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THE NUMBER OF SPRINKLER HEADS OPENING IN FIRES

by

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SUMMARY

Statistics of the number of sprinkler heads opening in fires are used to investigate the influence of various factors on sprinkler behaviour. It is shown that fewer sprinklers open in older premises, but there are insufficient data to investigate the reasons. More heads open in dry sprinkler systems, presumably because of delays in tripping the dry pipe valve, and these delays are estimated by means of a simple theoretical model of the early stages of the fire.

KEY WORDS: Fire statistics, sprinkler.

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This note examines the statistical distribution of the number of sprinkler heads opening during a fire. This number is of importance since it is an indirect measure of fire size and the extent of water damage, and because it is important in the design of sprinkler systems. Ideally a fire should be controlled with the minimum number of heads opening: too much water can cause excessive water damage, too little will result in the sprinklers not controlling the fire. Sprinkler systems are designed so that the working pressure can be maintained with an assumed maximum number of heads open. The design factors are described in the Fire Offices' Committee Rules[1].

The statistics are drawn from the U.S. National Fire Protection Association[2], and from U.K. fire brigade reports. Data on fire losses supplied by the British Fire Protection Association are also used. In none of the fires considered has the sprinkler system been designed to the latest standards imposed by the F.O.C.[1].

Statistical distribution of number of heads opening

In Fig. 1 the proportion $q(N)$ of fires in which N or more heads operated is plotted for all fires in which sprinklers operated, both in U.K. (1967 - 68) and in the U.S.A. (1925 - 1964). A regression line of the form

$$q(N) = N^{a + b \log N}$$

gives a good fit to the data. The values of the parameters were:-

(i) American data (73,667 fires)

$$a = -0.68, \quad b = -0.12$$

(ii) British data (689 fires)

$$a = -0.78, \quad b = -0.13$$

(iii) All data (American and British combined)

$$a = -0.68, \quad b = -0.12$$

The American and British data are not significantly different, and the parameters in (iii), biased naturally towards the much larger number of American data, give the best representation of the data as a whole, so that:-

$$q\ (N) = N^{-0.68 - 0.12 \log N}$$

It is worth noting that, in the United Kingdom, about 90 per cent of the fires in which sprinklers operated were controlled or extinguished by the sprinklers.

Fire losses

Ramachandran[3] has shown that, for a wide range of occupancies and for sprinklered and non-sprinklered buildings grouped together, the distribution of fire losses is

$$\phi\ (x) = x^{-0.08 - 0.11 \log x}$$

where $\phi\ (x)$ is the probability of the loss exceeding x.

This is the same type of distribution as derived above for the number of sprinkler heads operating, and we are led to investigate whether there is any relationship between the two. One would expect some degree of correlation because both are indirect measures of fire size.

The fires in the United Kingdom from 1965 to 1968 in which sprinklers operated were divided into three groups on the basis of the total loss suffered in each fire. Regression lines of the above form were fitted to these groups and are shown in Fig 2. It can be seen that these lines give a good approximation to the data. The regression line constants are:-

Loss range	a	b
£1 - £1,000	-0.27	-0.69
£1,001 - £10,000	-0.22	-0.35
more than £10,000	-0.05	-0.24

The data reflect the tendency for more sprinkler heads to operate in the larger loss fires.

Factors influencing the number of heads opening

(a) Hazard of different occupancies

Sprinkler standards[1,4] recognize three main hazard groupings based on the occupancy of a building. British rules specify 'Extra Light Hazard' (XLH), 'Ordinary Hazard' (OH) and 'Extra High Hazard' (XHH). The Ordinary Hazard is further sub-divided into three chief categories OH1, OH2 and OH3. These various groupings are used to specify the required density of water discharge, the assumed maximum area of operation of the sprinkler system, and the maximum area coverage per sprinkler head. By combining the latter two design requirements, the maximum number of heads, N_m, expected to operate in any particular hazard can be calculated. These values are given in Table 1.

