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THE EXTINCTION OF PRACTICAL FIRE RISKS BY AUTOMATIC SPRINKLERS

by

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

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SUMMARY

This note reviews the work of a number of laboratories in investigating the performance of automatic sprinkler systems over a wide range of "practical" fires in various combustibles. It shows the hazard of high stacking of combustibles in relation to ceiling height and illustrates how wood crib fires may be used experimentally to represent a wide range of fire hazards.

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1. Introduction

Research into the performance requirements for automatic sprinkler installations has recently been carried out at J.F.R.O., using wooden crib fires[1][2]. Other work on this subject (notably in the United States) has used both wooden cribs and practical fires, and the purpose of this note is to compare the results of other workers with those obtained at J.F.R.O., and to compare the results for wooden crib fires with those for practical types of risk, both in regard to rate of fire development and to the water requirements for control and extinction.

2. Experiments on practical fires

A number of experiments has been reported on a variety of materials representing practical risks. It is of interest that data compiled by the N.F.P.A.[3] shows that sprinklers are ineffective in 10.5 per cent of fires occurring in storage risks, compared with an average of 3.8 per cent for all occupancies. These figures are based on 67,457 fires reported during the years 1925-1959. Hence the storage of goods presents a problem which is of concern to sprinkler engineers, and a large proportion of the experimental work has consequently been made on serious storage risks, such as high-piled stacks and/or high hazard materials.

An extensive series of experiments was made at the Underwriters' Laboratories, Inc.[4] on stacks of cardboard cartons piled to a height of 21 ft. The cartons were filled with 2 lb of shredded paper, or with 2 lb of ground polystyrene foamed plastic. Bray and Hoyle[5] have studied fires in foamed latex rubber and foamed polyether urethane, stacked in the form of regular blocks, and also in random piles of "off-cuts". The Underwriters' Laboratories have studied fires in foamed polystyrene packages[6], and the Factory Mutual Laboratories have examined the hazard of rubber tyres, piled up to 12 ft high[7]; the latter experiments included some in which horizontal wooden baffles were introduced into the piles to inhibit the upward spread of flame. The N.B.F.U. have made experiments on which their Standard on the protection of rubber tyres and foam or sponge rubber[8] is based. Other experiments have examined the extinction of textile materials (cotton and rayon, and cotton/rayon mixture) arranged on racks (8-9 ft in height), in boxes and hanging freely[9], of books arranged on library bookstacks to a height of 30 ft[10] and of empty cartons containing cardboard liners stacked on wooden pallets to a height of 13½ ft[11]. In the latter case, it was established that the empty cartons represented a fire risk equivalent to boxes filled with non-combustible components. In other experiments, the problem of the storage of whisky and other spirituous liquors[12][13] was examined.

Other experiments have been performed in which the fire has not been extinguished, or no information is given about its extinction, but where air temperatures have been recorded during the fire growth. These include fires in textiles packed in cartons to a height of 6 ft[14], 2000 lb of hardwood flooring[15], wooden boards supported vertically in two contiguous planes[7], and in rolled paper stacked vertically[16].

In many papers the amount of information reported is limited, and only tentative comparisons with the J.F.R.O. work can be made. Table I summarises

the experimental work carried out by various workers, and Table II summarises the information which is available on the extinction of the practical fires examined.

3. Rate of air temperature rise at ceiling

In most of the experimental work described, the air temperature rise was recorded immediately above the burning material, or at a point on the ceiling relatively near the point of fire origin. In order to facilitate comparison, curves are given for the work carried out at J.F.R.O. which represent the extremes of rate of air temperature rise immediately above the crib fires. The upper limit is for the most rapidly developing fire (crib C) for a 12 ft ceiling, and the lower limit is for the slowest developing fire (crib A), under a 36 ft ceiling (see Figures 1, 2, and 3).

An examination of the data available shows that in some experiments there was a more rapid rate of rise of air temperature than in the J.F.R.O. work. In Figures (1) and (2) this is evident for rolls of paper stacked on end(16), a 21 ft stack of cartons containing shredded paper(4), a random stack of polyether urethane foam(5), and racks of boxed goods and hanging materials(9). Where there is data available, it is evident that the rapid rise in temperature is due in part to the fact that the top of the combustible material was close to the ceiling. For example, the top of the 21 ft stack of cartons containing shredded paper was only 3 ft below the ceiling, and the tops of the racks of boxed goods and hanging materials were only 1-2 ft below ceiling level. In these circumstances the air temperature rise at the ceiling would certainly be rapid, and the observations may not necessarily represent a significantly more rapid rate of fire development than in the J.F.R.O. work.

This point is confirmed by an extrapolation of the J.F.R.O. work to a ceiling height of 6 ft, equivalent to a distance between the top of the cribs and the ceiling of 2-3 ft. The temperature rise expected is shown in Figures (1) and (2), and it can be seen that the curve is similar to those obtained in practice with the most severe fires. Hence the most rapidly developing crib fire used in the J.F.R.O. work can result in a rate of air temperature rise at ceiling level comparable with that from rapidly developing practical fires.

It is interesting that in one of the experiments reported by Troutman(4), a 21 ft stack of carbons, each containing 2 lb of ground polystyrene foamed plastic, showed a very slow fire development during the first 4 minutes (see Figure (1)), and then a rate of rise of air temperature similar to that of the upper limit of the J.F.R.O. work. This highlights the significance of the method by which the fire is initiated. It is apparent that if the ignition is such as to produce a rapid fire spread through the material, then there will be a rapid rise in air temperature at a very early stage. If, however, the ignition is such that there is a slow spread initially, then there will be a delay before any appreciable temperature rise is observed. Thus, two fires which may be in similar types of storage may result in quite different air temperature rises, as shown by the curves for cartons containing shredded paper and ground polystyrene foamed plastic in Figure (1). This is further illustrated in Figure (2), where two entirely different air temperature rise characteristics are shown from a report of experiments on racks of boxed goods and hanging textile materials, under similar experimental conditions(9).

Other experiments for which air temperature records are available are shown in Figures (2) and (3), and it can be seen that the temperature rise characteristics lie within the range used in the J.F.R.O. work. There is, however, one feature in which the curves differ from the J.F.R.O. work. In general, the shape of the curves shows a relatively slow rise in temperature in the early stages, followed by a rapid increase of slope at a particular time, after which the rate of rise is comparable with the most rapid rate in the J.F.R.O. work. In the J.F.R.O. work the air temperature rise was more rapid in the early stages of the fire; this effect is probably due to the fact that the practical fires were initiated so that there was a slow increase in burning rate in the early stages, whereas the cribs were easily ignited and the burning zone spread progressively.

4. Rate of convective heat output

The size of the fires used in the experiments on practical hazards was generally too large to permit direct measurements of the burning rate (from which the rate of convective heat output can be deduced), as in the J.F.R.O. work. In some papers the operating times of the first sprinkler is given, from which it is possible to make an estimate of the rate of convective heat output at sprinkler operation.

In the F.I.A./N.B.F.U. experiments on high-piled stock[17], the average time for the operation of the first sprinkler was 2.9 min, correcting for time delays in which no temperature rise was recorded at ceiling level. In other work[5][9] mean times of operation of the first sprinkler of approximately $1\frac{1}{2}$ and 2 min have been recorded. If it is assumed that the rate of fire development in these experiments is approximately equivalent to that of crib fire C in the J.F.R.O. work, then these operating times correspond to rates of convective heat output in the range, 100-500 Btu/s. This range is comparable with the rates of convective heat output required to operate sprinklers immediately above the fire in the J.F.R.O. work, for the most rapidly developing fire (crib C), below a 12 ft ceiling. The result implies that the "effective" ceiling height in the F.I.A. experiments is approximately 12 ft, i.e. measured from about the centre of the high stacks.

Experiments with $13\frac{1}{2}$ ft stack of cardboard boxes under a $33\frac{1}{2}$ ft ceiling[11] have indicated first sprinkler operating times of about 10 min. In these experiments the rate of fire development was often slow (equivalent to crib A in the J.F.R.O. work (see Figure (2)), and the sprinkler operation corresponds to a rate of convective heat output of approximately 1000 Btu/s. This is in good agreement with results of the J.F.R.O. work for sprinklers immediately above the fire, for a ceiling height of about 30 ft.

