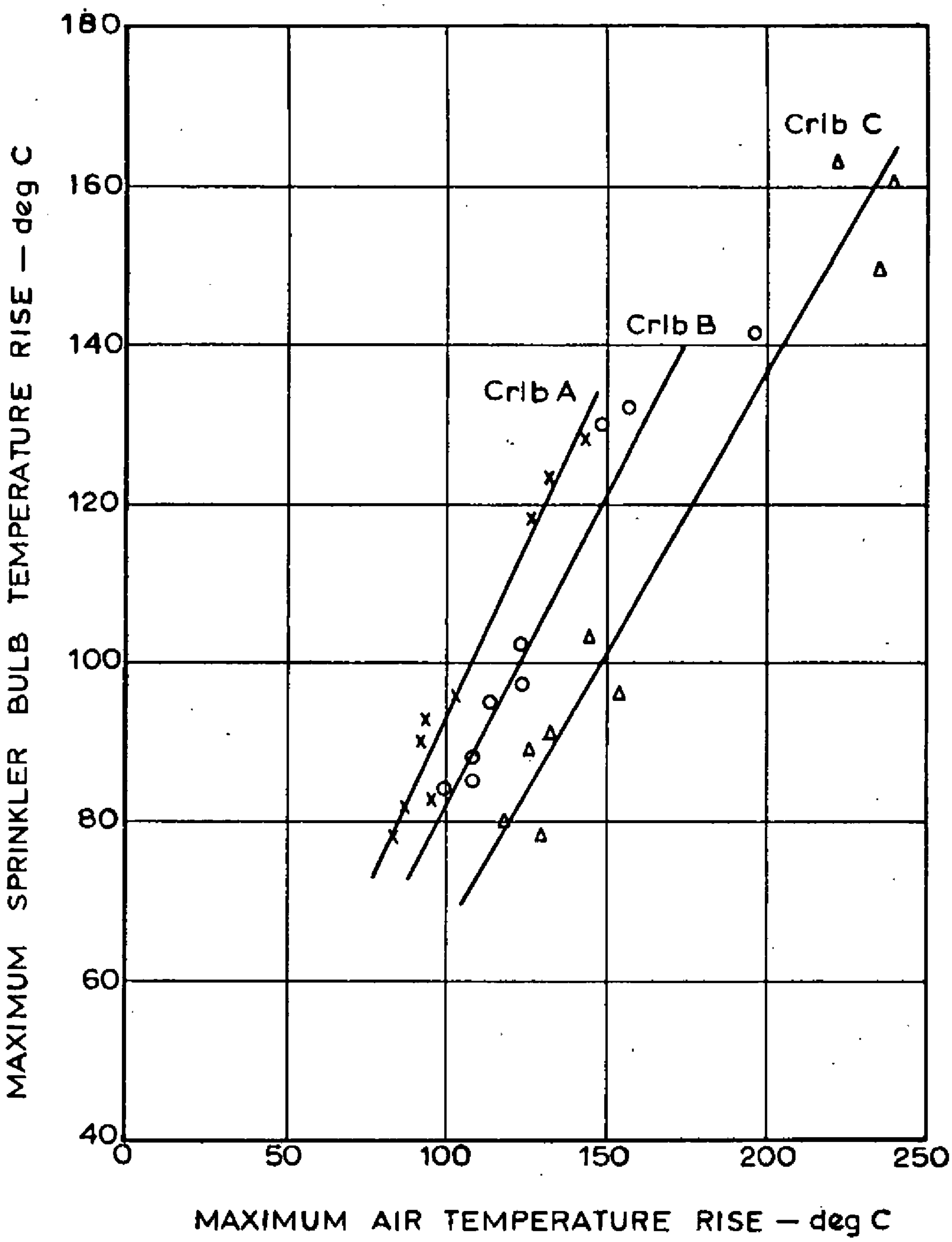

36 ft ceiling height: sprinklers at 8 in below ceiling joist

FIG.10. RELATIONSHIP BETWEEN MAXIMUM SPRINKLER BULB TEMPERATURE AND MAXIMUM AIR TEMPERATURE

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