Table 1

Design maximum number of heads operating

Hazard	N_m
XLH	4
OH1	6
OH2	12
OH3	18
XHH	29

The FOC ratings were based on insurance and manufacturers statistics, which showed clear differences between occupancies. For Ordinary Hazard the following criteria[5] were adopted as a basis for classification, where

$$p(x) = P(N < x)$$

Table 2

Basis of FOC risk classification

Hazard	Design maximum number of heads	Probability criterion
OH1	6	$P(6) > 0.80$ $P(12) > 0.95$
OH2	12	$P(6) > 0.80$ $P(18) > 0.95 > P(12) > 0.80$
OH3	18	$P(12) > 0.80$ $P(30) > 0.95 > P(18) > 0.80$

The records of fires attended by the Fire Brigades in the United Kingdom during 1967-8 were inspected and, where possible, the Standard Industrial Classification as given was converted into the Hazard Category of the premises. This method is far from ideal, as a fair amount of subjective interpolation is needed, but it is the only method available at present. The number of fires in each Hazard are given in Table 3.

Table 3

Fires by Hazard Group

Hazard	No. of fires	Percentage
XLH	30	4.8
OH1	8	1.3
OH2	91	14.7
OH3	476	76.9
XHH	14	2.3
Total	619	100.0

As can be seen the numbers in some Hazards are too small to permit inter-group comparisons.

In Table 4, two further parameters are tabulated, as estimated from the data, namely the percentage (P) of fires in which the design maximum number of heads is exceeded and the percentage (C) of fires that were controlled by the sprinklers, given that the sprinklers operated. These statistics are in good agreement with the design probabilities given in Table 2. It also appears that a smaller proportion of fires in XHH group are controlled by sprinklers, but the difference is not statistically significant.

Table 4

Sprinkler performance by hazard group

Hazard	N_m	P	C
XLH	4	23	90
OH1	6	17	88
OH2	12	9	93
OH3	18	6	95
XHH	29	3	79

(b) Age of sprinkler system

No information on the age of a sprinkler system is included in brigade fire reports, but the date of construction of the building is available, and it has been assumed here that these dates coincide. The performance curves are shown in Fig. 3 for three different age groups. The differences between the distributions are significant at the one per cent level.

In Table 5 the control probability (chance of a sprinkler system controlling a fire, given that it operates) for the three age groups is given.

Table 5

Control probabilities for different ages of buildings

Age	Control probability
pre-1900	0.98
1900-29	0.92
1930-67	0.91

It can be seen in Fig. 3 that in older buildings fewer heads operate, but the chance of control is higher, although not significantly so. There are insufficient data to identify the reasons for the difference between old and new buildings, but it may well be associated with changes in building design, particularly in the heights of ceilings and the higher incidence of single storey buildings in modern times, or with the effects of age on the sensitivity ratings of certain types of sprinkler.

(c) Wet and dry sprinkler systems

In wet sprinkler systems the pipes are normally filled with water but, where there is risk of freezing in unheated buildings, a dry system is fitted, in which the pipes are filled with air under pressure. When a head operates, the air is exhausted and replaced by water, which leads to some delay before water is applied to the fire[5]. No information on the type of system is available from the Fire Brigade reports in the United Kingdom but the NFPA[2] give information on the number of heads operating in both systems. This data is plotted as Fig. 4 and the fitted regression lines have the parameters:-

$a = -0.78$, $b = -0.16$ for wet systems and

$a = -0.27$, $b = -0.22$ for dry systems

The difference between the lines indicates that a higher proportion of fires in buildings protected by dry systems will attain any given size than in buildings with a wet system. A possible explanation is that the fire spreads rapidly before the air is exhausted from the system and water is sprayed onto the fire. Thus a larger fire exists which requires more heads to control it.

Discussion

It has been shown that the number of sprinkler heads opening is linked, to some extent, with the fire loss, and hence with the size of the fire, and some of the factors influencing the number of heads opening have been investigated.