5. Water requirements

5.1. Rate of application

There is no information available in published papers on the relationship between the spread of fire and the rate of water application, as was obtained in the J.F.R.O. work. In the latter work, a minimum rate of 0.08-0.10 gal $ft^{-2} min^{-1}$ was required to arrest the flame front in a 6 ft long crib, the rate depending on the crib construction. The data available on rates of application required for fire control, from a number of sources, is shown in Figure (4). The range given for the J.F.R.O. work (0.10-0.15 gal ft^{-2} min^{-1}), is considered a reasonable practical working range to obtain good fire control in the cribs used in the experiments. It is interesting that the N.B.F.U. quote a range of

0.13-0.17 gal ft^{-2} min^{-1} for ordinary combustibles[13], which is in good agreement with the J.F.R.O. work. The nature of the combustibles is not specified, but it is probable that they are the wooden racks used for the storage of whisky barrels.

The F.I.A. give detailed recommendations for high-piled stock (in the range 16-25 ft) for various defined degrees of hazard and ceiling constructions[17]. These recommendations are based on work done at the Underwriters' Laboratories, and similar recommendations are published by the N.B.F.U.[18]. The recommended minimum water densities are plotted in Figure (4) for plank-on-timber ceiling constructions. It should be emphasised that these values are not the minima required to prevent spread of the flame front within the stack, as in the J.F.R.O. work. The F.I.A. conclude that it is not possible to prevent fire spread in stacks of height greater than 11 ft using overhead sprinklers alone. The figures quoted are the rates of application which will prevent spread of the fire from the stack of origin to adjacent stacks, provided that minimum stack separations are observed (approximately half the stack height). The difficulty of preventing fire spread within the stack arises because of the tightly-packed storage, which prevents water penetrating easily to the bottom of the stack. It is interesting that wood patterns, pallets, and flats are considered as a high hazard material, which requires a water application rate of 0.33-0.42 gal ft^{-2} min^{-1}. This is a factor of 2.7-3.3 times that required for wooden cribs (taking a value of 0.125 gal ft^{-2} min^{-1} for the J.F.R.O. work) with a corresponding ratio of heights of approximately 5-7. The maximum rate given in the F.I.A. recommendations for a 25 ft pile of very hazard material, under a wooden joisted or unprotected steel ceiling, is 0.63 gal ft^{-2} min^{-1}. This rate of discharge represents a pressure at the sprinkler head of 70 lbf/in^2, assuming an 8 ft sprinkler spacing[19] as can be seen by reference to Figure (5).

The work carried out at the Factory Mutual Laboratories on $13\frac{1}{2}$ ft piles of cardboard cartons[11] showed that a range of water application rates of 0.19-0.25 gal ft^{-2} min^{-1} was required for fire control. This material corresponds to a medium hazard in the F.I.A. classification, and the rate of application shows reasonable agreement, taking into account the lower stack height. Work carried out by Mather and Platt Ltd., on clothing on racks and in boxes[9], showed that a rate of application of 0.225 gal ft^{-2} min^{-1} was sufficient to achieve fire control. This hazard is also in the average category of the F.I.A. but the rate is slightly higher than would be expected in view of the fact that the work of Mather and Platt Ltd., was carried out on racks only 8-9 ft high.

Experiments on the protection of whisky storage have shown that rates of between 0.18 and 0.225 gal ft^{-2} min^{-1} are required[13], depending on whether the storage is single or double rack. (See Figure (4)). These figures apply to sprinkler deflector plates not less than 12 in above the bilge of the barrels. If this distance is 6 in or less, the rate of application must be at least 0.31 gal ft^{-2} min^{-1}. These figures are in general agreement with the figure of 0.29 gal ft^{-2} min^{-1} obtained as a result of experiments by the Factory Mutual Laboratories[12].

Information on the protection of storages of rubber tyres and of foamed rubber and plastics is given by the N.B.F.U.[8], F.I.A.[17] and by Bray and Hoyle[5]. The N.B.F.U. give recommended rates of application over a range of heights of storage from 6 to 14 ft (see Figure (4)).

The rate of application required increases very rapidly for heights above 10 ft. The work of Bray and Hoyle which was carried out on stacks from 6-9 ft high, shows excellent agreement with the N.B.F.U. recommendations, with a rate of application of 0.27 gal ft^{-2} min^{-1}. Work done by the Factory Mutual Laboratories on piles of rubber tyres(7) shows higher rates of water application necessary for fire control than those recommended by the N.B.F.U. For a 12 ft pile, for example, a rate of 0.67 gal ft^{-2} min^{-1} is quoted, compared with the N.B.F.U. figure of 0.33 gal ft^{-2} min^{-1}. An interesting feature of these experiments was that horizontal wooden baffles were introduced into the stacks for some of the experiments. It was found that this technique reduced the rate of water application required for fire control. For example, with an 8 ft stack of tyres, the rate of application required for control was reduced from 0.42 gal ft^{-2} min^{-1} to 0.29 gal ft^{-2} min^{-1}.

In Figure (6) an attempt has been made to show how the rate of water application needed to control a fire increases with the height to which materials are stacked. The F.I.A. recommendations for high-stacked goods are plotted for average hazards and very high hazards, together with the N.B.F.U. recommendations for rubber tyres, and foamed rubber and plastics. The smallest rate of application for average hazards is based on the minimum residual pressure under the roof of 15 lbf/in^2, recommended in the N.F.P.A. Standard for sprinkler systems(19). This recommendation applies to stock piles not more than 6-8 ft in height, and corresponds to a rate of water application of 0.13 gal ft^{-2} min^{-1}, assuming a 10 ft sprinkler spacing, and taking an average figure for the frictional loss of head in the supply pipes(20), as plotted in Figure (5).

The F.I.A. figures for very high hazard materials do not apply to stack heights below 16 ft, but the N.B.F.U. rates for rubber tyres(8) have been used for the lower stack heights, and a straight line drawn through the two sets of data. This procedure is justified since the F.I.A. "very high hazard" classification includes rubber, and foamed plastic and rubber products. The N.B.F.U. recommendation for a 14 ft stack is considerably higher than would be expected from the general trend of the recommendations. It is significant that the line for ordinary hazards, when extrapolated to a stack height of 3-4 ft, indicates a rate of water application for control of just over 0.1 gal ft^{-2} min^{-1} which is in excellent agreement with the J.F.R.O. work.

The rates of water application necessary to control fires in stacks of foamed polystyrene packages are also plotted in Figure (6), taken from the results of tests at the Underwriters' Laboratories(6). For stacks of about 10 ft in height, the rates required to control the fire are much lower than would be expected for a very high hazard material, when compared with other values given in the Figure. For stack heights of 20 ft or more, the rates approach those recommended by the F.I.A.

The total range of application rates is from about 0.1 gal ft^{-2} min^{-1} to 0.55 gal ft^{-2} min^{-1}, a ratio of $5\frac{1}{2}$ to 1. The values given on the graph are for a ceiling construction of plank-on-timber. For wooden joists or unprotected steel, the maximum recommended rate of water application is 0.63 gal ft^{-2} min^{-1} for a 25 stack of very high hazard material, which extends the range to over 6 to 1.

5.2. Total water quantity for extinction.

The total quantity of water required for extinction is given in Figure (7), in gal/ft^2 of plan area, for the experiments for which this data is available. The figures from the experiments in the Underwriters' Laboratories(4)(7) represent the quantity at the stage when there was no danger of fire spread to

adjacent stacks, at which point the water was turned off. Hence the criterion of extinction is not as severe as in the J.F.R.O. work, for which extinction was defined as the point at which all flaming had ceased. There is a considerable scatter of results in the F.I.A./N.B.F.U. work, with a mean value of 17.8 gal/ft^2 for the 21 ft stacks. This value shows excellent agreement with the work of the Factory Mutual Laboratories on 13½ ft stacks of cardboard boxes, for which the mean value was 17.9 gal/ft^2. These figures compare with values of 1.3-2.7 gal/ft^2 obtained in the J.F.R.O. work on wooden cribs, the range applying to different crib constructions. Comparable quantities to those obtained in the J.F.R.O. work were found by Mather and Platt Ltd.(9) in their work on racks of hanging and boxed textiles, for which a mean water quantity of 1.7 gal/ft^2 was required for extinction.

