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A STATISTICAL APPROACH TO THE SPREAD OF FIRE IN BUILDINGS

by

R. BALDWIN

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FIRE
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SUMMARY

The spread of fire in buildings is studied in this paper by examining the statistics of fires attended by the brigades. It is suggested that since traditional methods of specifying fire resistance based on a 'burn-out' tacitly recognize some element of risk, one should find some means of making an appropriate allowance quantitatively, including the beneficial action of fire fighting, sprinklers etc.

One way is to evaluate the probability of spread beyond the room of origin, which is shown to be a useful measure of the incidence of large fires, and hence to evaluate the influence of various factors on the spread of fire. Only limited analysis is possible because of few data, but it is shown that spread is much less likely in modern buildings, that the effect on it of early attendance by the brigade is small, but that early discovery is very important.

It is also shown that small reductions in the frequency with which fires spread beyond the room of origin can result in relatively large reductions in the incidence of large fires, a result of considerable economic significance, and strong statistical evidence of the value of compartmentation.

DEPARTMENT OF THE ENVIRONMENT AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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INTRODUCTION

Legislation for building controls exists largely to reduce the hazard to life by providing means of escape and by inhibiting the spread of fire in and between buildings to give adequate time for inhabitants to escape. In this paper we shall be concerned almost entirely with studies of fire spread in buildings, which is admittedly only one aspect of the problem of life safety though an important one for large buildings. It is hoped soon to extend this work to a direct consideration of the life safety problem.

The purpose of this paper is primarily to suggest new methods of approach and to outline some of the problems involved in such studies. Clearly, at this early stage of the research it is important to establish a suitable technique and to demonstrate that its application will lead to useful results. Nevertheless, in spite of the limited data available, particularly on the role of the building structure in inhibiting fire spread, several interesting results have emerged, notably in describing the relationship between large and small fires, and in estimating the influence of various factors on the spread of fire.

The main source of data for this work is the brigade fire reports collated and processed at the Fire Research Station. A report is received on every fire attended by the brigade, giving information about the circumstances of the fire, and the fire fighting effort for control and eventual extinction. These are coded and then processed on a computer; the resulting data are summarised annually in the U.K. Fire Statistics[1]. Data on fire losses are obtained from insurance claims, and for the past few years the Fire Research Station has been collecting information on fires in which the loss exceeded £10 000. These are usually regarded as being large fires, and although numerically they constitute only about 1 per cent of all fires, they account for about 60 per cent of the annual fire loss[2].

Of course, the fire reports do not provide all the necessary information. For example, where combustible linings have made a significant contribution to the rapid spread of fire this will be reported, but otherwise their presence would probably be ignored. The same is true of many other features of buildings which are the subject of design codes or regulations, and indeed there are other matters on which the brigade could not be expected to report adequately. To overcome these limitations, staff of the J.F.R.O. have been visiting fires systematically on a full time basis, and their reports will provide valuable supplementary data to be used in conjunction with the statistical returns.

THE CHANCE OF FIRE SPREADING BEYOND THE ROOM OF ORIGIN

Traditionally, we think of buildings as being divided into compartments or rooms, some of which we lable 'fire compartments' because their boundaries meet particular specifications of fire resistance. The required fire resistance may be estimated by reference to experimental data, reported elsewhere, and from a knowledge of the shape and size of the compartment, its ventilation conditions and contents. However, legislation for fire resistance must necessarily specify requirements for a range of buildings, usually with the same building occupancy, because design for individual buildings is not practicable, and in these circumstances it is necessary to conduct a survey of the contents and configuration of buildings for each occupancy in order to estimate realistic fire resistance requirements.

Such a survey has recently been completed for office buildings in several different countries, and we have now made a preliminary analysis[3] of a small sample of a survey carried out by the British Building Research Station. Some typical data are given in Fig. 1, the frequency distribution of fire load densities. There is a considerable range of fire loads and the distribution is very skew with a long tail. Thomas and Heselden[4] and Margaret Law[5] in interpreting results of experiments have related fire resistance to the parameter $L\,(A_W A_T)^{-\frac{1}{2}}$, involving fire load, window area and size and shape of the room. Using their results and combining them with the frequency distribution of this parameter derived from the survey, we arrive at a frequency diagram for fire resistance requirements, shown in Fig. 2. Once again a skew distribution with a large range of fire resistance.

The application of these results presents some difficulty. According to conventional philosophy of fire grading the fire resistance should be sufficient to survive a 'burn-out', but in view of the wide variation of predicted fire resistance requirements, even within this narrow range of building occupancy, the maximum (75 minutes) will grossly over-protect most of the buildings of this type whose predicted mean fire resistance is about 25 minutes, and any lesser value will nominally under-protect a few. Regulations compromise by taking a representative value so that they tacitly incorporate a probablistic element. Similarly one introduces relaxations into, say, the area limitation for the presence of sprinklers, or requires increased fire resistance for high buildings, so that one is recognizing some risk element over and above the 'burn-out' concept. So far it is clearly done qualitatively not quantitatively; recent interest in a points system, is one response to this recognition. Having accepted this probablistic view of fire resistance, or accepted an element of risk, we must also ask whether we should make some allowance for early detection or for the beneficial effect of fire fighting by the brigade, or for sprinklers. Clearly there is a high chance of early discovery and extinction in most fires, reducing considerably the chance of occurrence of a burn-out, and thus reducing the risk involved in taking representative values of fire resistance. The difficulty remains as to the means of making an appropriate allowance quantitatively, without being arbitrary or expedient.