On average, twice as many heads open in dry systems as in wet systems, and in view of the possibility of excessive water damage, it may be more economical to install effective heating to prevent freezing in wet systems where possible or, alternatively, to use some triggering device such as a smoke detector. More data are necessary to investigate this possibility, and also the effects of age. It is interesting to note that the statistical distribution of the number of sprinklers opening in a fire is of the same kind as that found for fire losses. Models leading to this type of distribution have been discussed by Ramachandran[3], based on "wear out" failure, and by Mandelbrot[7], leading in this case to a Pareto distribution. These models could also be applied to some extent to the distribution of sprinkler heads opening, but a simpler explanation follows, if we assume that, prior to the sprinklers opening, the fire grows exponentially, so that the area A of the fire is related to time by a growth law

$$A \propto e^{Kt}$$

This would follow for small fires where the rate of growth is a function of the size of the fire, but for larger fires the growth may be determined more by conditions at the boundary.

We now suppose that the delay between ignition and control is distributed at random, for example as a Normal distribution, or as a Poisson distribution. This random element is introduced because of the random position of the fire relative to the sprinklers, ceiling height, etc., and strictly fire growth should also be expressed in probabalistic terms to allow for different types and configurations of the fuel. We now derive the probability density function (p.d.f.) for the various distributions mentioned above.

1. Normal

$$\text{p.d.f. } (t) \propto \exp\ (-K_2 t^2)$$

$$\therefore \quad \text{p.d.f. } (A) \propto \exp\ (-K_3 \log^2 A)$$

and hence the assumption of a normally distributed delay time leads to a log-normal distribution of fire area.

2. Poisson:

$$\text{p.d.f. } (t) \propto \exp\ \left(- \int_0^t \mu \, dt \right)$$

where μ (t) is the probability of control in the time interval t, t + dt.

$$\therefore \quad \text{p.d.f. } (A) \propto \exp\ \left(- {}^1\!/_K \int_0^{\log A} \mu \, dt \right)$$

If μ is constant, then

$$\text{p.d.f. } (A) \propto A^{-\mu/K}$$

which is the well known Pareto distribution. If $\mu = \alpha + \beta t$, so that the chance of control is an increasing linear function of time, then

$$\text{p.d.f. } (t) \propto \exp \left[- {}^1\!/_K \ (\alpha t + {}^{\beta}\!/_2 \ t^2) \right]$$

$$\therefore \quad \text{p.d.f. } (A) \propto \exp \left[- {}^1\!/_K \ (\alpha + \beta \log A) \log A \right]$$

which leads to the distribution of the number of sprinkler heads opening if we assume $N \propto A$. We can use the latter model to discuss the differences between wet and dry sprinklers described earlier.

For wet sprinklers, we have, from the data (see section (c) above):

$$a = \frac{\alpha}{K} = 0.78; \quad b = \frac{\beta}{K^2} = 0.32$$

For dry sprinklers,

$$a = \frac{\alpha}{K} = 0.27; \quad b = \frac{\beta}{K^2} = 0.44$$

Hence for wet sprinklers

$$\mu = 0.78\ K + 0.32\ K^2\ t$$

and for dry sprinklers

$$\mu = 0.27\ K + 0.44\ K^2\ t$$

We may now calculate the mean delay, T.

$$T_{wet} = \int_0^{\infty} t \exp \left[- {}^{1}/_{K} \left(\alpha t + \frac{\beta}{2} t^2 \right) \right] dt = \frac{0.96}{K}$$

$$T_{dry} = \frac{1.4}{K}$$

$$\therefore \frac{T_{dry}}{T_{wet}} = 1.46$$

and therefore the delay is 50 per cent longer for dry sprinklers. Even a small delay such as this can result in a considerably larger number of sprinklers opening, a product of the exponential growth law.

It is evident that if we know either K or T then the other can be estimated. Little is known about K, but if we assume that a representative value for T_{wet} is 5 mins, then T_{dry} = 7.5 min, and K = 0.19 min^{-1}. This means that the fire doubles its size every 4 min, a not unreasonable result.

These calculations are necessarily somewhat speculative in view of the paucity of the data, and the approximate nature of the model. However, they do show that, even with the present crude assumptions, such a model can lead to meaningful results and provides a means of estimating some important properties of fires in sprinklered risks.

Conclusions

Statistics of the number of sprinkler heads opening during a fire have been examined. They show that:

(1) There is no difference between American and British data, leading to a distribution

$$q\ (N) = N^{-0.68\ -\ 0.12\ \log N}$$

(2) There is a tendency for more sprinkler heads to operate in fires with a larger loss.