The work of Bray and Hoyle on foamed plastic and rubber(5) shows a mean value of 3.9 gal/ft^2. This figure is relatively low for such a high hazard material, and suggests that provided a sufficient rate of water application is used, control and extinction can be effectively achieved, in stacks of the material 6-9 ft in height. Very limited information given by Auck(6) confirms the magnitude of these results, with a value of 4 gal/ft^2 for foamed polystyrene packages, and 1.4 gal/ft^2 for similar packages with flame-retardant treatment. For cardboard cartons, values of 5 and 8.3 gal/ft^2 are given. The stack heights to which these results apply are not stated.

The experiments of the Factory Mutual Laboratories on whisky barrel storage(12) show a mean value of 9.5 gal/ft^2 for extinction.

6. Time for extinction.

In the J.F.R.O. work, the time required to extinguish the fire varied over the range 5-40 minutes, the highest time corresponding to a rate of water application just sufficient to control the fire spread within the crib length. These values compare with average times of 15 minutes required by Bray and Hoyle to extinguish fires in foamed plastic and rubber (maximum 25 mins), 7½ min. in the work of Mather and Platt, Ltd. on boxed and hanging textiles (maximum 8¾ min), and 43½ mins in the work of the Factory Mutual Laboratories on whisky storage hazards (maximum 60 mins). Isolated results quoted by Auck(6), give extinction times of 33 and 55 minutes in stacks of cardboard cartons (height not given), and 9 and 20 minutes in stacks of foamed polystyrene packages, the lower figure referring to packages treated with a flame-retardant. The work on high stacks of cartons indicates longer times before extinction is complete. The work of Underwriters Laboratories(4)(17) indicates a mean time of water application of 53½ min. (maximum 140 mins), and that of Factory Mutual Laboratories(11), an average of 81 min (maximum 107 min). These relatively long periods almost certainly arise because the fire spread is not halted by water application, so that it eventually spreads throughout the stack, and water has to be applied until there is no longer a danger of spread to adjacent stacks. In the other hazards the fire spread is limited, and water is applied only until the burning zone is extinguished.

7. Number of sprinklers operating.

In most of the experiments in which the number of sprinklers which opened was recorded, it is evident that a high proportion of the total

operated during the course of the fire, as can be seen by reference to Table II. This result would be expected from the nature of the experiments, which were generally conducted in relatively small enclosures, involving from 4 to 24 sprinkler heads. They do not therefore represent a wide range of practical installations. In such circumstances, it would be expected that unless the rate of burning of the fire was very much reduced by the application of water from the first sprinklers to open, the temperature at ceiling level would build up to a relatively uniform level over its area, with eventual operation of all the sprinklers. The uniform temperature rise over the ceiling, when the area of the ceiling is relatively small, has been shown in work carried out at J.F.R.O.[21][22]. Where the area of the ceiling is large there is evidence that there is a fall in the air temperature with increasing horizontal distance from the fire, up to distances of 30-40 ft[1][23], and it is possible that the number of sprinklers which open will be smaller in a large building than would be suggested by some of the experiments discussed in this Note. Another interesting feature can occur with high stacked goods in that the fire is apparently controlled in the early stages of water application with only a few sprinklers opening, but continues to spread in the lower levels of the stack. This results in a later outbreak of fire, often with a much increased rate of burning, with the consequent operation of many more sprinklers[11].

It is interesting that the records of the N.F.P.A. (fires reported to their Department of Fire Records[3]) show that in 90.2 per cent of fires the number of sprinklers operating is 15 or less. In 75 per cent of fires reported the number operating is 5 or less, and in 55.3 per cent of incidents only one or two sprinklers operated. A cumulative frequency graph is plotted in Figure (8), which gives the N.F.P.A. figures for the period 1925-1959, representing a total of 67,457 reported fires. The graph also includes information on 517 fires from a British source for the period January, 1950-April, 1959[24], the results from which are similar to the American figures. Large numbers of sprinkler heads (50 or more) open in only about 3 per cent of fires reported, for both sets of data.

8. Discussion and conclusions.

There is a considerable amount of information available from a number of sources, which when collated, gives a reasonable guide to the requirements for sprinkler systems for various practical fire risks. Most of the experimental work has been concerned with storage risks, since these present an increasingly serious problem to the sprinkler engineer. In designing a system, the factors which are of prime interest to the sprinkler engineer when estimating the water requirements to achieve efficient extinction are (1) the rate of application likely to be required (2) the total time likely to be required for extinction (which gives the total quantity of water per sprinkler) and (3) the number of sprinklers likely to open. The information available on these factors is discussed below, in relation to risks which have been examined.

The range of rates of fire development chosen in the J.F.R.O. work gives rates of air temperature rise at ceiling level which are representative of the majority of practical hazards examined by other workers. This is true even for very rapidly developing practical fires, with materials stacked 2-3 ft below ceiling level, which show close agreement with the most rapidly developing J.F.R.O. crib fire, when the results are extrapolated to give a similar distance of the fire below the ceiling.

The minimum rate of application of about 0.1 gal ft^{-2} min^{-1} required for control of fire spread, obtained in the J.F.R.O. work, is in agreement with the minimum rate suggested as the result of other work for average hazard materials, and with the minimum quoted in the N.F.P.A. Standard[19] (0.13 gal/min with a maximum of 130 ft^2 per sprinkler). Thus the wooden cribs used are representative of an average hazard piled to a height of not more than 6-8 ft. The minimum working pressure of 5 lbf/in^2 at the level of the highest sprinkler, laid down by the rules of the Fire Offices' Committee[25], may result in a rate of application of only 0.08 gal $ft^{-2}min^{-1}$ (mean value per sprinkler), when allowance is made for head loss due to frictional resistance[20]. This value may be too small for a rapidly developing fire in an average risk (crib C in the J.F.R.O. work), and a pressure of about 8 lbf/in^2, sufficient to maintain an average flow rate of 0.1 gal ft^{-2} min^{-1} would be a better minimum value.

The maximum pressure to which sprinklers are normally tested is 50 lbf/in^2, corresponding to a mean flow rate of approximately 0.35 gal ft^{-2} min^{-1} at the sprinkler heads, assuming a 10 ft sprinkler spacing. From Figure (5) it can be seen that this pressure is sufficient to provide a water flow rate to protect an average hazard material stacked to a height of 25 ft. In practice the frictional head losses in the pipework may reduce the mean application rate to 0.25 gal $ft^{-2}min^{-1}$[20]. For more severe hazards, however, much higher rates of water application are required, ranging from about 0.2 gal ft^{-2} min^{-1} to 0.55 gal ft^{-2} min^{-1} for very high hazard materials, stacked from heights of 4 to 25 ft (or even up to 0.63 gal ft^{-2} min^{-1} in some circumstances). These rates require a range of pressures of 15-100 lbf/in^2 at sprinkler level, assuming an 8 ft spacing, and making an allowance for the frictional head loss in the pipework[20] (see Figure (5)).

There is relatively little information on the total quantity of water required to extinguish fires. The J.F.R.O. work on cribs shows good agreement with the work of Mather and Platt, Ltd. on boxed and hanging textiles (in the range 1.3-2.7 gal $ft^{-2}min^{-1}$). The work of Bray and Hoyle on foamed rubber and plastic shows a relatively small total quantity (3.9 gal ft^{-2} min^{-1}) for stacks of about 8 ft in height, indicating efficient extinction. The work of the Factory Mutual Laboratories and the Underwriters' Laboratories on high stacked goods shows much higher total quantities, (approximately 18 gal ft^{-2} min^{-1}). This almost certainly arises from the closely packed nature of the storage, resulting in shielding of the burning zone from the water flow, so that extinction becomes relatively inefficient.

The total time for extinction to be effectively achieved is very variable, ranging from about 5 minutes, up to about 60-80 minutes, with occasional times of up to 2 hours or more. The extinction time is very dependent on the rate of water application, and the effectiveness with which the water is able to penetrate the stacked material and so prevent fire spread.

