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CONSIDERATIONS OF THE FIRE SIZE TO OPERATE, AND THE WATER DISTRIBUTION FROM AUTOMATIC SPRINKLERS

by

M. J. O'DOGHERTY and P. NASH

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SUMMARY

A method is suggested for specifying an acceptable level of uniformity of water distribution below a sprinkler array. The method is based on the area of fire just sufficient to operate 16 sprinklers, and is expressed in terms of a maximum acceptable percentage of the wetted floor area receiving less than a minimum acceptable water flow per unit area.

The effects of ceiling height, fire load, sprinkler rating and area of sprinkler coverage on the specified requirements are examined.

KEY WORDS: Area; burning rate; distribution; fire load; sprinkler; water.

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1. INTRODUCTION

Measurements of the water distribution from sprinkler arrays generally show an area at the centre of the array where the rate of flow per unit floor area is lower than at other places[1,2] and if it is too low, there is danger that a fire starting in this area may grow to sufficient size to continue to spread. Sprinklers may then be opened progressively over a wider area until the water available becomes insufficient to feed all the opened sprinklers at the necessary flow rate, and the fire gets beyond the control of the system.

The purpose of this note is to indicate the largest size of fire which can be tolerated if the maximum number of sprinklers to be operated is specified. It is also to suggest criteria for the uniformity of water distribution below sprinkler arrays which will ensure that the calculated maximum permissible size of fire is not exceeded.

2. OPERATION OF SPRINKLERS IN AN ARRAY

A sprinkler matrix of 3.05 m (10 ft) square module is shown in Figure 1, together with the radial distances of surrounding sprinklers from the central point of the central array of four sprinklers. The centre of the array is chosen as the point of fire origin, as it is in this region that the rate of water application per unit area is generally at a minimum[1,2] and the fire is at its furthest distance from the nearest sprinkler. The square of four sprinklers immediately surrounding the fire is the 'first line of defence' and will be in operation when the fire has a sufficient rate of convective heat output to operate sprinklers at a distance of 2.16 m (7.1 ft). The second square of sprinklers surrounding the fire will be operated when the fire is large enough to open sprinklers at a distance of 6.45 m (21.2 ft), making a total of 16 sprinklers in operation at this stage of fire growth. The third square of sprinklers will be operated if the fire continues to develop to a size where it can open sprinklers at distances from 7.77 m (25.5 ft) to 10.8 m (35.4 ft), at which stage there would be a total of 36 sprinklers in operation. The foregoing statements assume uniform radial air velocity distribution from the fire, and that all sprinklers have the same operating temperature.

The records of the National Fire Protection Association, covering a total of 67,457 reported fires involving sprinkler operation in the period 1925-1959[3], show that 70 per cent of fires involve 4 sprinklers or less, 91 per cent involve 16 sprinklers or less and 96 per cent involve 36 sprinklers or less.

3. FIRE SIZES AT SPRINKLER OPERATION

The 'size' of fire required to operate a sprinkler is most suitably expressed as the rate of convective heat output at the moment of operation. A number of factors affect the size of fire at sprinkler operation, such as rate of fire development, ceiling height, horizontal distance of the sprinkler from the fire, and depth of the sprinkler below the ceiling or roof[4]. In order to study the size required to operate sprinklers at various distances, the results of research on sprinklers have been taken for a fire with an intermediate development rate (crib B)[4], which had a fire load of wood of approximately 125 kg/m^2 (25.6 lb/ft^2), representing 550,000 k cal/m^2 (205,000 Btu/ft^2). The rates of convective heat output at operation of a 155°F (68°C) sprinkler, up to horizontal distances of 6.10 m (20 ft) from the fire are shown in Figure 2, for ceiling heights of 11.0 m (36 ft) and 3.66 m (12 ft). These results were obtained for sprinklers mounted 20.3 cm (8 in) below the ceiling, and are extrapolated for the 6.10 m (20 ft) distance, since the maximum distance used in the experiments was 4.57 m (15 ft)[4].

The rates of convective heat output shown in Figure 2 can be transformed into fire plan areas from measurements of fire spread made on the particular fire considered; the relationship obtained between the rate of convective heat output and fire plan area is shown in Figure 3. The plan areas of the fires at sprinkler operation are shown plotted against horizontal distance of the sprinkler from the fire in Figure 4, for the two ceiling heights considered. Areas appropriate to ceiling heights of 6.10 and 8.55 m (20 and 28 ft) are also included in this figure.

4. LIMITATION OF FIRE SIZE

The size to which a fire develops must be limited so as to avoid the operation of a large number of sprinklers, with the consequent danger of a reduction in the rate of water flow to the sprinklers actually discharging onto the fire. The number of sprinklers which can open without an appreciable fall in water flow rate is dependent on the system design and on the pressure-flow characteristics of the water supplies. It is reasonable in normal risks to expect the sprinklers to control the fire by the operation of not more than the second square surrounding the fire (Figure 1), i.e. to a total of 16 sprinklers, on the assumption that if more sprinklers operate there is a danger that the system will be unable to control the fire spread. If the fire considered in Section 3 is taken as an example, assuming a 3.05 m sprinkler spacing, then the maximum permissible area of fire, to limit sprinkler operation to 16 heads, can be obtained from Figure 4. The relevant size of fire is that applicable to operation of a sprinkler at 6.45 m (21.2 ft) (the maximum distance in the square of 16 sprinklers), which means the fire must be restricted to within 1.13 m^2 (12.1 ft^2) and 0.42 m^2 (4.4 ft^2) for the 11.0 m and 3.66 m ceiling heights, respectively. For the 3.05 m spacing, these areas represent percentages of the sprinkler coverage 9.29 m^2 (100 ft^2) of 12.1 and 4.4 per cent respectively for the two ceiling heights.

5. WATER DISTRIBUTION

The water distribution below the sprinkler array must be such that for a fire occurring at the centre of the array, there is a sufficient rate of flow per unit plan area around the fire to prevent it spreading beyond the critical area required to cause operation of 16 sprinklers. The flow rate of water per unit area required to prevent fire spread is dependent on the nature and geometrical arrangement of the burning material. In the case of the fire described in Section 3, a minimum rate of 3.8 mm min^{-1} (0.075 gal $ft^{-2} min^{-1}$) was generally required, although in a few experiments a rate of 2.5 mm min^{-1} (0.05 gal ft^{-2} min^{-1}) was found to be adequate[4]. As a criterion of design of a sprinkler installation to control this particular fire, a mean rate of water application of 4.9 mm min^{-1} (0.1 gal ft^{-2} min^{-1}) is suggested.

To establish a criterion for the <u>eveness</u> of the water distribution measured under an array of sprinklers, it is suggested that not <u>more</u> than the area of the fire required to operate 16 sprinklers should receive <u>less</u> than 2.5 mm min^{-1} (0.05 gal ft^{-2} min^{-1}) of water. For the 3.05 m spacing discussed in Section 3, this means that for a 11.0 m high ceiling, not more than 12.1 per cent of the area of coverage beneath the array shall receive less than 2.5 mm min^{-1}, and for the 3.66 m ceiling, not more than 4.4 per cent shall receive less than 2.5 mm min^{-1}.

6. FIRE LOAD AND SPRINKLER SPACING

The fire load can be expressed in terms of the calorific value of the combustible material per unit floor area, e.g. in units of k cal/m^2 (Btu/ft^2). For a particular value of fire load, the rate of burning per unit plan area is dependent on the nature of the materials, on their size and shape and on their geometric arrangement. In order to simplify the treatment, a configuration of fuel similar to that for crib B is assumed, so that if the fire load is doubled, the material would be stacked to twice the height. In addition, it is assumed that for a given fire area, the rate of burning is proportional to the height of stack.