(3) In older buildings fewer sprinkler heads operate, but there are insufficient data to investigate the reasons.

(4) More sprinkler heads operate in dry systems. A tentative model suggests that this is due to delays in operation, so that dry sprinklers take about half as long again to operate compared with wet systems.

References

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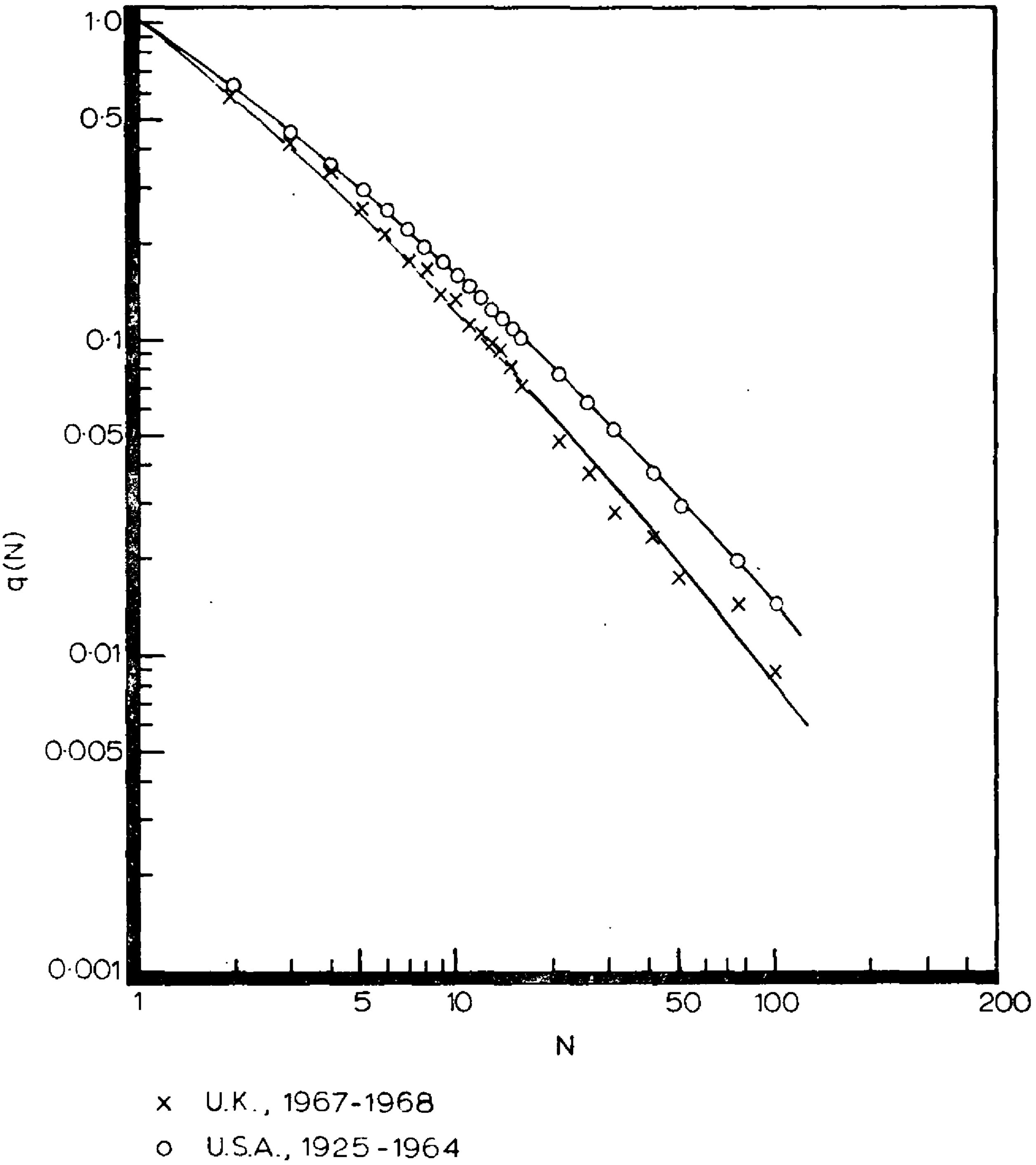

FIG. 1. FIRES IN WHICH SPRINKLERS OPERATED, U.S.A. AND U.K.