One way of bridging this gap between idealized burn-out experiments on the one hand and actual fires on the other, is to study the frequency with which fire spreads beyond some given size, e.g. the room or compartment of origin, linked to the circumstances of the fire and the characteristics of the building[6]. From the fire statistics it is a simple matter to calculate the proportion of a given class of fire which spread beyond the room of origin, and to study its association with various events in a fire[7,8,9].

Some typical data are shown in Table 1, giving the numbers spreading beyond the room of origin, denoted by n_s, and the total numbers of fire occurring in buildings of different types, denoted by p_s, and is derived from the equation $p_s = n_s/N$.

The quantity p_s is a fundamental property of a class of building occupancy, expressing not only variations in contents and the configuration, but also an element of chance. The course of a fire in a building is governed as much by the laws of chance as by physical or chemical laws. In the early stages of the fire, when the first item is ignited, further spread will depend on the availability and proximity of more fuel, and at a later stage, spread beyond the room of origin will depend on whether doors are open, the fire resistance of its bounderies and so on. In the absence of automatic detection, the fire may be discovered, at random, by a passer-by or occupant, and the fire rapidly fought by the brigade. All these uncertainties are now incorporated into a single statistic, p_S, and although it is not the only statistic of spread, nor necessarily the best, it is readily available for a large group of fires.

LARGE FIRE AND THE SPREAD OF FIRE BEYOND THE ROOM OF ORIGIN

Interpretation of p_S is made difficult by the ambiguity in the meaning of the word 'room', which is not necessarily a fire compartment. It is desirable also to be able to attach some economic value to compartmentation and the reduction of spread by various measures. These problems can be overcome to some extent by studying the incidence of large fires, defined as those in which the direct fire loss exceeds £10 000, and relating this to the chance of spread beyond the room of origin. As pointed out above, large fires account for more than 60 per cent of the fire loss, so that study of the incidence of large fires is of considerable economic significance.

In Fig. 3 the probability of a fire becoming large, is plotted against p_S for various occupancies ranging from industrial building to domestic houses, and for the year to year variations of the Distributive Trades, a more homogeneous set of data. The parameter p_L is derived by dividing the number of large fires in each occupancy by the total number of fires in the occupancy during the year.

It is clear that there is a strong correlation between p_L and p_S, and regression analysis yields $p_L = 1.23\, p_S^{3.2}$ and incidently shows that it is a relationship between probabilities, not numbers of fires.

There is therefore approximatlely a cube power law relating p_L and p_S. This correlation has been supported theoretically by simulating a model in which fire spread is represented as a random walk on the cells of a lattice, using a computer[10]. Comparison of theory and data suggests that large fires correspond on average to fires involving four or more rooms, and the chance of a large fire calculated by theory is then in close agreement with the data. The estimate of four rooms is supported by data on loss and areas of fires.

Some important conclusions follow from this correlation. First we have now attached some practical significance to the term p_S in spite of difficulties about definition of a 'room'. Clearly the incidence of large fires is related to spread beyond the room of origin, which is therefore a useful measure of the chance of a fire becoming large. Hence large fires as a group may be studied by research on those factors which influence whether or not fires spread beyond the room of origin. This is of considerable practical importance because most of our experimental and statistical data relate to this stage of the fire.

Secondly, because of the cube power law, quite small reductions in p_s should result in relatively large reductions in the chance of large fire. This, perhaps, is the strongest statistical evidence we have of the value of compartmentation, even if the rooms studied do not conform to traditional fire resistance ratings. Of course improvements in p_s may derive from many sources, for example, by providing more adequate walls and floors separating compartments, by a policy of closing doors, by earlier detection etc. In the following sections we will attempt to identify some of the factors influencing p_s.

It is worth noting that the extent of structural damage is also related to p_s[11], as shown in Fig. 4, again reinforcing the importance of this statistic.

FACTORS INFLUENCING FIRE SPREAD

The scope of a study of fire statistics in order to identify factors influencing fire spread is limited by the amount of data supplied by the brigades. Since the present reporting system was devised some years ago and for a quite different purpose it is not surprising that there are insufficient data to determine, for example, the effect of varying degrees of fire protection, fire fighting or delays, as we would wish. Instead we must resort to variables which can be expected to give some indication of the importance of various events in fires.