The effect of changes in sprinkler spacing is to change the size of fire at sprinkler operation. For a fire at the centre of a square array of four sprinklers, the distance to the furthest sprinkler in a square of 16 sprinklers is 5.18, 6.46 and 7.38 m (17, 21.2 and 24.2 ft) for spacings of 2.44, 3.05 and 3.48 m (8, 10 and 11.4 ft) respectively, i.e. coverages of 5.95, 9.29 and 12.08 m^2 (64, 100 and 130 ft^2).

Table 1 shows the plan areas of fires at operation of the furthest of the 16 sprinklers from the fire, for fire loads ranging from 136,000 to 1,084,000 k cal/m^2 (50,000 to 400,000 Btu/ft^2), and for sprinkler coverages ranging from 5.95 to 12.08 m^2. The areas are based on the experimental results for crib B (fire load 555,000 k cal/m^2 (205,000 Btu/ft^2)) (Figure 3) assuming that the convective heat output per unit plan area is proportional to the fire load.

The plan areas shown in Table 1 are given in Table 2 as percentages of the sprinkler coverage; these percentages are plotted in Figures 5 and 6 for the 3.66 m and 11.0 m ceiling heights respectively.

Figures 5 and 6 show that as the fire load increases progressively from 136,000 k cal/m^2, the plan area of fire necessary to operate the first 16 sprinklers reduces inversely. Thus for a 9.29 m^2 sprinkler coverage under an 11 m ceiling, 47.6 per cent of the nominal coverage would be involved in order to operate 16 sprinklers, whereas at 1,084,000 k cal/m^2, only some 6.0 per cent would need to be involved.

The higher the fire load, therefore, the smaller the proportion of the covered area which can be permitted to receive less than a minimum water distribution necessary to check growth of the fire. There is also likely to be a <u>maximum</u> acceptable proportion of the covered area with less than the stipulated minimum, however light the fire load may be. This is set by the need to avoid the conjunction of areas of low water distribution, across the common boundaries of adjacent sprinkler patterns. An upper limit of 20 per cent of the coverage is suggested to avoid this conjunction of areas, equivalent to the difference between the nominal coverage and a circular area of diameter approximately equal to half the sprinkler spacing.

At higher fire loads the permissible area must be reduced, so that at 1,084,000 k cal/m^2, not more than 5 per cent of the coverage should receive less than the stipulated rate of water discharge per unit area. In addition, at such higher fire loads, the average rate of water discharge per unit area will also have to be increased, and a stipulated rate of half the average is suggested on the appropriate permissible area. Hence if the average rate required is 9.8 mm min^{-1} (0.2 gal ft^{-2} min^{-1}), then not more than 5 per cent of the coverage should receive less than 4.9 mm min^{-1} (0.1 gal ft^{-2} min^{-1}) for a fire load of 1,084,000 k cal/m^2.

Table 1

Plan area of fire at operation of 16 sprinklers

Fire load k cal/m^2 (Btu/ft^2)	Fire plan area - m^2 (ft^2)					
	Sprinkler coverage					
	5.95 m^2 (64 ft^2)		9.29 m^2 (100 ft^2)		12.08 m^2 (130 ft^2)	
	11.0 m (36 ft) ceiling	3.66 m (12 ft) ceiling	11.0 m (36 ft) ceiling	3.66 m (12 ft) ceiling	11.0 m (36 ft) ceiling	3.66 m (12 ft) ceiling
136,000 (50,000)	3.94 (42.4)	1.49 (16.0)	4.43 (47.6)	1.64 (17.6)	4.85 (52.4)	1.71 (18.4)
271,000 (100,000)	1.97 (21.2)	0.74 (8.0)	2.22 (23.8)	0.82 (8.8)	2.44 (26.2)	0.85 (9.2)
542,000 (200,000)	0.99 (10.6)	0.37 (4.0)	1.11 (11.9)	0.41 (4.4)	1.22 (13.1)	0.43 (4.6)
1,084,000 (400,000)	0.49 (5.3)	0.19 (2.0)	0.55 (5.95)	0.20 (2.2)	0.61 (6.55)	0.21 (2.3)

Table 2

Area of fire as a percentage of coverage at operation of 16 sprinklers

Fire load (k cal/m²)	Fire area as percentage of sprinkler coverage					
	Sprinkler coverage (m²)					
	5.95		9.29		12.08	
	11.0 ceiling	3.66 m ceiling	11.0 m ceiling	3.66 m ceiling	11.0 m ceiling	3.66 m ceiling
136,000	66.0	25.0	47.6	17.6	40.2	14.2
271,000	33.1	12.5	23.8	8.8	20.2	7.1
542,000	16.5	6.3	11.9	4.4	10.1	3.5
1,084,000	8.3	3.1	6.0	2.2	5.1	1.8

Similar considerations for a 12.08 m^2 coverage on a 3.88 m ceiling (Fig. 5) show that more severe criteria are required because a relatively small fire can operate a large number of sprinklers on a low ceiling. For example, not more than 3.5 per cent of the area should receive less than 2.5 mm min^{-1} for fire loads up to 542,000 k cal/m^2 and even smaller areas for the higher fire loads.

The effect of changes in ceiling height on the fire area at operation of 16 sprinklers can be seen from Figure 7. This curve is plotted for a fire load of 555,000 k cal/m^2 (crib B) and a sprinkler coverage of 12.08 m^2. The fire area ranges from 3.5 to 10 per cent of the coverage (see above) over the range of ceiling heights from 3.66 to 11.0 m. The form of the curve would be expected to be linear[4], but a considerable extrapolation is required for the layer coverages, i.e. to 7.4 m (24.2 ft) for 12.8 m^2 compared with a maximum distance of 4.57 m used in the experimental work, which results in a measure of uncertainty.

Figure 8 shows the effect of changes in sprinkler coverage on the fire area at operation of 16 sprinklers expressed as a percentage of the coverage, taking a ceiling height of 11.0 m. The fire areas have been extrapolated to include a coverage of 20.9 m^2 (225 ft^2). The curves show that as the area of sprinkler coverage is increased, the criterion for water distribution becomes more severe, because the fire must be confined to a smaller percentage of the coverage. For example, taking a fire load of 542,000 k cal/m^2, an increase of coverage from 12.08 to 20.9 m^2 results in a reduction of the permissible fire area from 10 to 7 per cent. Therefore the criterion of water distribution for a 20.9 m^2 coverage must be that not more than 7 per cent should receive less water than 2.5 mm min^{-1}.

7. SPRINKLER RATING

An increase in sprinkler rating above the normal value of 68°C (155°F) results in a larger fire when sprinklers operate. In some circumstances, however, the size of fire for high rated sprinklers may be such that it is in danger of spreading beyond the first square of four sprinklers (Figure 1) if the water distribution is inadequate. Therefore, to avoid the danger a second criterion has to be adopted in which the maximum area of fire which can be tolerated has to be defined (see also section 5). It is suggested that a circle of diameter equal to half the sprinkler spacing be the limitation of fire spread, which represents 19.6 per cent of the sprinkler coverage, or 20 per cent in practical terms. This criterion will minimize the danger of fire spread between sprinklers where the rate of water discharge is likely to be relatively low.

Figures 9 and 10 show the plan areas of fires at sprinkler operation (for a fire configuration similar to crib B) for sprinkler ratings ranging from 68 to 260°C (155 to 500°F), at ceiling heights of 3.66 and 11.0 m.