The results of experiments by a number of workers have led to the conclusion that a large number of sprinklers are likely to open in a fire. This conclusion appears unrealistic in view of the experience from large numbers of fires reported over a long period of years, which show that in 75 per cent of all fires only 5 sprinklers or less have opened. In storage risks, however, sprinklers are not effective in 10.5 per cent of reported fires, about 3 times the average rate for all types of fire.

The figures for the number of sprinklers opening are not broken down into types of risk, and it is possible that part of the high failure rate in storage risks may be attributed in part to a larger number of sprinklers opening than in other types of risk.

The foregoing analysis suggests that it may be possible, given more complete and precise data from experiments on "practical" fires, to establish general relationships based on the type of combustible, closeness and height of stacking, height and type of ceiling construction, etc., to enable the required density of water distribution, time to extinction, and number of sprinklers likely to open, to be calculated with a fairly high degree of accuracy. This would give the design data necessary to provide a sprinkler system which could contain a fire with only a small number of heads being operated.

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(24) HIRD, D. et alia. Siting of Heat-Sensitive Fire Detectors in Buildings. F.R. Note No.475/1961.

(25) Rules for Automatic Sprinkler Installations. Fire Offices' Committee. 28th ed. October, 1960.

TABLE I - SUMMARY OF EXPERIMENTS ON PRACTICAL RISKS

Reference	Material	Arrangement of material	Stack dimensions	Position of thermocouple on ceiling for air temperature measurements.	Ceiling height (ft)	Lateral dimensions of laboratory (ft)	Method of ignition
(16)	Rolled paper	Vertical stacks	-	On fire axis	-	-	-
(4)	Corrugated paper cartons containing either 2 lb shredded paper or 2 lb ground polystyrene foamed plastic.	Cartons arranged on wooden pallets.	(a) 21 ft high x 16 ft x 8 ft (b) 21 ft high x 8 ft x 8 ft	Over stack.	24 (in part of building in which fires were situated.	66 x 37	Generally 2 lb shredded paper ignited at base of stack.
(5)	Foamed polyether urethane and foamed latex rubber	Vertical stacks	6-9 ft high	Over stack	$14\frac{1}{2}$	21 x 20	Match applied.
(7)	(a) Wooden boards (b) Rubber tyres	Supported vertically in two contiguous vertical planes. Piled 4 rows x 5 rows with scattered interlocking piles above.	(a) 16 ft high x 4 ft (b) 4 ft high x 4 ft 8 ft high	Temperatures are mean of all ceiling thermocouples. Over pile.	33 15 (?)	60 x 40 -	Petrol soaked wood-cellulose igniter. -
(9)	Cotton, rayon, and cotton-rayon mixture	Three racks, the central one of which had hangings of material. Other two racks had cardboard boxes containing cotton-rayon waste.	8-9 ft high racks, approx. $2\frac{1}{2}$ ft wide and 3 ft apart.	In centre of gangway between two racks.	10	20 x 20	Materials ignited at bottom corner of a rack.

(Cont'd) .....

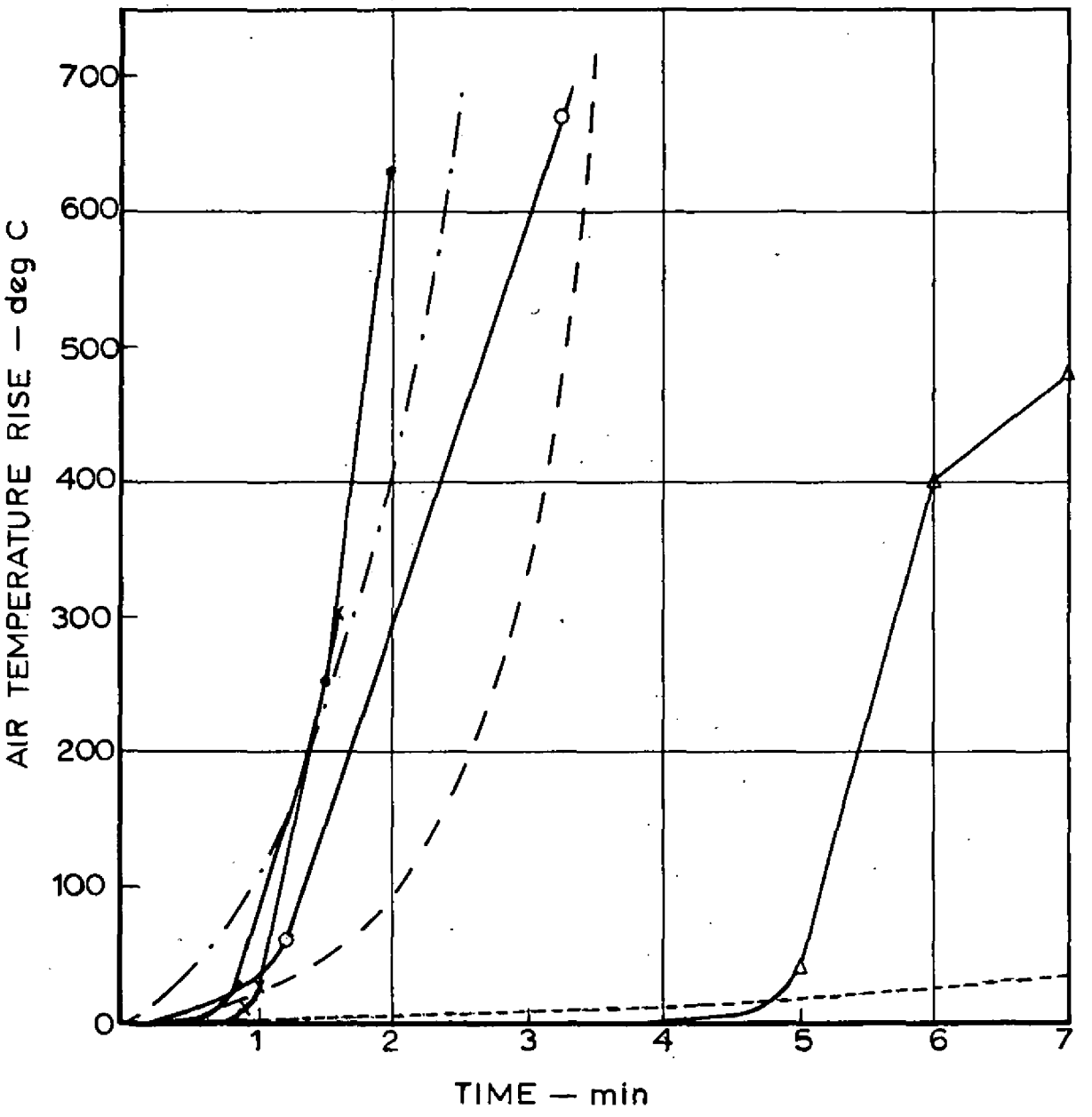
TABLE I (Cont'd)

Reference	Material	Arrangement of material	Stack dimensions	Position of thermocouple on ceiling for air temperature measurements	Ceiling height (ft)	Lateral dimensions of laboratory (ft)	Method of ignition
(10)	Books	Stored on steel shelving in four ranges, with two 4½ ft aisles.	30 ft high with overall plan of 12 ft x 9 ft	22½ ft high, between back of shelves.	-	-	Books ignited in a library trolley placed in an aisle.
(14)	Textiles packed in cardboard (?) cartons.	Boxes stacked in a small stack, in an unordered way.	Approx. 6 ft max.	-	-	-	Match (?)
(11)	Cartons containing cardboard liners.	Boxes stacked on wooden pallets.	13½ ft high x 25 ft x 12½ ft (18 ft high in one test).	Over centre of stack.	33½	60 x 40	-
(15)	Hardwood flooring.	2000 lb arranged in a random pile on theatre stage.	-	Close to edge of pile.	81	94 x 28	One gallon of kerosine ignited.
(12)	Whisky barrels containing alcohol.	Four tiers of barrels on wooden pallets.	13½ ft high x 26 ft x 19½ ft (plan dimensions 26 ft x 26 ft in some of tests)	-	21	66½ x 37	-
(6)	Foamed polystyrene packages.	Stacks on wooden pallets.	6 ft x 16 ft base dimensions, with heights from 8-21 ft.	-	24	66 x 37	-