Typical data for industrial buildings are shown in Table 2. Similar data are available for other types of building[12], but their behaviour is rather similar qualitatively and hence for the sake of brevity they are omitted from the present paper, and average values for other building regulation purpose groups given in Table 3. The average value of p_s associated with each variable is given in Table 4 for industrial buildings. The chance of spread appears to be highest in industrial and storage buildings, as might be expected, since these fires account for a very high proportion of large fires.

Perhaps the most important new result to emerge from this analysis is that spread is much less likely in modern buildings, particularly in multi-storey buildings. The chance of spread in post-1950 multi-storey buildings is about one half that in corresponding pre-1920 buildings, but this difference is much smaller in single storey buildings. It is worth noting that during the period 1950-1967 legislation for building controls was introduced, applying mainly to multi-storey buildings. Since the statistics show more variation with age in multi-storey buildings, it seems possible that increased building controls are having a significant effect on firespread. There are many possible explanations, however, and more data are urgently required to identify which is correct.

Another factor clearly exerting considerable influence on spread is the time of discovery of the fire, with spread more likely at night. This probably reflects the longer delays in discovery at night, and has been noted previously in studies of large fires, where the chance of a fire becoming large is four or five times as great at night.

Brigade activities are represented in the analysis by the risk classification of the building and by the brigade attendance time, defined as the time of discovery of fire to arrival of the brigade. The risk classification is based on the brigades assessment of the risk of fire spread and determines the size and speed of the first attendance. The analysis shows little variation in spread between the risks, perhaps because the system compensates adequately for varying risks.

It is somewhat surprising at first sight that the attendance time has little effect on the spread of fire. The most likely explanation is that the differences in attendance time, of the order of a minute or so, are small compared with the variation in the time from ignition to discovery. This is reflected in a considerable variation in the size of fire confronting the brigade on arrival, so that the benefit of early attendance is unlikely to be measurable. It seems therefore, that there would be few material benefits from measures to reduce attendance time. However, it has been shown that the brigade use about five times as much water in controlling fires as in experimental fires of the same area[13], suggesting that the main problems of the brigade are associated with assessing the size of the fire and directing water on to it. This aspect would repay further study. We have yet to examine the effect of attendance time on life loss.

TIME TAKEN TO CONTROL A FIRE

Thomas[6] has studied the distribution of control times and its relationship to fire spread. In Fig. 5 we show the probability of a fire being out of control at different times after the arrival of the brigade. The exact meaning of 'control time' is not known, but it is almost certainly related to the size of the fire on arrival of the brigade, because Thomas[14] and Baldwin[13] have shown that if A is the ultimate area of the fire and T the control time, then approximately $T \propto \sqrt{A}$. However, during this period the building is being evacuated and life is at hazard, so although control time may not necessarily be identified with fire duration, it is of some value in examining fire resistance requirements. In any case, this is the only statistical information available on fire duration; there is none on temperatures in fires.

According to this distribution about one fire in 15 lasts more than 30 mins, and about one in 50 more than an hour. Durations longer than an hour are so rare that they cannot be included on the graph, as one might expect.

The use of data on control times has not yet been fully explored, (for example, as an indication of fire resistance requirements), but some interesting results have already emerged. For example Thomas[15] has shown that there is an almost linear relationship between p_S and the control time, and the slope of the line may be related to a rate of spread.

MODELS OF FIRE SPREAD

One aspect of this type of work that has not been discussed above is the need for a probablistic model of fire spread. In common with most other regression models, the approach described above is of limited use unless there is some model describing the basic laws governing the system, if only because of the difficulty of extrapolating to situations other than those covered by the data which represent what is, not what might be. One such model has been described earlier, in which the rooms of the building are represented by the cells of a lattice, and fire spread is represented by a random walk on these cells. This was used to justify the cube power law between p_L and p_S. Another random walk model, in which both fire spread and fire fighting are represented has been described by Mandlebrot[16], and Thomas[17] has used this to suggest connections between various simple relationships between size, loss and duration.

One model which is required is some means of estimating the economic gains from reductions in p_S. Suppose, for example, that by provision of detection systems, fires at night are discovered as quickly as day time fires. Since $p_L \propto p_S^3$, and from the statistics, p_S would be reduced by about $\frac{1}{3}$, the chance of a large fire and hence the number of large fires would be reduced by about $\frac{2}{3}$. Furthermore, as shown in Fig. 6, the statistical distribution of losses in excess of £10 000 is virtually identical by day or night, implying that once the fire has exceeded some critical size, its ultimate size is determined by some other factor, presumably the size of the building or compartment. Ramachandran[18] has shown, for example, that the expected loss is approximately proportional to the square root of the area of the building.

The critical size suggested by this theory is clearly of importance in determining the maximum permissible size of a fire compartment, but its exact value is not easy to estimate. Senior NFPA engineers have stated that a fire of about 230 m^2 (2500 ft) is uncontrollable by present means, whilst the National Bureau of Standards[19], by studying fire losses, have shown that 'large fire characteristics' are associated with fires between 7.5 and 22 m^2 (80 and 230 ft^2). However, if we plot the statistical distribution of control times, shown in Fig. 5, we see that there is some evidence of two populations, with a transition at about 20 mins. Since this curve is a measure of fire fighting difficulties this provides evidence of increasing difficulties with fires lasting more than 20 mins. Using the relationship $T \propto \sqrt{A}$ this implies an area of about 35 m^2 (400 ft^2).