Considering the curves for the 11.0 m ceiling (Figure 10), it can be shown that if the rating is raised to 93°C (200°F) it is possible for the fire to spread to 14.3 per cent of the coverage before 16 sprinklers have operated, assuming a sprinkler coverage of 12.08 m^2. Therefore, the criterion of water distribution can be reduced from the 10 per cent appropriate to a 68°C rating, to say, not more than 14 per cent of the area of coverage shall receive less than 2.5 mm min^{-1} of water. If a rating of 141°C (286°F) is considered, then the fire size has to be limited to 20 per cent of the coverage because a larger fire than this (22.3 per cent) is needed before 16 sprinklers are opened. The curves show that when a fire occurs at the centre of the area covered by the array, four sprinklers of 141°C rating will be operated. If the fire is limited to 20 per cent of the area covered, it will not be large enough to operate sprinklers rated at 182°C (360°F) and higher.

The curves for the 3.66 m ceiling (Figure 9) show that 16 sprinklers will operate before the upper limit of fire area of 20 per cent is reached for ratings up to 260°F (500°F). Therefore all normally used ratings can be employed, with a restriction on the fire area which is dependent on the rating. For example, for a 141°C rating the criterion is that not more than 8.2 per cent of the coverage (12.08 m^2) should receive less than 2.5 mm min^{-1} of water.

8. DISCUSSION AND CONCLUSIONS

1. The purpose of this note is to establish quantitative criteria for water distribution patterns beneath sprinkler arrays. The approach is to specify that not more than a certain percentage of the area of sprinkler coverage shall receive less than a specified rate of water flow per unit area. The maximum area has been defined as that of the fire which can cause operation of the 16 sprinklers adjacent to the point of fire origin. The specification of the rate of water flow per unit area is dependent on the fire risk, and a figure of 50 per cent of the average rate required for the control of fire spread has been suggested. As an example, it is shown that for a crib type of fire with fire loads of 542,000 k cal/m^2 and below, operating sprinklers on a 11.0 m ceiling, if a 12.08 m^2 coverage is assumed, not more than 10 per cent of the coverage should receive less than 2.5 mm min^{-1} of water.

2. In some circumstances the area of fire required to cause operation of 16 sprinklers may form a relatively large percentage of the coverage, e.g. for small fire loads and/or high sprinkler ratings. This means that a further condition is necessary to avoid the possibility of fire spread between sprinklers and a figure of 20 per cent of the coverage is suggested as an upper limit to the area which can be permitted to receive less than a particular flow rate of water per unit area.

3. The criterion specified for the water distribution is dependent on such factors as fire load, sprinkler spacing, ceiling height and sprinkler rating, since these factors all affect the size of fire which may result in the operation of 16 sprinklers. The effects of these factors have been discussed, and a summary table is given in Table 3. This table includes percentage fire areas for a 20.9 m^2 coverage, although these represent a considerable extrapolation of the experimental results.

Table 3

Area of fire as a percentage of coverage at operation of 16 sprinklers

Fire load (k cal/m2)	Sprinkler rating (°C)	Ceiling height (m)					
		11.0			3.66		
		Coverage (m^2)			Coverage (m^2)		
		9.29	12.08	20.90	9.29	12.08	20.90
271,000	68	20 (1)	20 (1)	13.8	9.0	7.0	4.6
	93	20 (1)	20 (1)	19.8	12.6	10.4	6.8
	141	20 (1)	20 (1)	20 (1)	19.8	16.4	10.8
542,000	68	12.0	10.0	6.9	4.5	3.5	2.3
	93	17.2	14.3	9.9	6.3	5.2	3.4
	141	20 (1)	20 (1)	15.4	9.9	8.2	5.4
1,084,000	68	6.0	5.0	3.5	2.3	1.8	1.2
	93	8.6	7.2	5.0	3.2	2.6	1.7
	141	13.4	11.0	7.7	5.0	4.1	2.7

(1) Maximum percentage area to which fire can be allowed to spread.

The effect of increasing the sprinkler coverage and the fire load is that a more severe criterion of the limits of fire spread, i.e. a smaller percentage fire area can be tolerated. Increases in ceiling height and sprinkler rating, however, result in a less severe criterion.

The rate of water flow per unit area will be dependent on fire load. For loads of 542,000 k cal/m^2 for example, it is suggested that not more than the areas shown in Table 3 should receive less than 0.041 l m^{-2} s^{-1}. At higher fire loads the mean rate of flow per unit area may have to be increased above the 5 mm min^{-1} suggested for the 542,000 k cal/m^2 load, and at lower fire loads a smaller figure may be adequate.

Table 3 includes, for completeness, the 20.9 m^2 coverage for all fire loads, but in practice it is unlikely that such a large coverage would be used for any but small fire loads.