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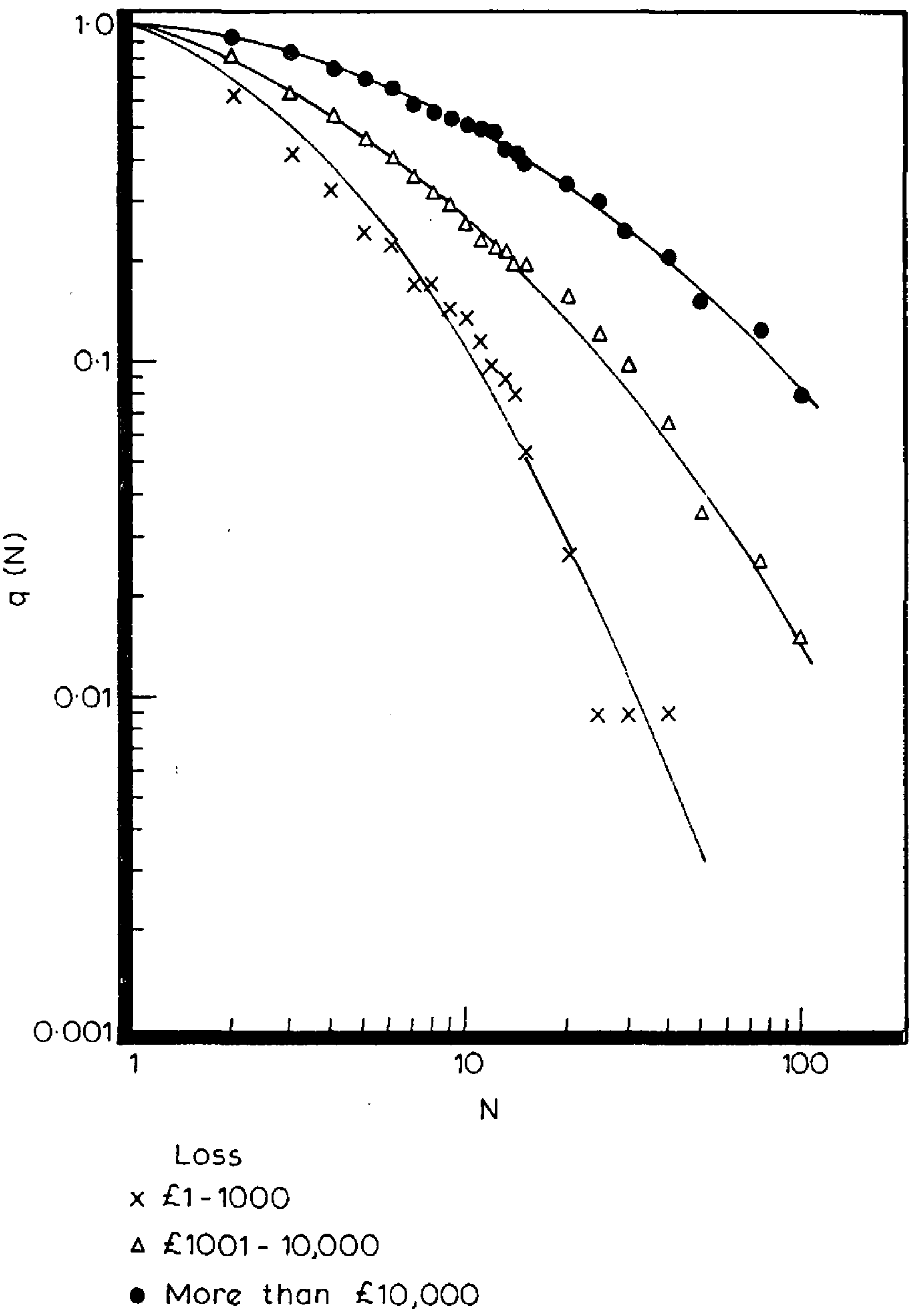