As a result of this discussion we see that a detection system designed to detect fires as early at night as during the day would reduce the incidence of large fires to about one third, but not their maximum size, and hence losses due to large fires at night would be cut to about a third. This estimate presupposes that a suitable system exists, clearly a profitable subject for research, and makes no allowance for the cost of providing it.

DISCUSSION AND CONCLUSIONS

Although the analysis described in the present paper is not yet completed, and the results are not altogether conclusive (largely because of lack of data) nevertheless the study of spread beyond the room of origin is clearly a valuable technique for studying the spread of fire in buildings. It has been shown that p_s is a useful measure of the incidence of large fires in any particular group of buildings, and this is of considerable economic importance because large fires, although small in number, account for more than 60 per cent of the annual fire loss. This and the cube power law connecting p_L and p_s form a strong argument in favour of compartmentation in buildings.

The results show that the effect of early attendance by the brigade is small, but that early detection is very important. More data are urgently required to investigate the reasons for reduced spread in modern buildings. These data are also required to investigate the benefits of different levels of fire protection and building controls, and the merits of different types of construction, so that ultimately one may be able to design building regulations on the basis of experience of real fires.

So far we have not studied hazard to life in this way, but in large buildings it is partly, if not wholly, concerned with the confinement of the fire. We have insufficient data at present to distinguish adequately between the spread of smoke and fire. Clearly, the work described in this paper is the beginning of a new approach to the fire grading of buildings. The main requisite is the support of responsible national and international authorities for this approach so that their co-ordinated efforts in obtaining suitable data may be brought to bear on the problem.

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Table 1

Some typical spread statistics (1967)

Hazard	Number of fires spreading n_s	Number of fires occurring N	Chance of spread p_s
Manufacturing industries	2 216	6 948	0.32
Distributive - retail	510	2 072	0.25
Distributive - other	334	808	0.41
Financial, professional etc	650	3 088	0.21
Hotels, restaurants, etc	498	2 318	0.22
Transport and communications	146	464	0.31
Public entertainment	160	478	0.30
Public administration and defence	146	632	0.23
Residential	5 300	37 118	0.14

Table 2a

Percentage of fires (1967) spreading beyond the room of origin in single storey industrial buildings

Time of discovery	Risk category	Age of building								
		pre-1920			1920-1949			1950-1967		
		Attendance time			Attendance time			Attendance time		
		0-5	6,7	8+	0-5	6,7	8+	0-5	6,7	8+
Day	A (high)	0	14	10	22	10	10	9	16	8
	B	11	17	0	10	17	13	5	7	11
	C	8	7	18	8	14	16	9	14	10
	D (low)	100	14	40	0	17	15	0	14	13
Night	A (high)	27	33	8	8	14	18	23	14	7
	B	22	8	17	18	16	19	13	9	12
	C	23	19	0	23	4	17	16	15	16
	D (low)	0	33	14	20	20	21	0	0	17

Table 2b

Percentage of fires (1967) spreading beyond the room of origin in multi-storey industrial buildings

Time of discovery	Risk category	Age of building								
		Attendance time			Attendance time			Attendance time		
		0-5	6,7	8+	0-5	6,7	8+	0-5	6,7	8+
Day	A (high)	31	26	27	23	12	13	12	14	0
	B	14	18	16	9	17	15	9	9	8
	C	13	24	27	14	23	13	8	15	21
	D (low)	33	33	25	0	33	27	0	0	26
Night	A (high)	45	41	25	41	24	33	14	15	14
	B	23	36	29	41	21	47	25	9	13
	C	22	28	44	31	39	47	23	57	26
	D (low)	50	33	33	0	0	45	0	100	0

Table 3

Average percentages spreading beyond the room of origin in different types of building (1967)

Type of building	Percentage spreading	
	Single storey	Multi-storey
Residential (residential clubs, schools, hotels etc)	-	12
Commercial (office premises)	-	13
Shops	14	14
Assembly (non-residential club, schools, theatres, etc)	25	17
Industrial	13	23
Storage	36	42
Flats, maisonettes	-	11

Table 4

Average percentages spreading beyond the room of origin for the variables studied

Variable	Level	Single storey	Multi-storey
Time of discovery	Day	12	18
	Night	15	30
Risk	A High	13	26
	B	12	19
	C	13	25
	D Low	16	30
Age of building	Pre 1920	15	26
	1920–1949	15	24
	1950–1967	11	15
Attendance time	0–5	12	23
	6,7	13	23
	8+	14	23