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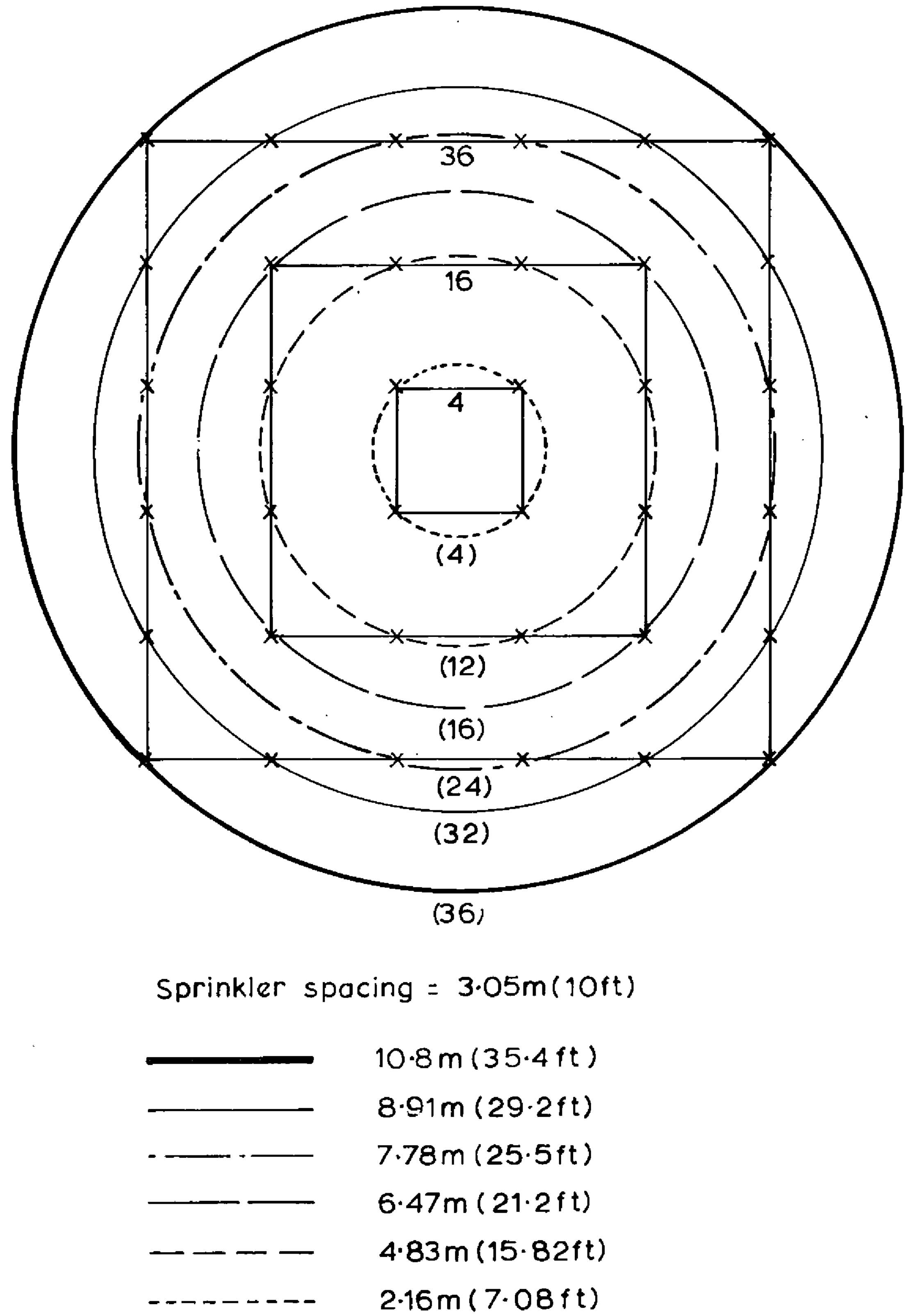
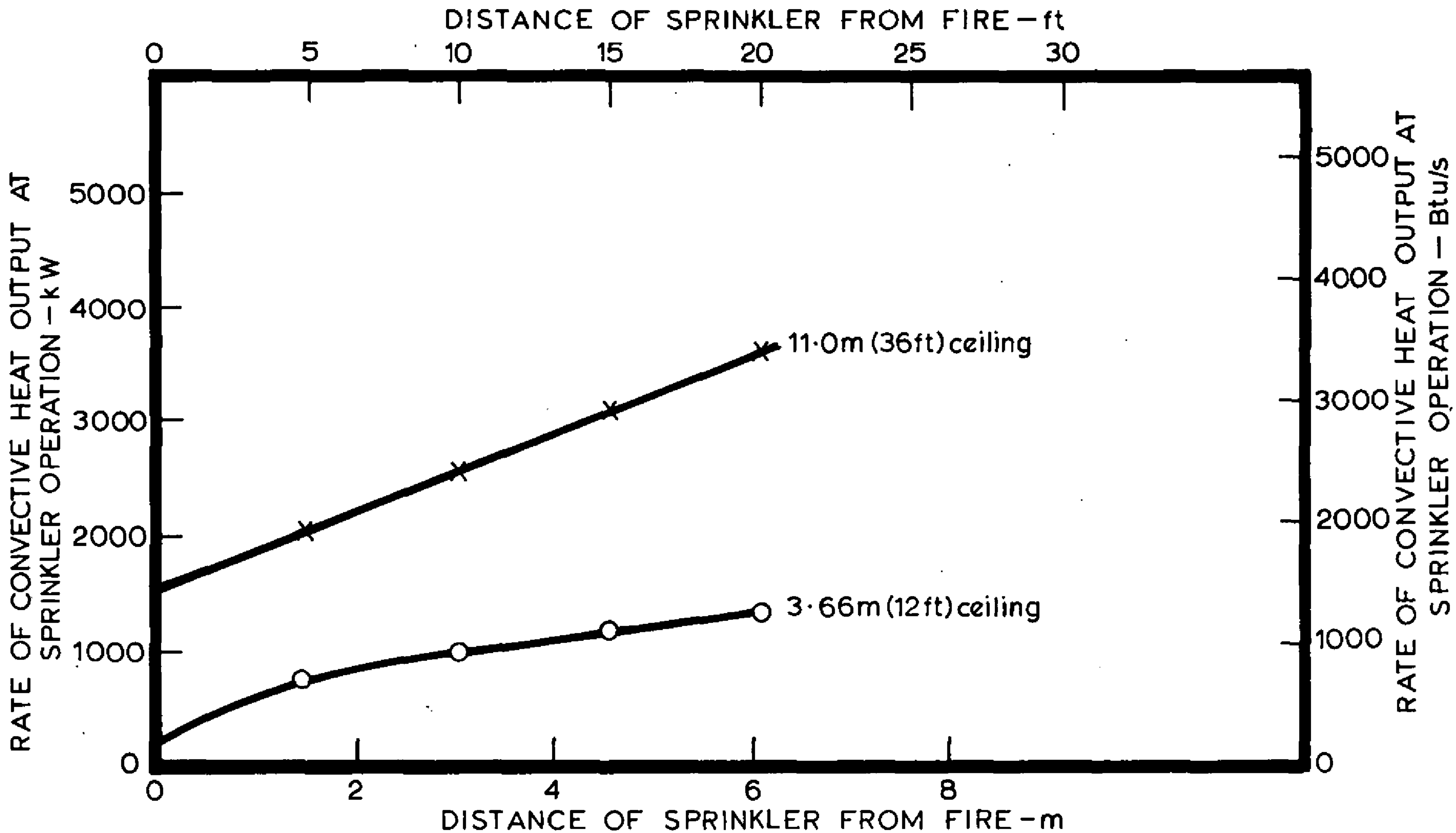
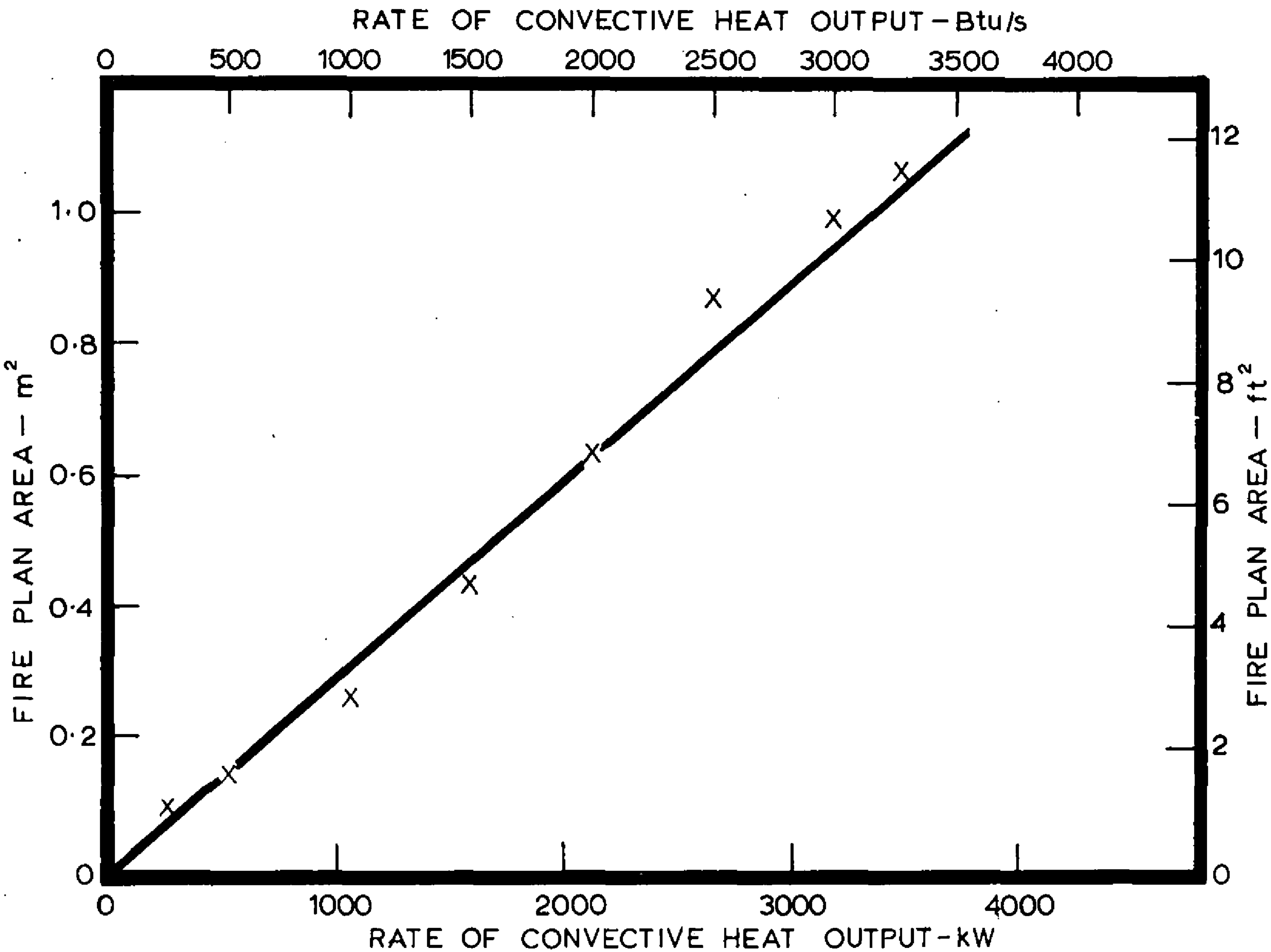