TABLE II - SUMMARY OF INFORMATION ON EXTINCTION OF PRACTICAL RISKS

Reference		Time of operation of first sprinkler (min - s)	Air temperature rise at operation of first sprinkler (deg C)	Rate of water application (U.S. gal $ft^{-2}min^{-1}$)	Time for which water applied (min - s)	Quantity of water used (U.S. gal/ft^2)	Number of sprinklers operating	Stack height (ft)	Material	Remarks
(4) and (17)	(i)	10 - 40(1)	274(1)	0.20	30 - 50	6.1	27/28	11	Empty cartons	Dry pipe system
	(ii)	7 - 45(1)	460(1)	0.40	36 - 00	14.4	26/28	21	Cartons containing ground polystyrene foamed plastic	
	(iii)	5 - 25	244	0.60	40 - 25	24.2	6/28	21		Wet pipe system
	(iv)	13 - 41(1)	294(1)	0.20	106 - 00	21.2	18/28	21		
	(v)	9 - 20(1)	154(1)	0.30	60 - 00	18.0	8/28	21		
	(vi)	15 - 20(1)	172(1)	0.40	140 - 00	56.0	6/28	21		
	(vii)	1 - 58(1)	266(1)	0.30	41 - 30	12.4	27/28	21	Cartons containing shredded paper	
	(viii)	0 - 44(1)	C.600(1)	0.30	50 - 00	15.0	28/28	21		Dry pipe system
	(ix)	13 - 05(1)	-	0.20	53 - 15	10.7	12/28	21		
	(x)	12 - 08(1)	-	0.40	70 - 00	28.0	12/28	21		
	(xi)	3 - 30(1)	-	0.40	63 - 00	25.2	4/28	21		
	(xii)	8 - 20(1)	-	0.40	40 - 00	16.0	23/28	21	Empty cartons	
	(xiii)	9 - 40	-	0.28	60 - 00	16.8	15/28	21 & 11	Cartons containing shredded paper	Wet pipe system
	(xiv)	17 - 35(1)	-	0.30	65 - 00	19.5	9/28	21		Dry pipe system
(5)	(i)	1 - 19	274	0.28 (increased to 0.32 after about 9 min)	25 - 00	7.6	4/4	7½	Foamed latex rubber	Stack of half cushions
	(ii)	1 - 10	-	0.32	20 - 00	6.4	4/4	6	" " "	Stack supported by wire mesh and solid panels.
	(iii)	1 - 25	-	0.28 (increased later to 0.32)	13 - 00	-	4/4	7	Foamed polyether urethane	Random pile of 'off-cuts'
	(iv)	1 - 40	411	0.28 (increased to 0.32 after 4 min 40 s)	C. 9 - 00	2.7	4/4	7	" " "	" " "
	(v)	1 - 20	C.630	0.32	7 - 00	2.2	4/4	7 - 9	" " "	Large blocks stacked in parallel piles.
(9)	(i)	1 - 57	261	0.225(2)	8 - 45	2.0(2)	-/6	8 - 9	Racks of boxed and hung textiles (cotton, rayon, and cotton/rayon)	
	(ii)	1 - 51	C.390	0.225(2)	6 - 00	1.4(2)	-/6	8 - 9		

(Cont'd) .....



Cartons containing shredded paper[4]

Cartons containing ground polystyrene[4] foamed plastic

Polyether urethane foam "off-cuts"[5]

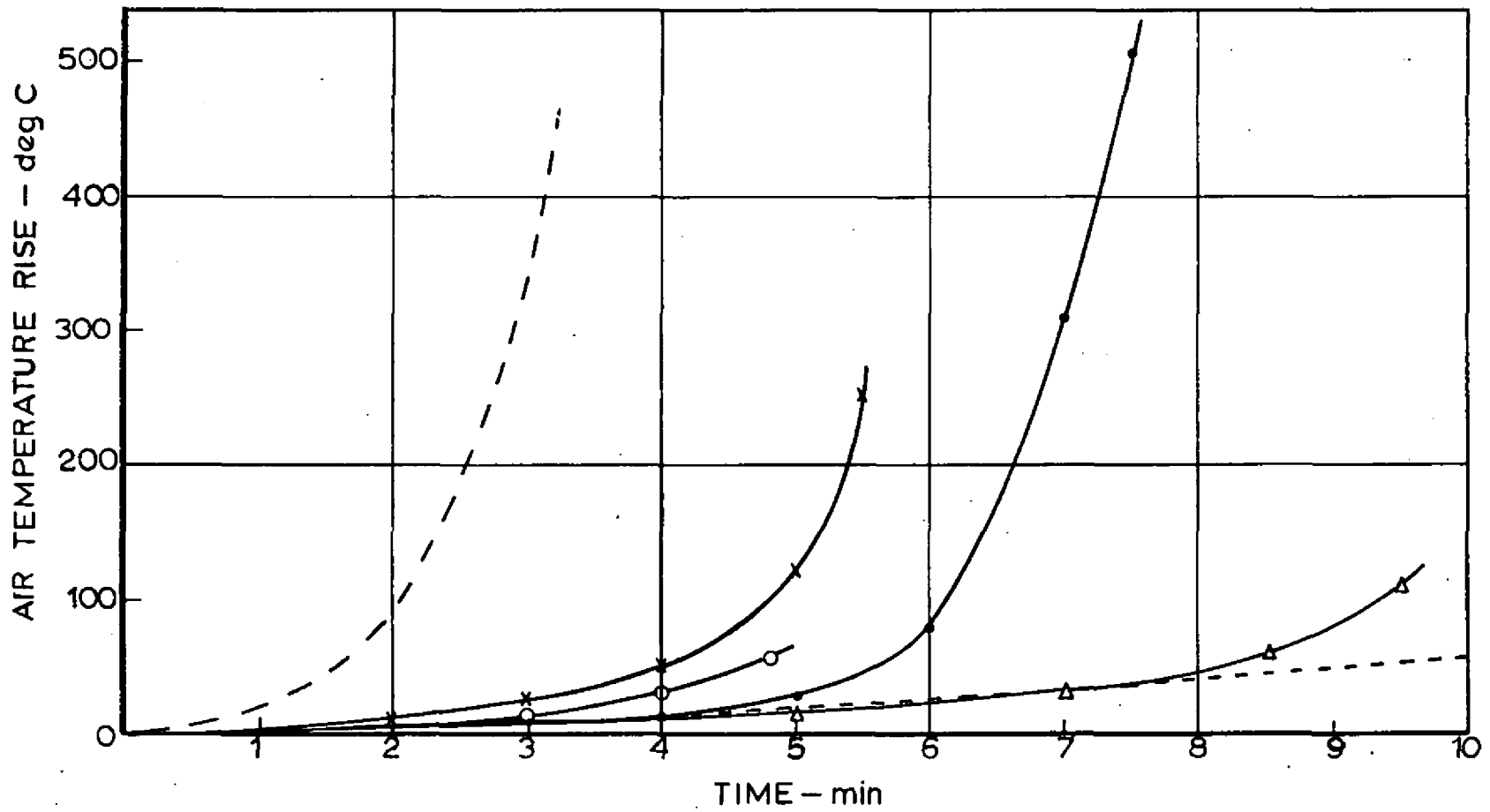
Rolls of paper stacked vertically[16]

Crib C (12 ft ceiling) } J.F.R.O. range (immediately above fire)[1]

Crib A (36ft ceiling) } J.F.R.O. range (immediately above fire)[1]

Extrapolation of J.F.R.O. results to a 6 ft ceiling height (crib C)

FIG.1. COMPARISON OF AIR TEMPERATURE RISE CHARACTERISTICS ABOVE FIRE



Cardboard boxes containing textiles[14]

Hardwood flooring (random pile)[15]