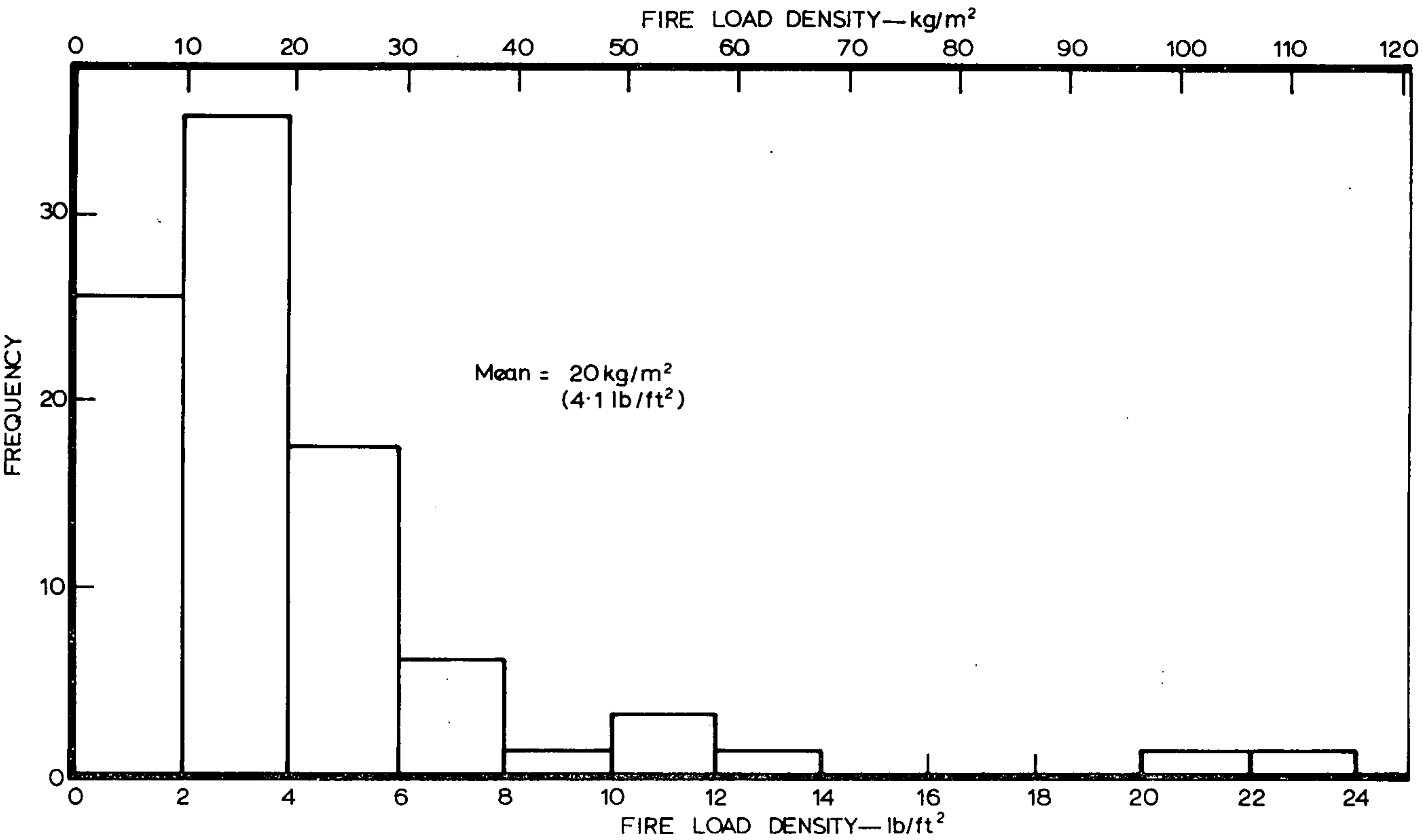

FIG.1. FREQUENCY DISTRIBUTION OF FIRE LOAD DENSITY—FIRE LOAD PER UNIT FLOOR AREA

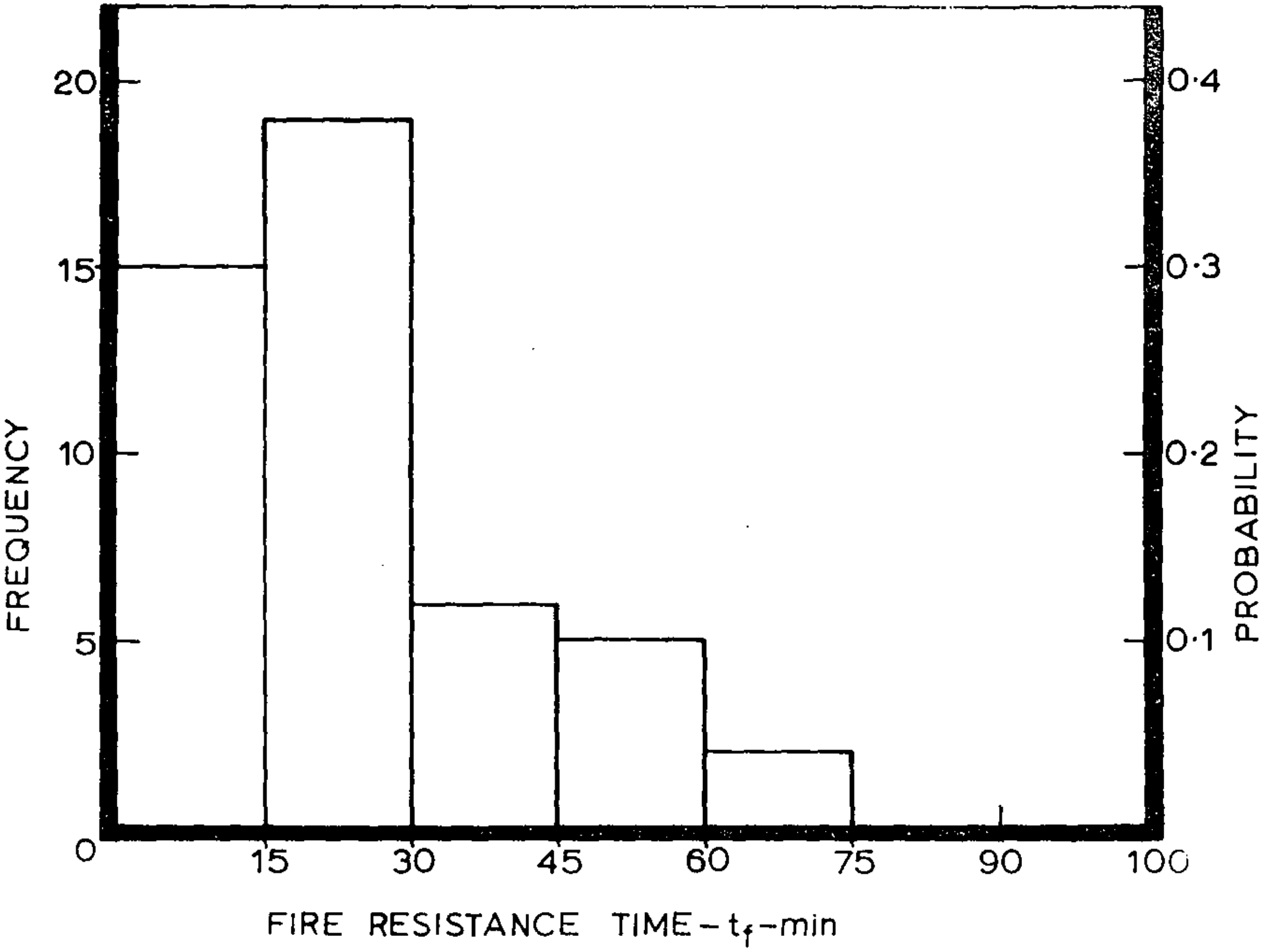