FIG. 1 DISTANCE OF SPRINKLERS FROM CENTRE POINT OF AN ARRAY OF FOUR



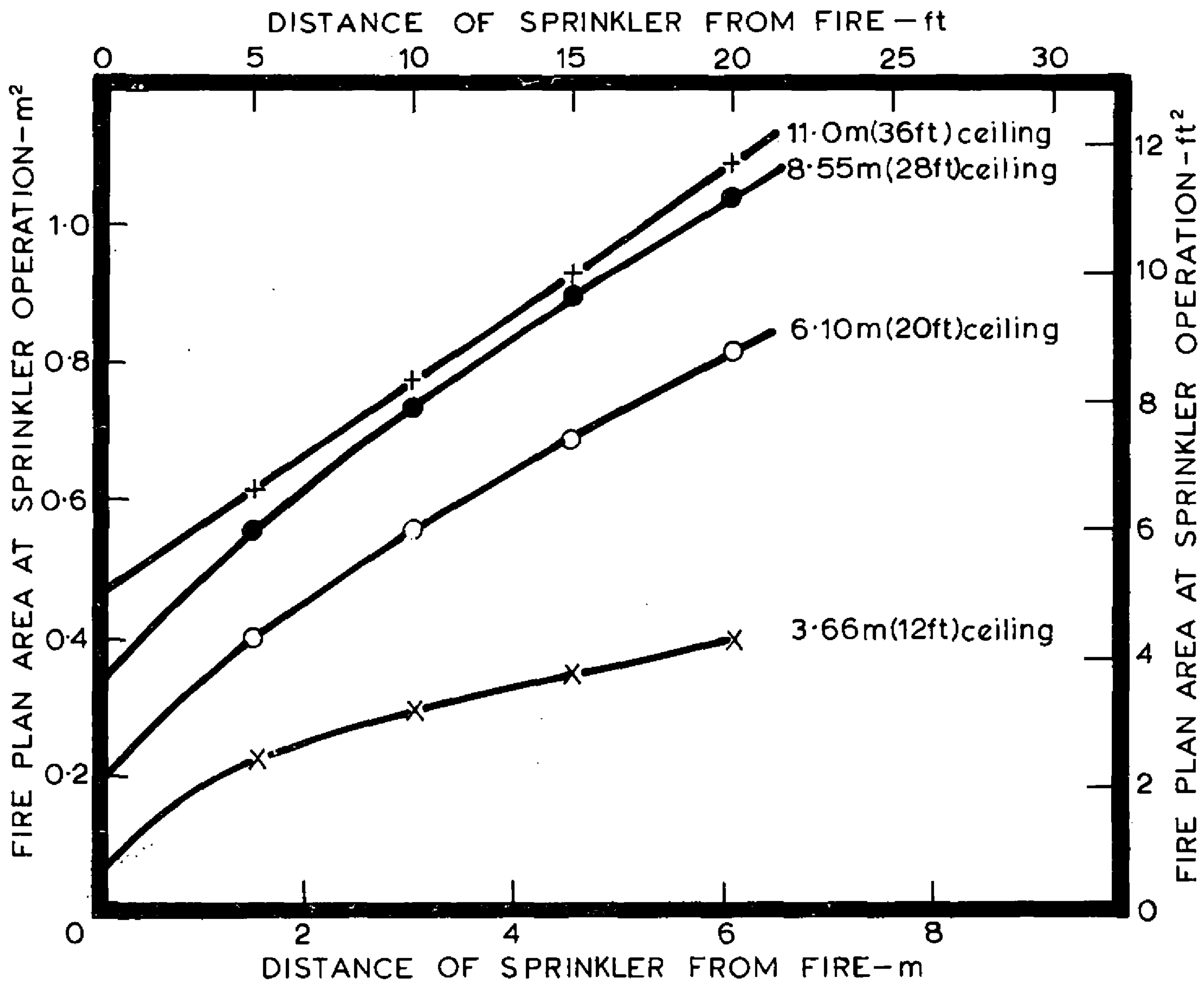
Fire load = 555,000 Kcal/m^2 (205 000 Btu/ft^2)