FIG. 2. SPRINKLER PERFORMANCE AND TOTAL LOSS

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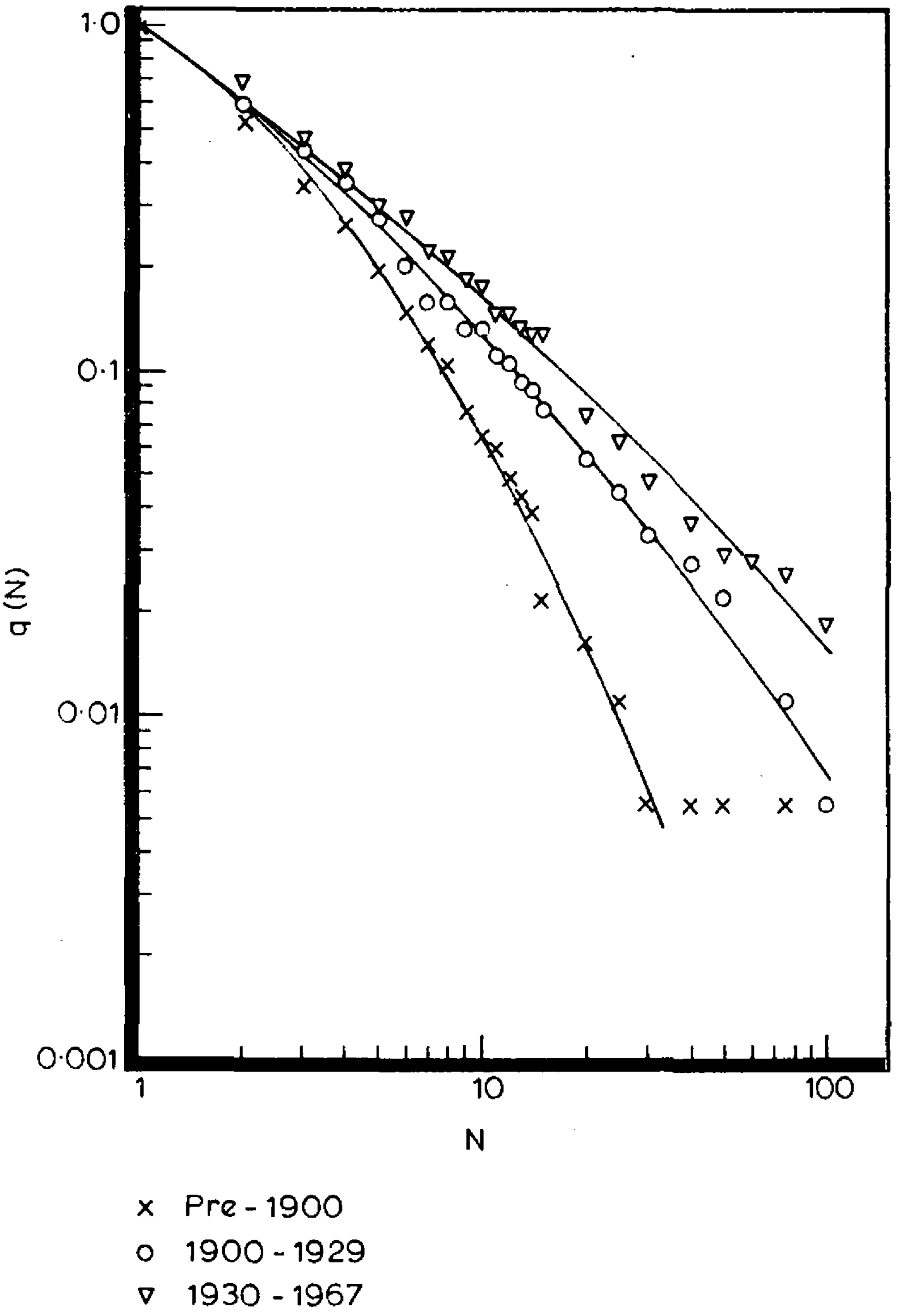