FIG. 2. FREQUENCY DIAGRAM FOR PREDICTED FIRE RESISTANCE REQUIREMENTS

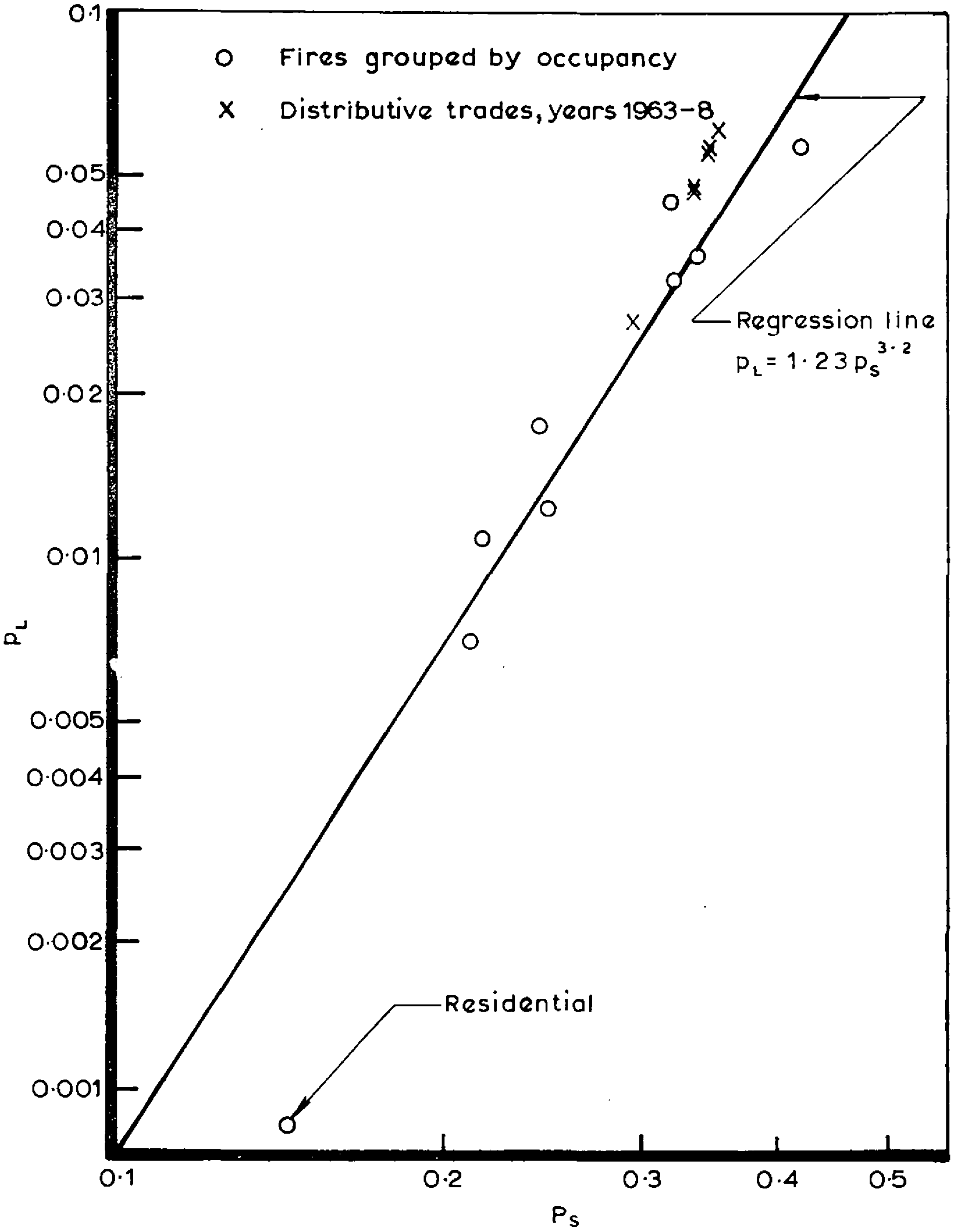