FIG. 2 VARIATION OF RATE OF CONVECTIVE HEAT OUTPUT AT SPRINKLER OPERATION WITH DISTANCE FROM FIRE



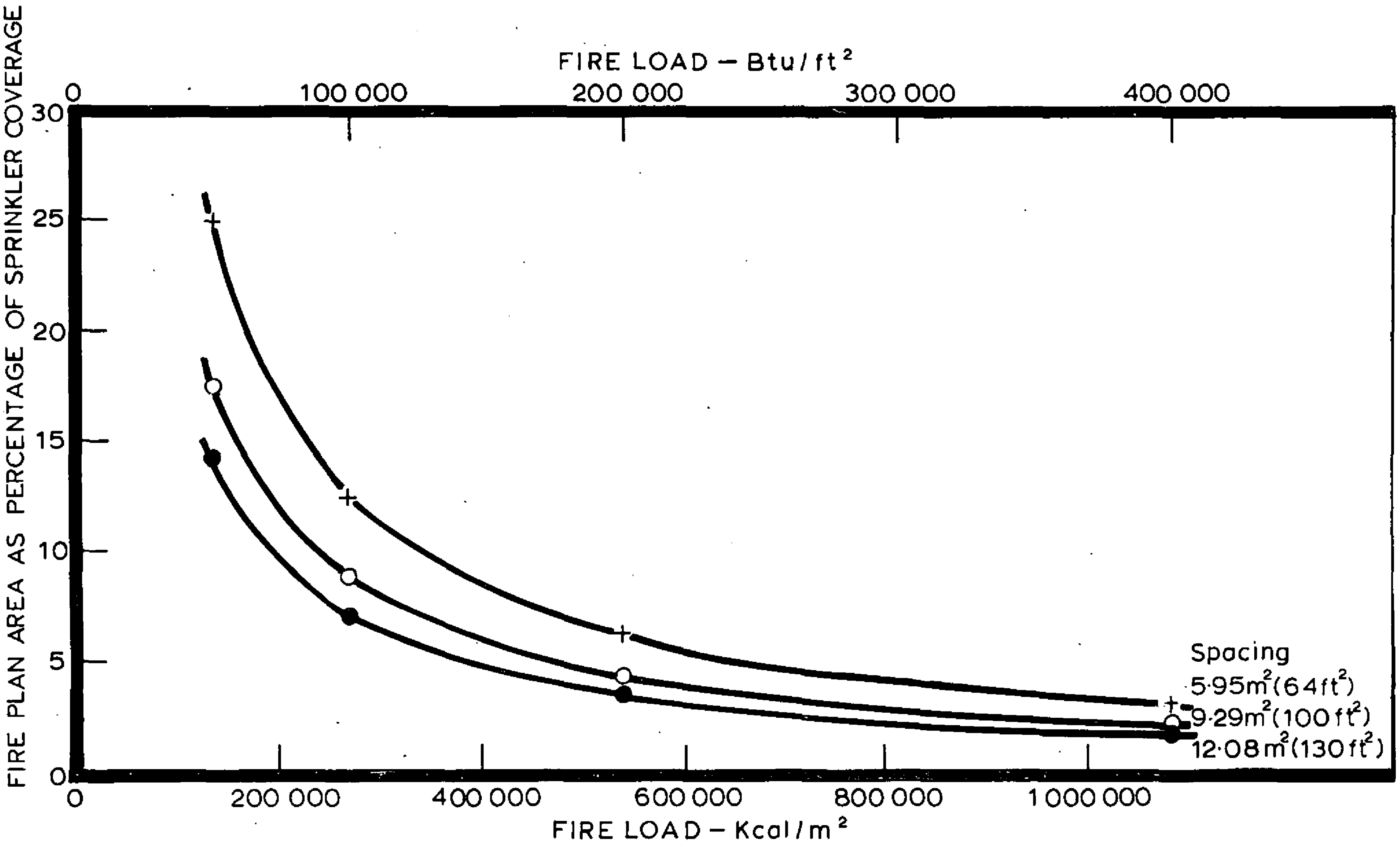
Fire load – 555 000 Kcal/m² (205 000 Btu/ft²)

FIG. 3 RELATION BETWEEN FIRE PLAN AREA AND RATE OF CONVECTIVE HEAT OUTPUT



Fire load = 555 000 Kcal/m² (205 000 Btu/ft²)