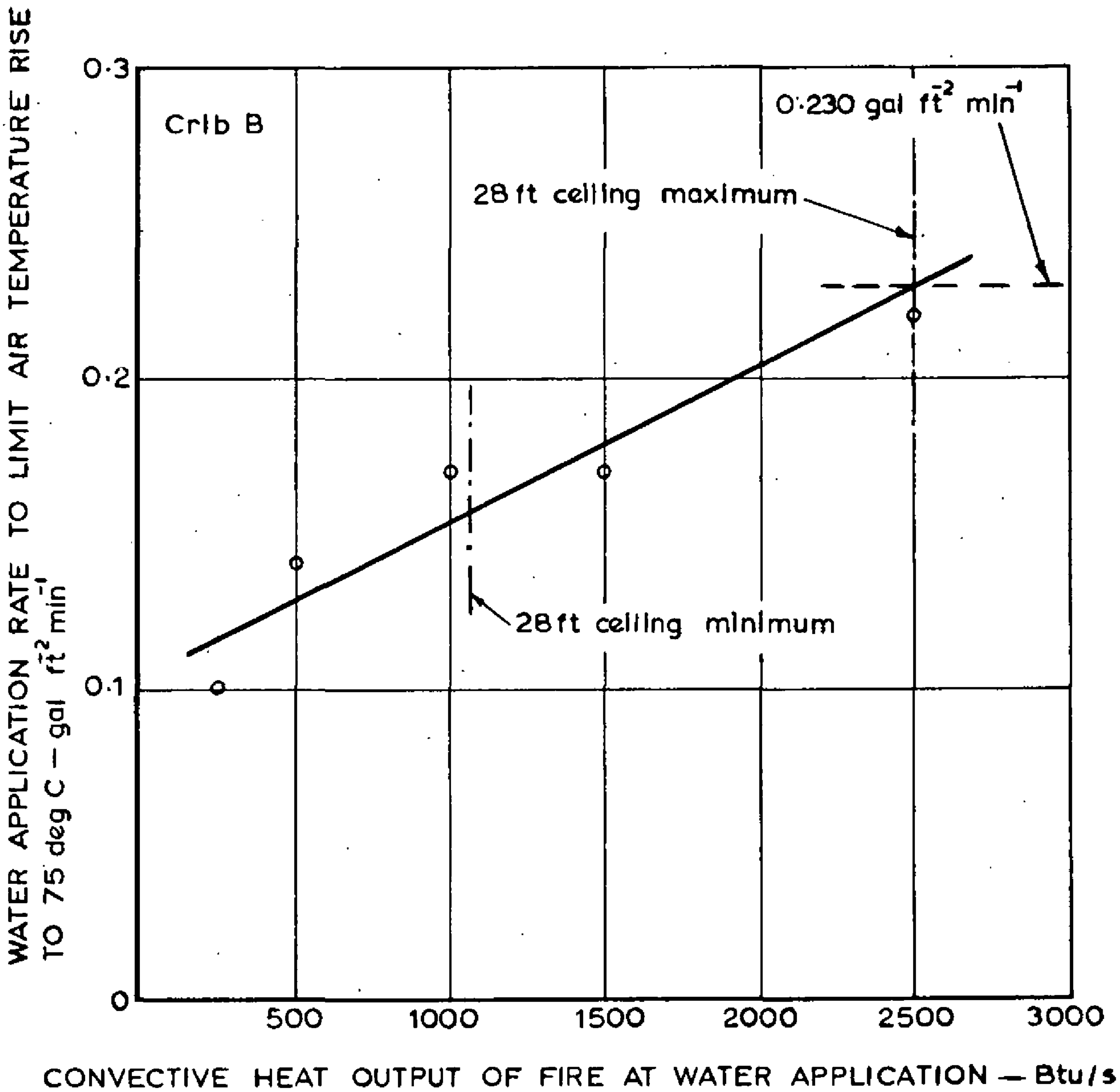

Measurements at 15 ft from vertical axis of fire

FIG. 11. VARIATION OF RATE OF WATER APPLICATION REQUIRED TO PREVENT SPRINKLER OPERATION WITH FIRE SIZE

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