FIG. 3. SPRINKLER PERFORMANCE AND AGE OF BUILDING, U.K. 1967 - 1968

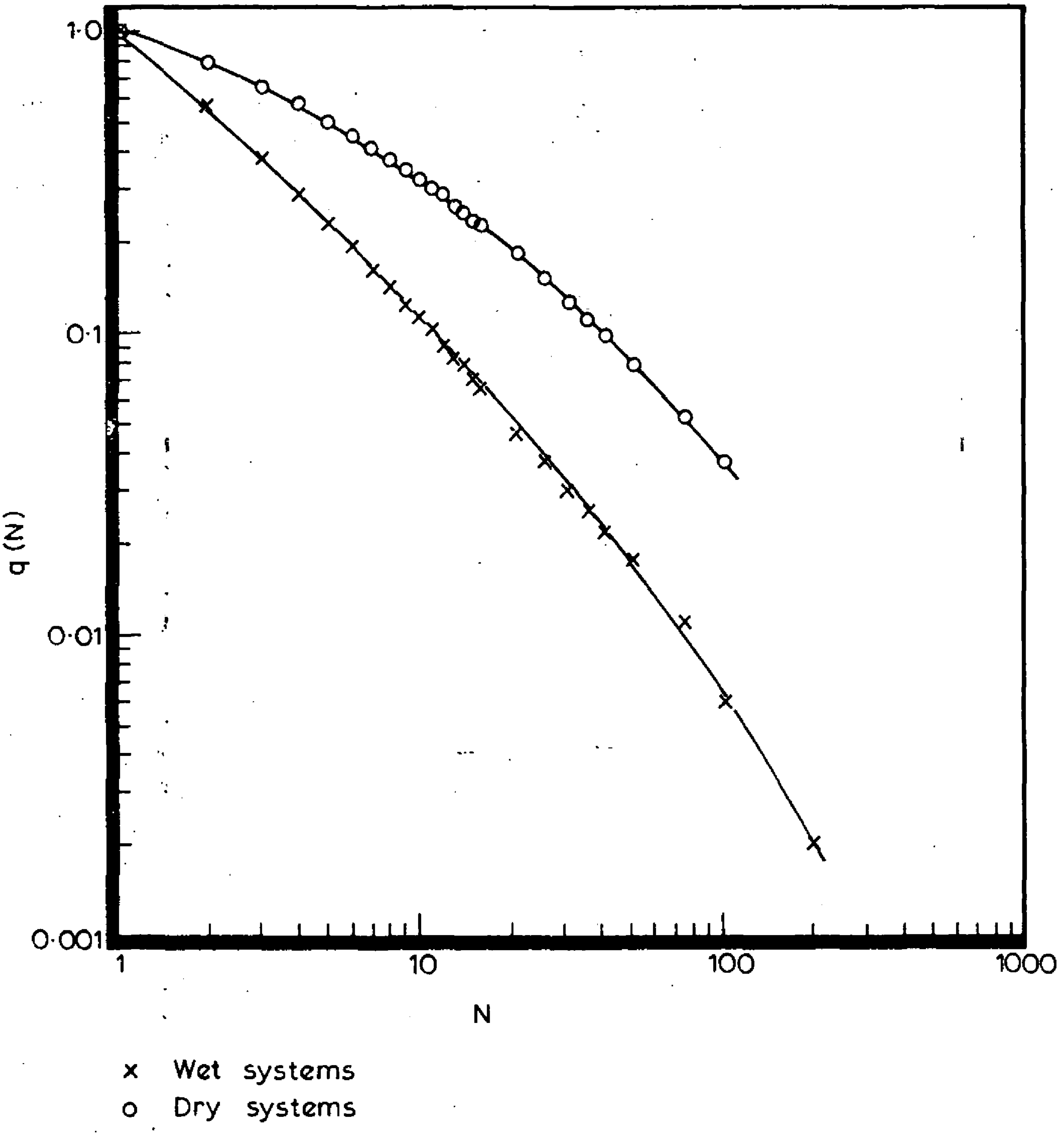

FIG. 4. PERFORMANCE OF WET AND DRY SPRINKLER SYSTEMS