FIG. 3 OBSERVED PROBABILITIES OF FIRES BECOMING LARGE

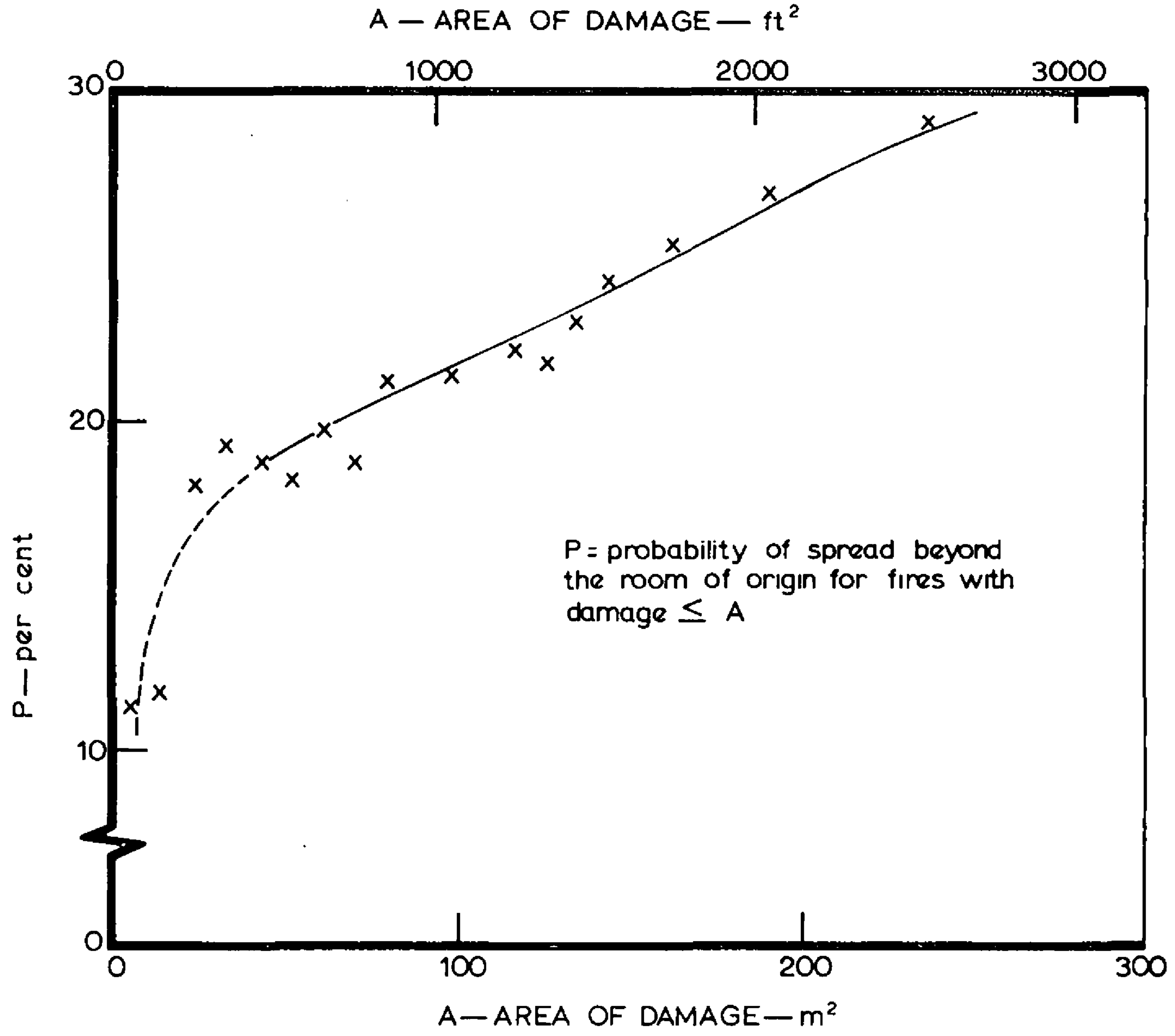

FIG. 4. CORRELATION BETWEEN THE AREA OF STRUCTURAL DAMAGE AND