FIG.4 VARIATION OF FIRE PLAN AREA AT SPRINKLER OPERATION WITH DISTANCE FROM FIRE



3·66m (12ft)ceiling Operation of 16 sprinklers

FIG.5 VARIATION OF PERCENTAGE FIRE PLAN AREA WITH FIRE LOAD

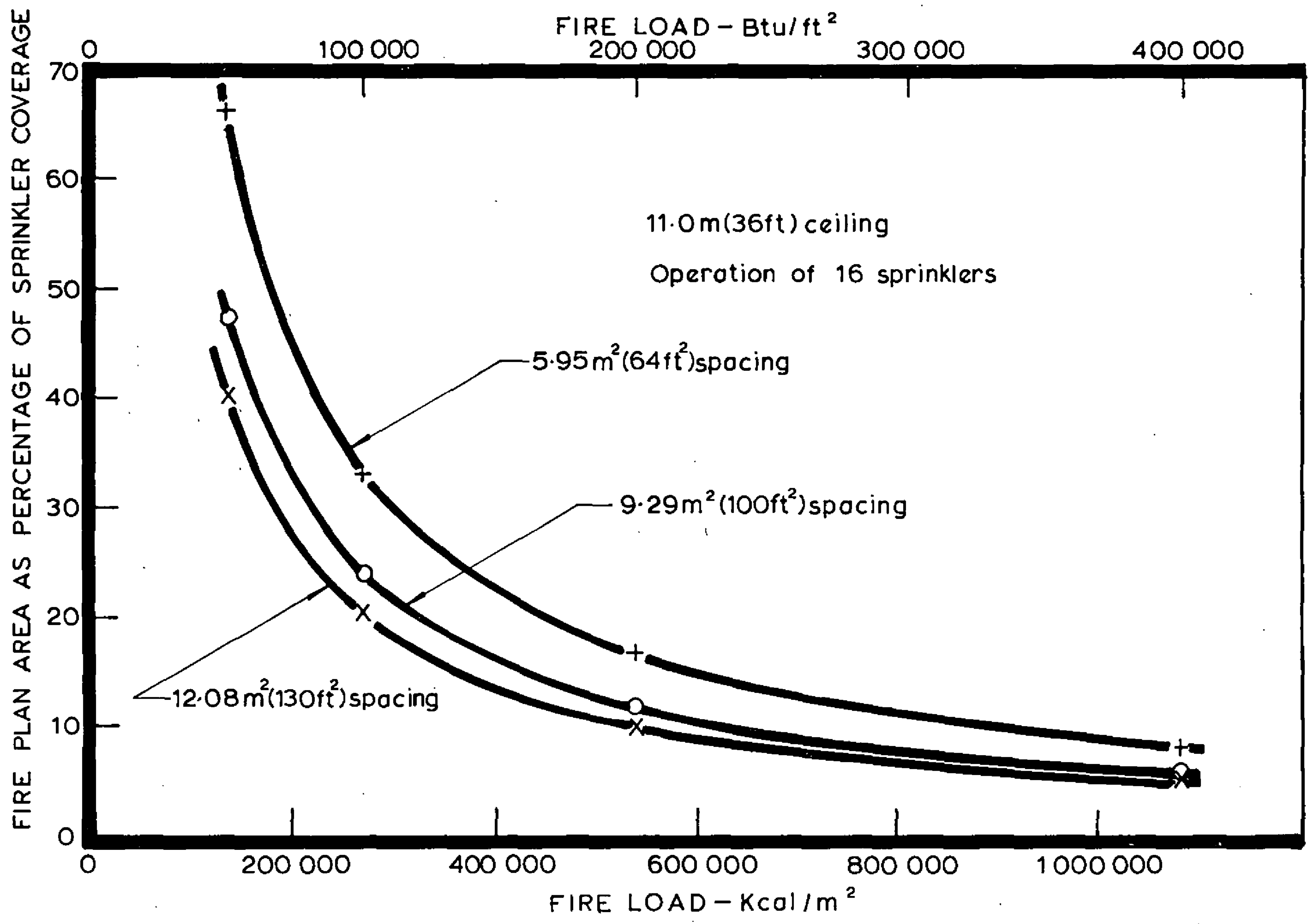
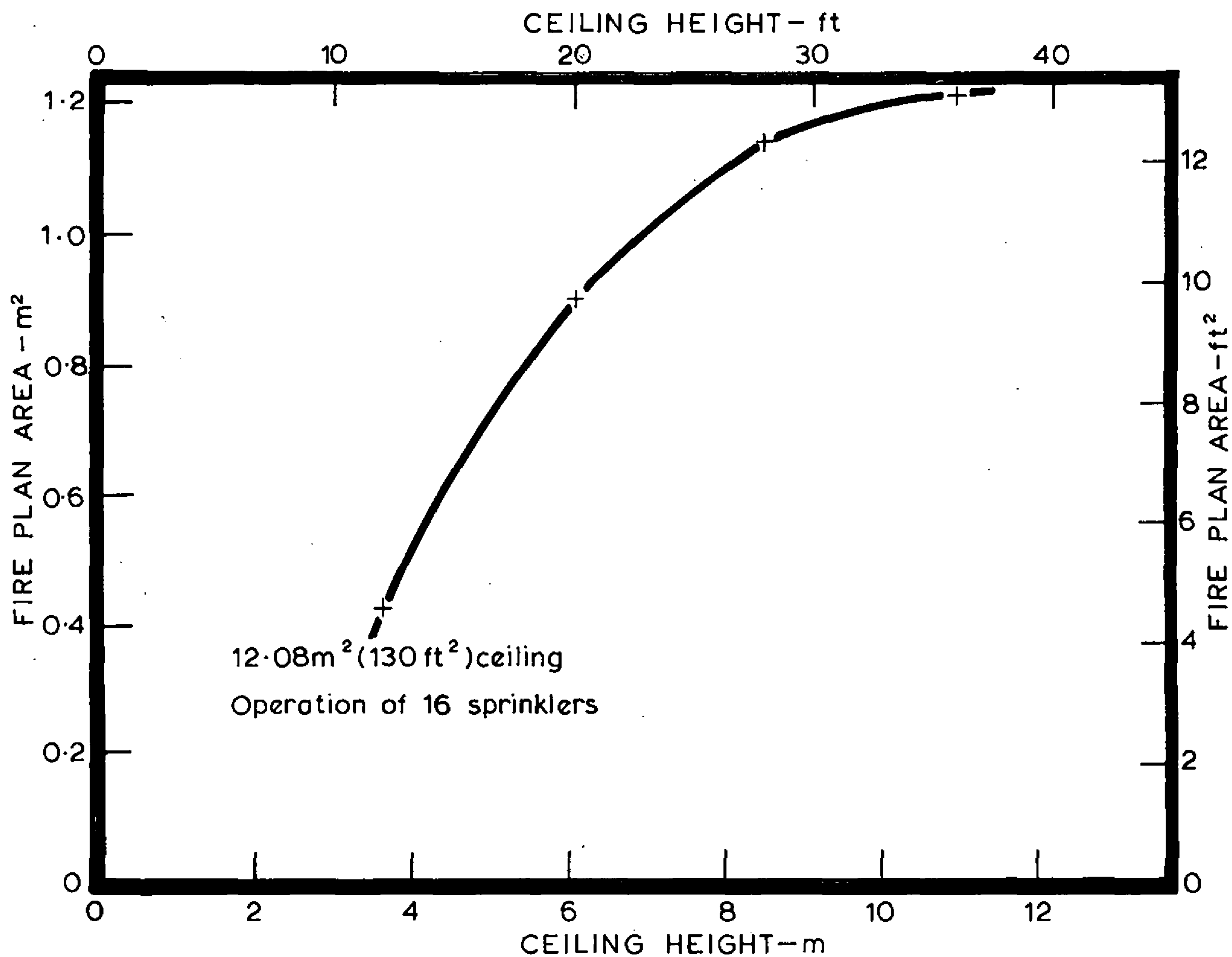
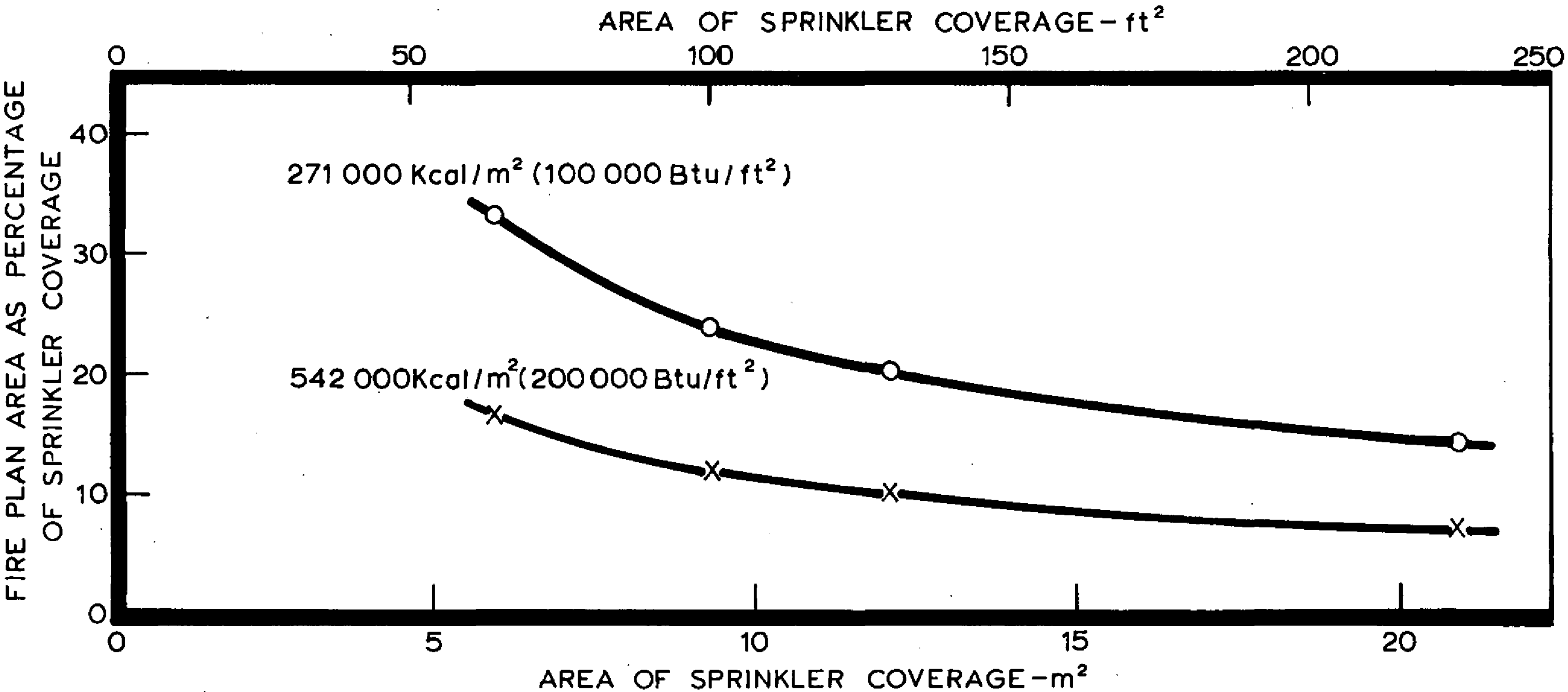