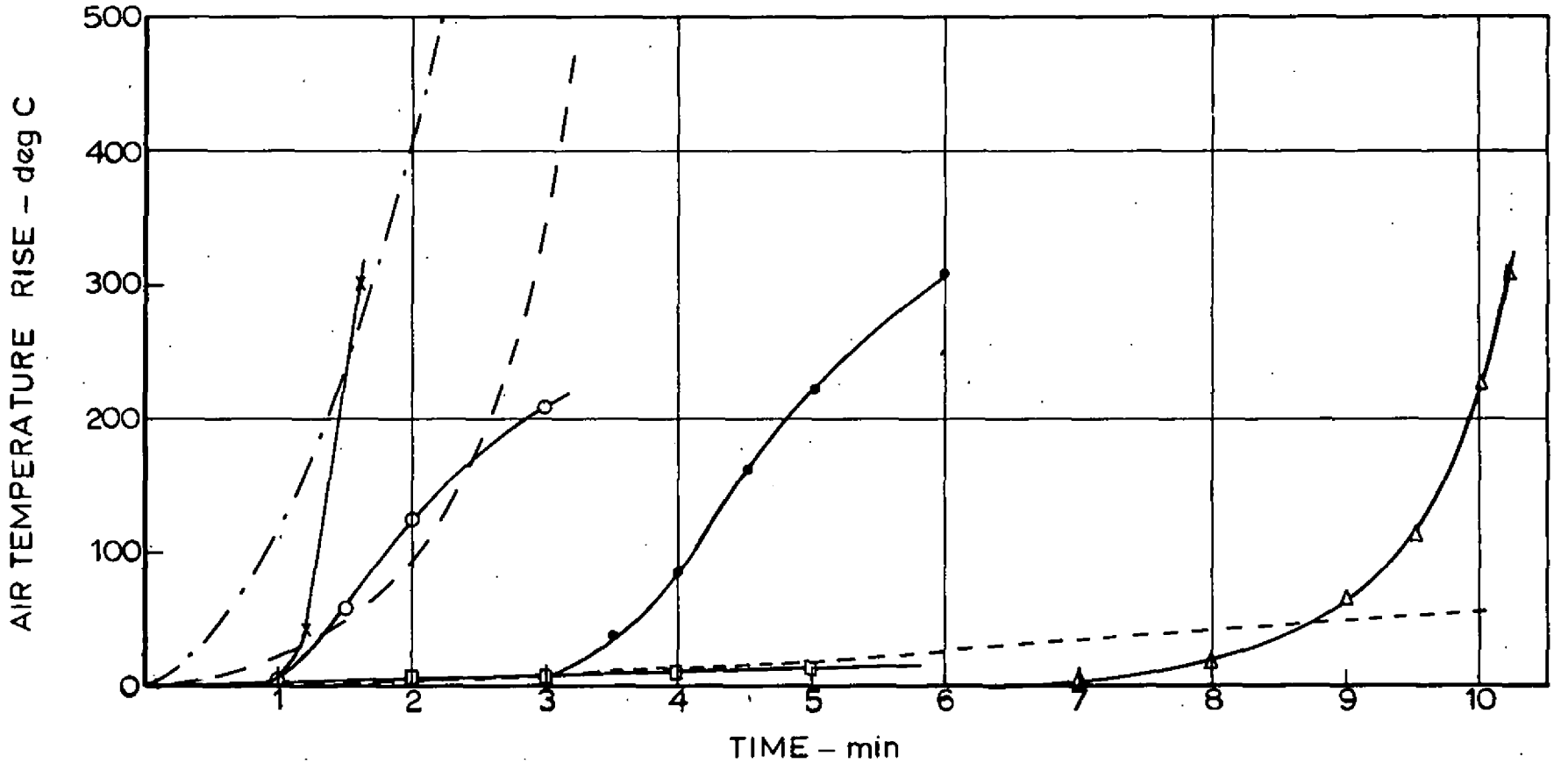
Library bookstacks[10]

Cartons containing cardboard liners[11]

Crib C (12 ft ceiling) } J.F.R.O. range (immediately above fire)[1]

Crib A (36 ft ceiling) }

FIG.2. COMPARISON OF AIR TEMPERATURE RISE CHARACTERISTICS ABOVE FIRE



Boxed and hanging textiles[9]
Boxed and hanging textiles[9]
Parallel vertical boards (16 ft high)[7]
Parallel vertical boards (4 ft high)[7]
Piled rubber tyres (8 ft high)[7]
Crib C (12 ft ceiling) } J.F.R.O. range (immediately above fire)[1]
Crib A (36 ft ceiling) }
Extrapolation of J.F.R.O. results to a 6 ft ceiling height (crib C)

FIG.3. COMPARISON OF AIR TEMPERATURE RISE CHARACTERISTICS ABOVE FIRE

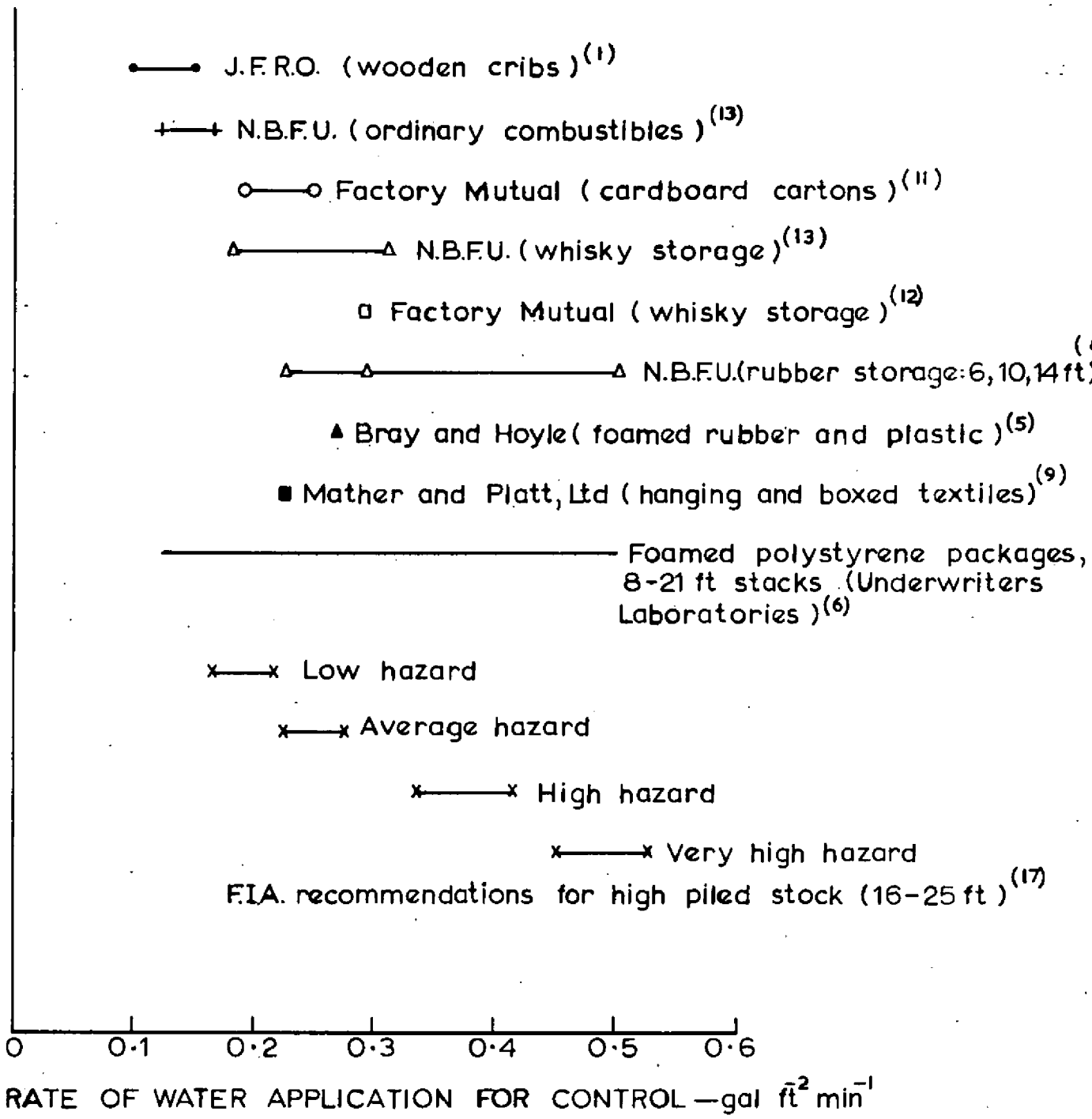


FIG.4. COMPARISON OF RATES OF WATER APPLICATION FOR FIRE CONTROL IN VARIOUS RISKS

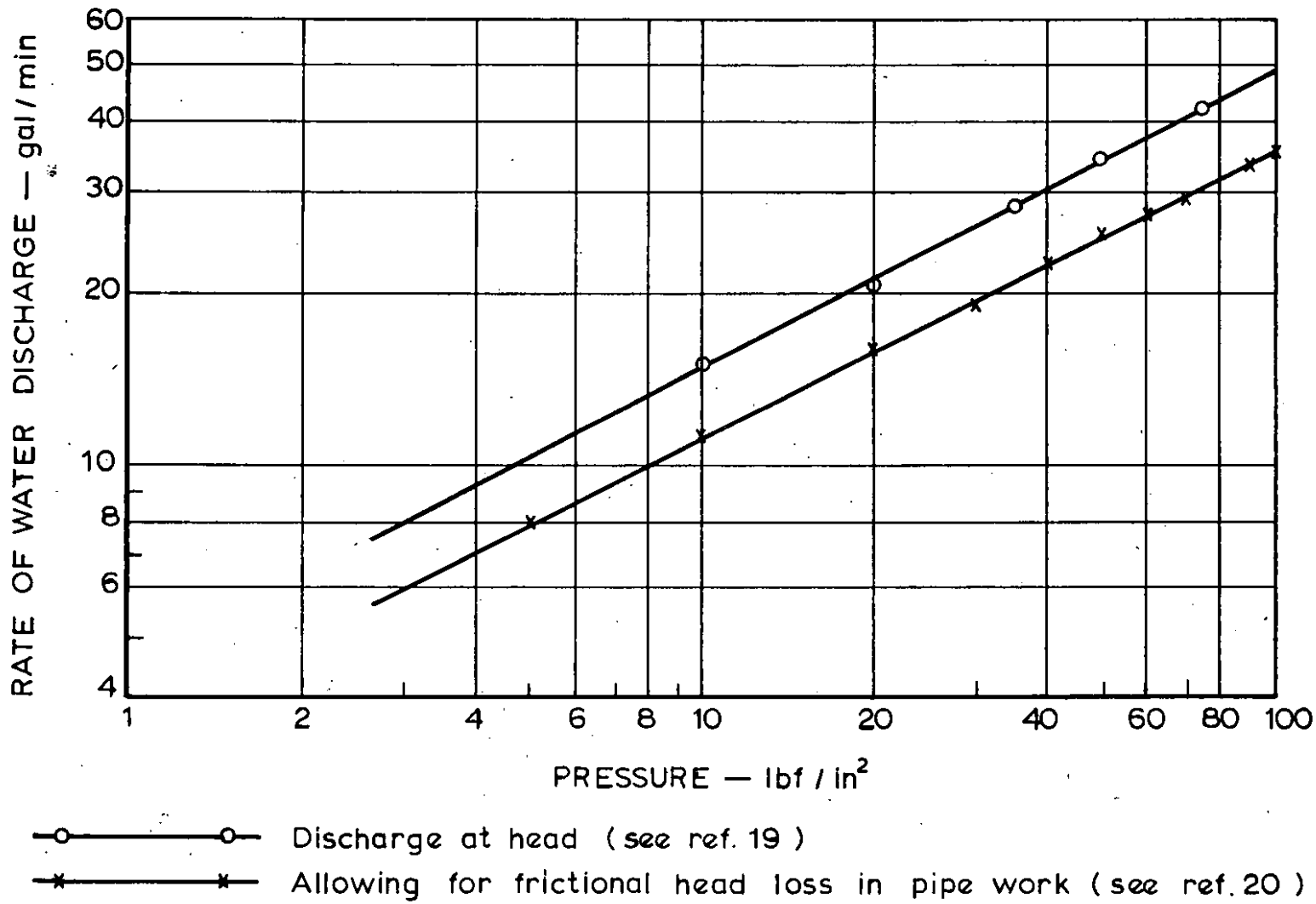


FIG. 5. VARIATION OF RATE OF WATER DISCHARGE FROM A $\frac{1}{2}$ IN. DIAMETER SPRINKLER ORIFICE WITH WATER PRESSURE

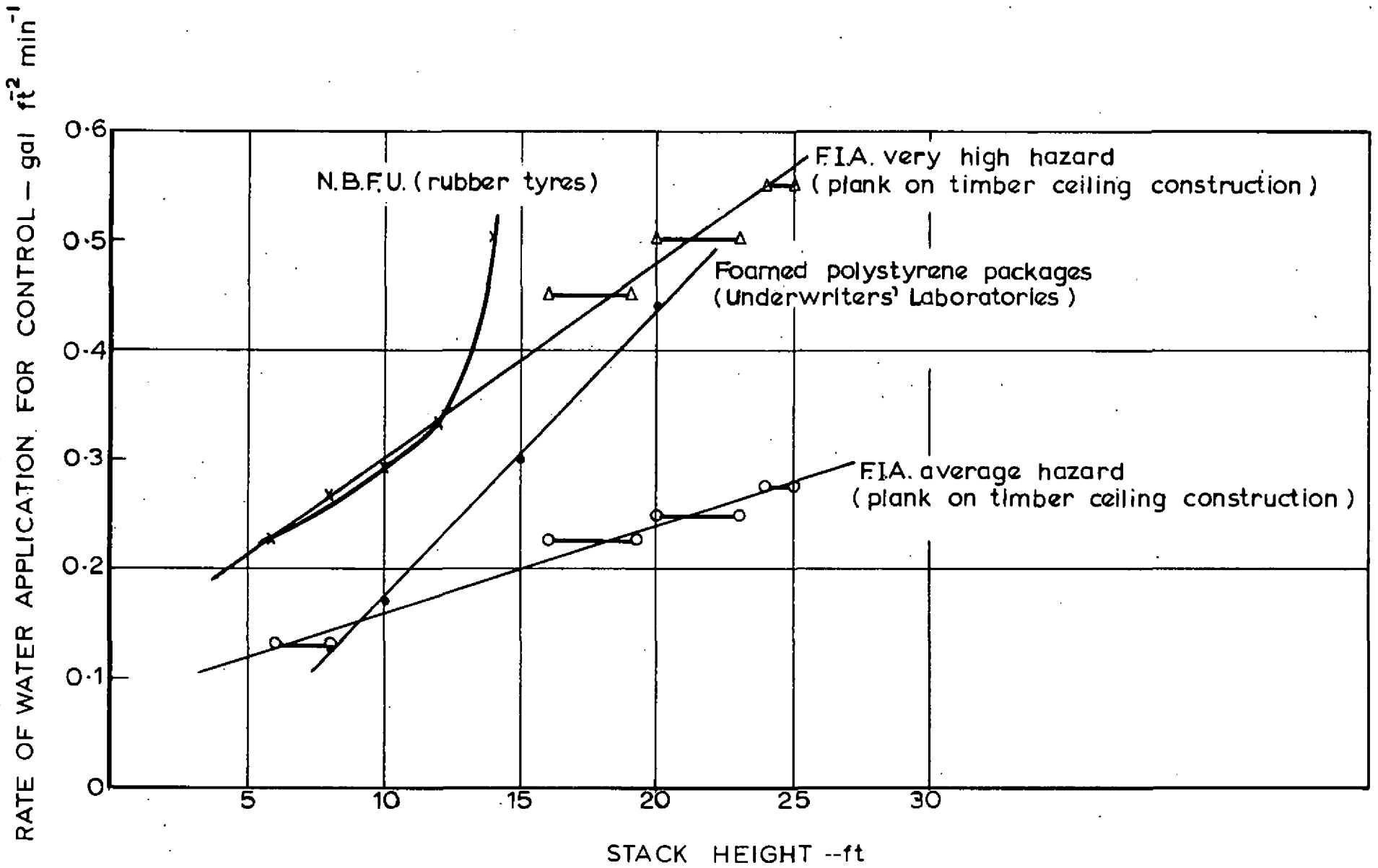
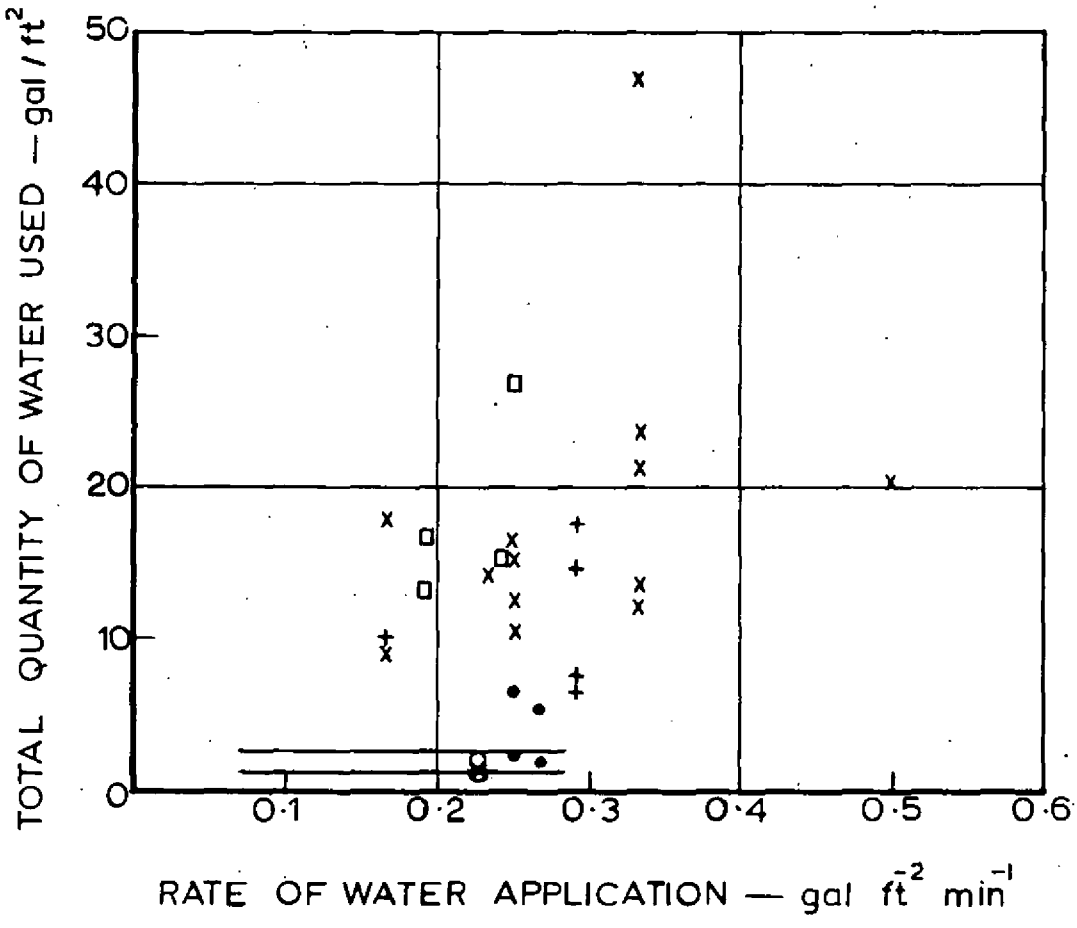