FIG.6 VARIATION OF PERCENTAGE FIRE PLAN AREA WITH FIRE LOAD



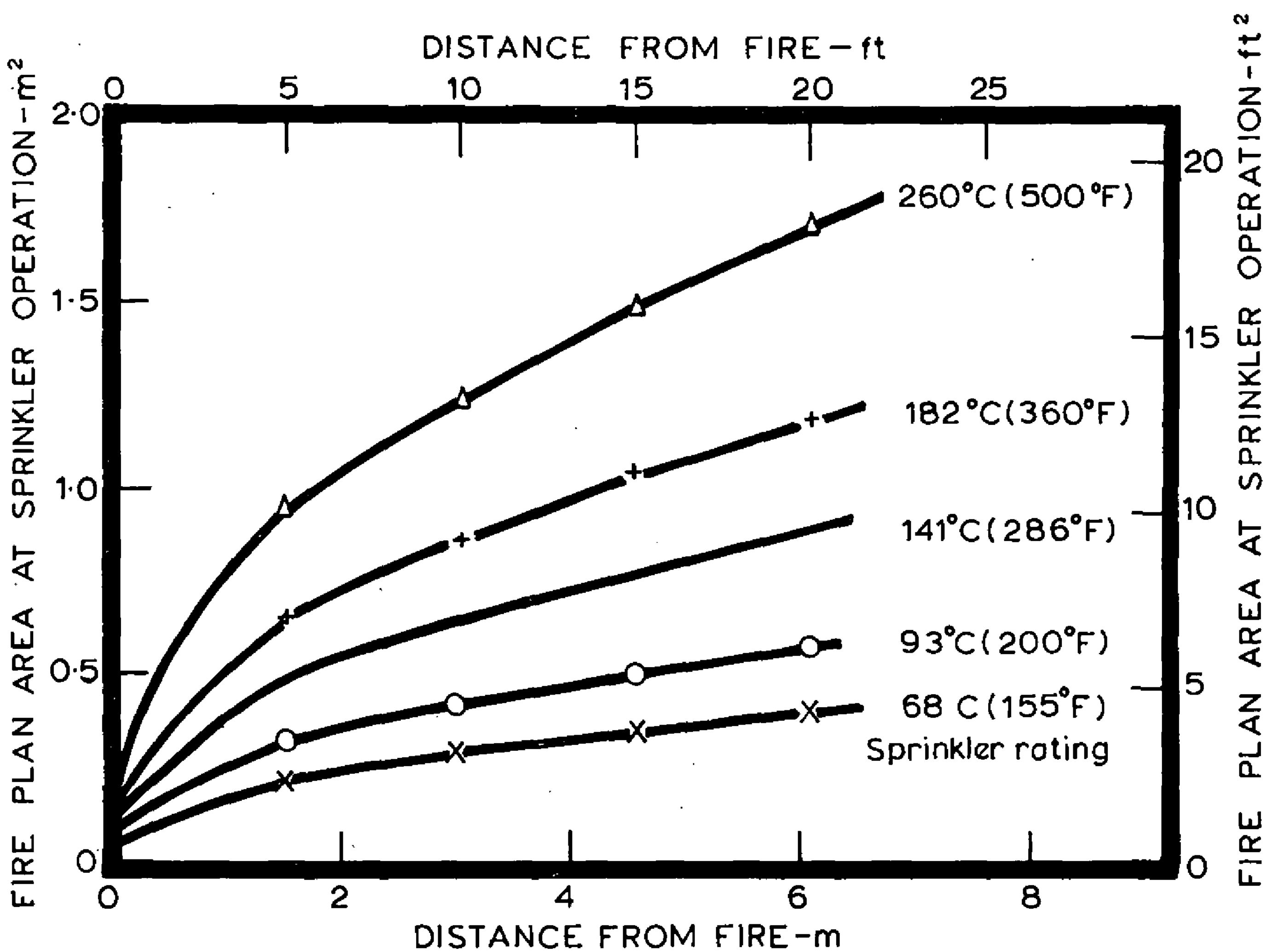
Fire load = 555 000 Kcal/m² (205 000 Btu/ft²)

FIG.7 VARIATION OF FIRE PLAN AREA WITH CEILING HEIGHT



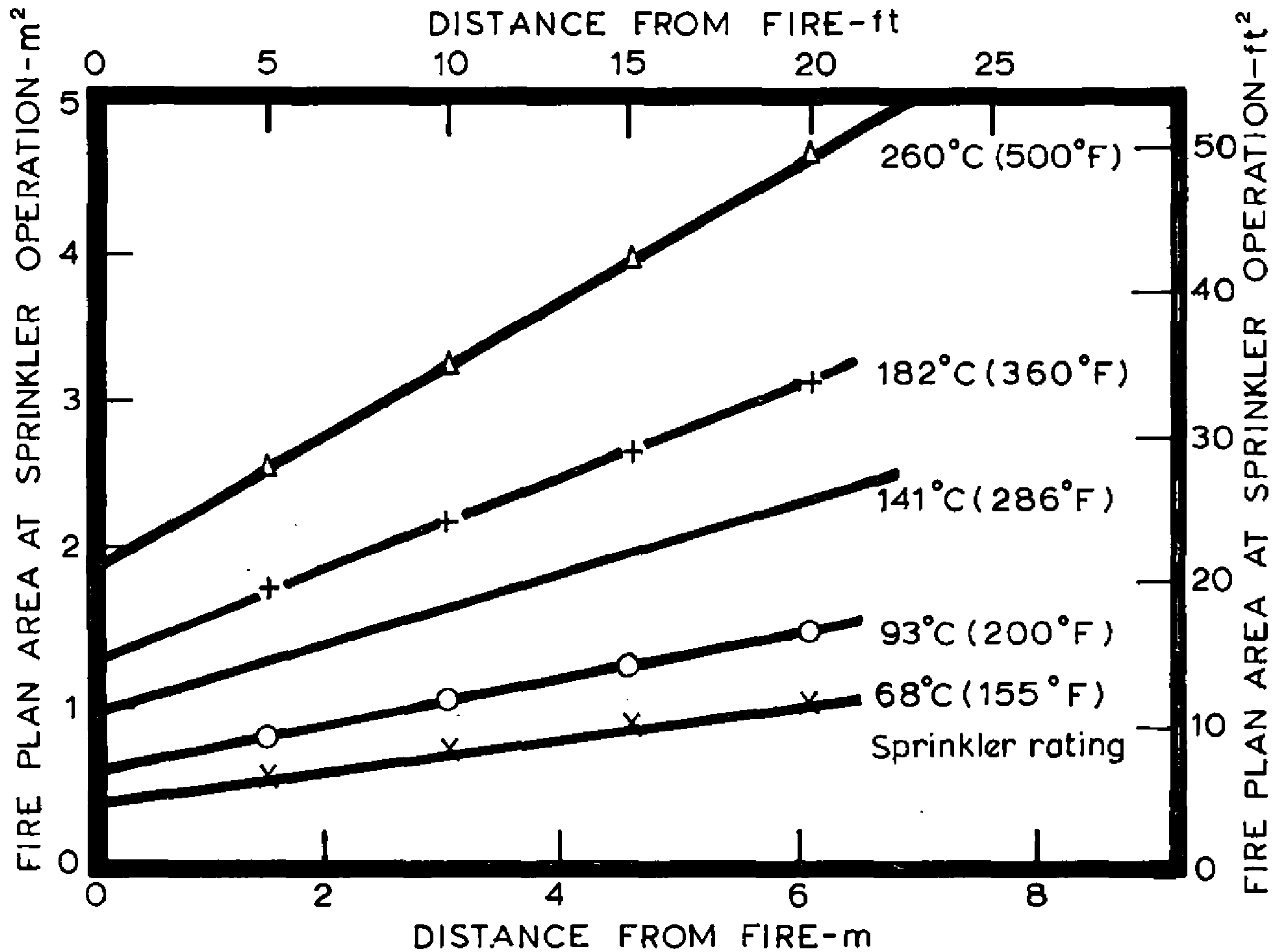
11·0 m (36 ft) ceiling   Operation of 16 sprinklers

FIG. 8 VARIATION OF PERCENTAGE FIRE PLAN AREA WITH SPRINKLER COVERAGE



3·66m(12ft)ceiling Fire load = 555 000 Kcal/m² (205 000 Btu/ft²)

FIG. 9 VARIATION OF FIRE PLAN AREA AT SPRINKLER OPERATION WITH DISTANCE FROM FIRE



11·0m (36ft) ceiling   Fire load = 555 000 Kcal/m² (205 000 Btu/ft²)

FIG.10 VARIATION OF FIRE PLAN AREA AT SPRINKLER WITH DISTANCE FROM FIRE