FIG. 6. RELATIONSHIP BETWEEN RATE OF WATER APPLICATION FOR FIRE CONTROL AND STACK HEIGHT



x Cartons containing shredded paper and ground polystyrene foamed plastic (21 ft stack)[17]

• Foamed latex rubber and polyether urethane[5]

□ Cardboard cartons containing cardboard liners[11]

+ Whisky barrels containing alcohol[12]

o Racks of hanging and boxed textiles[9]

——— Wooden cribs (J.F.R.O. work)[1]

FIG.7. VARIATION OF QUANTITY OF WATER USED IN FIRE CONTROL WITH RATE OF APPLICATION FOR VARIOUS RISKS

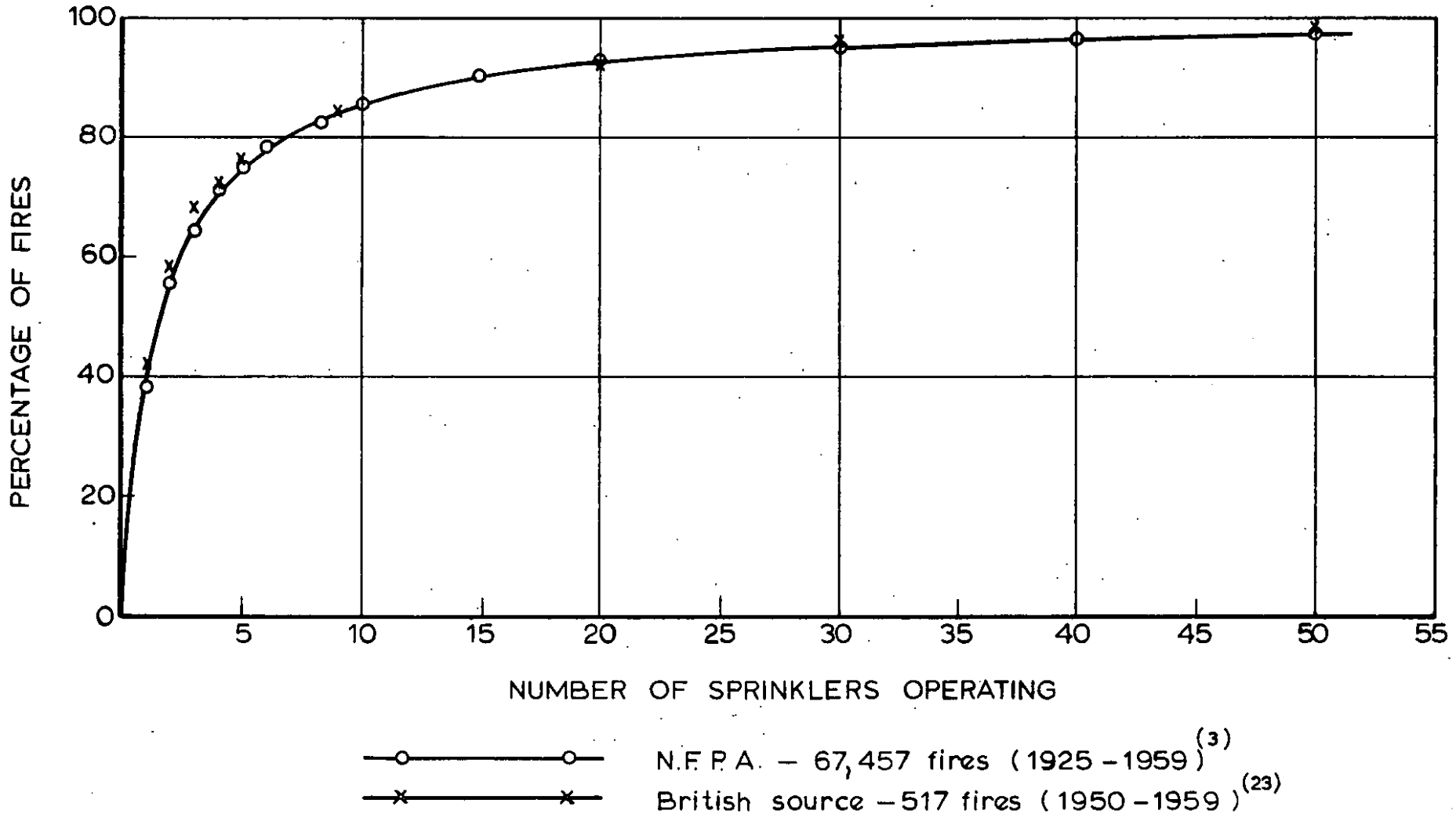


FIG.8. CUMULATIVE PERCENTAGE OF REPORTED FIRES IN WHICH A GIVEN NUMBER OF SPRINKLERS OPENED