THE PROBABILITY OF SPREAD BEYOND THE ROOM OF ORIGIN

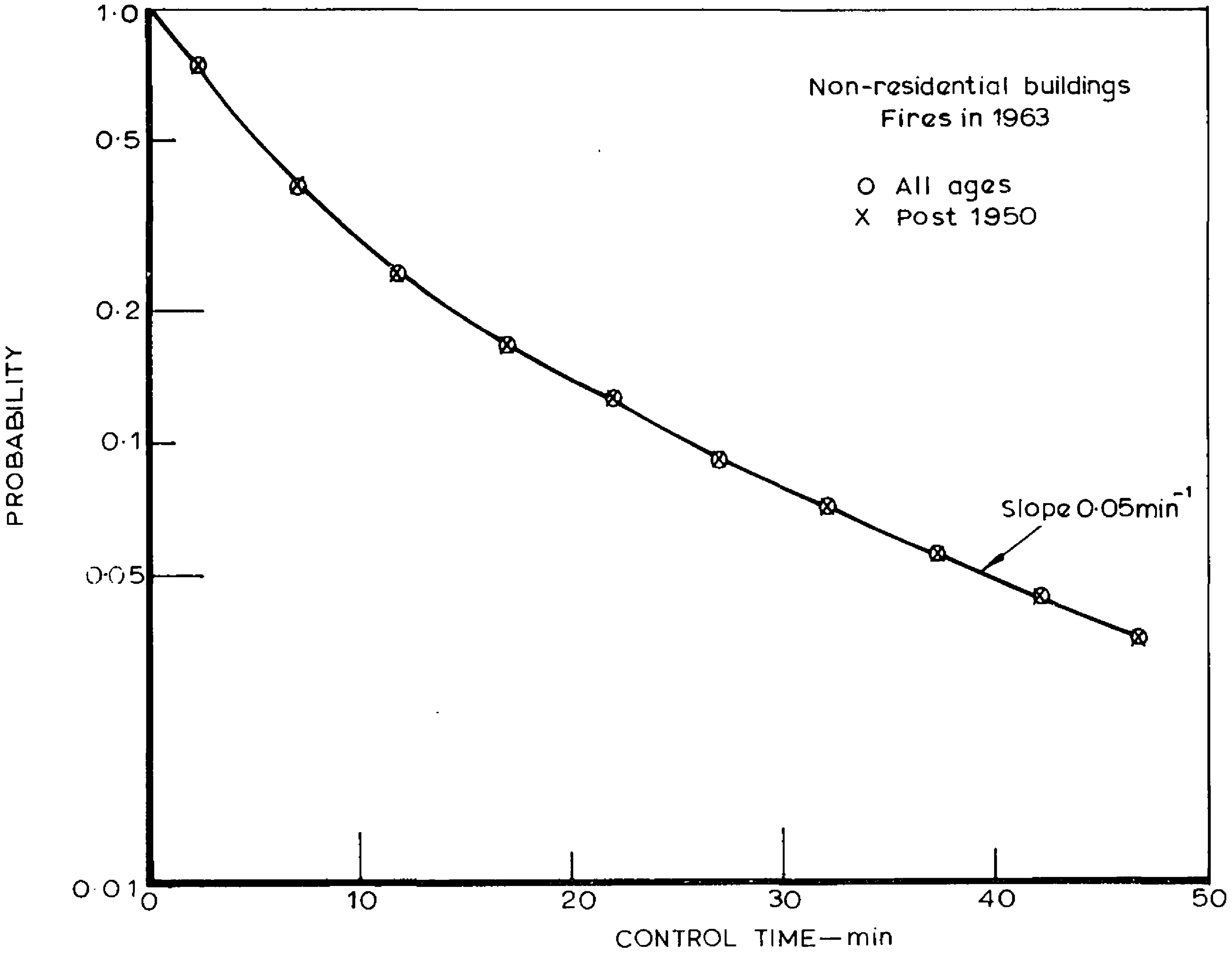

FIG.5. PROBABILITY OF FIRE REMAINING UNCONTROLLED

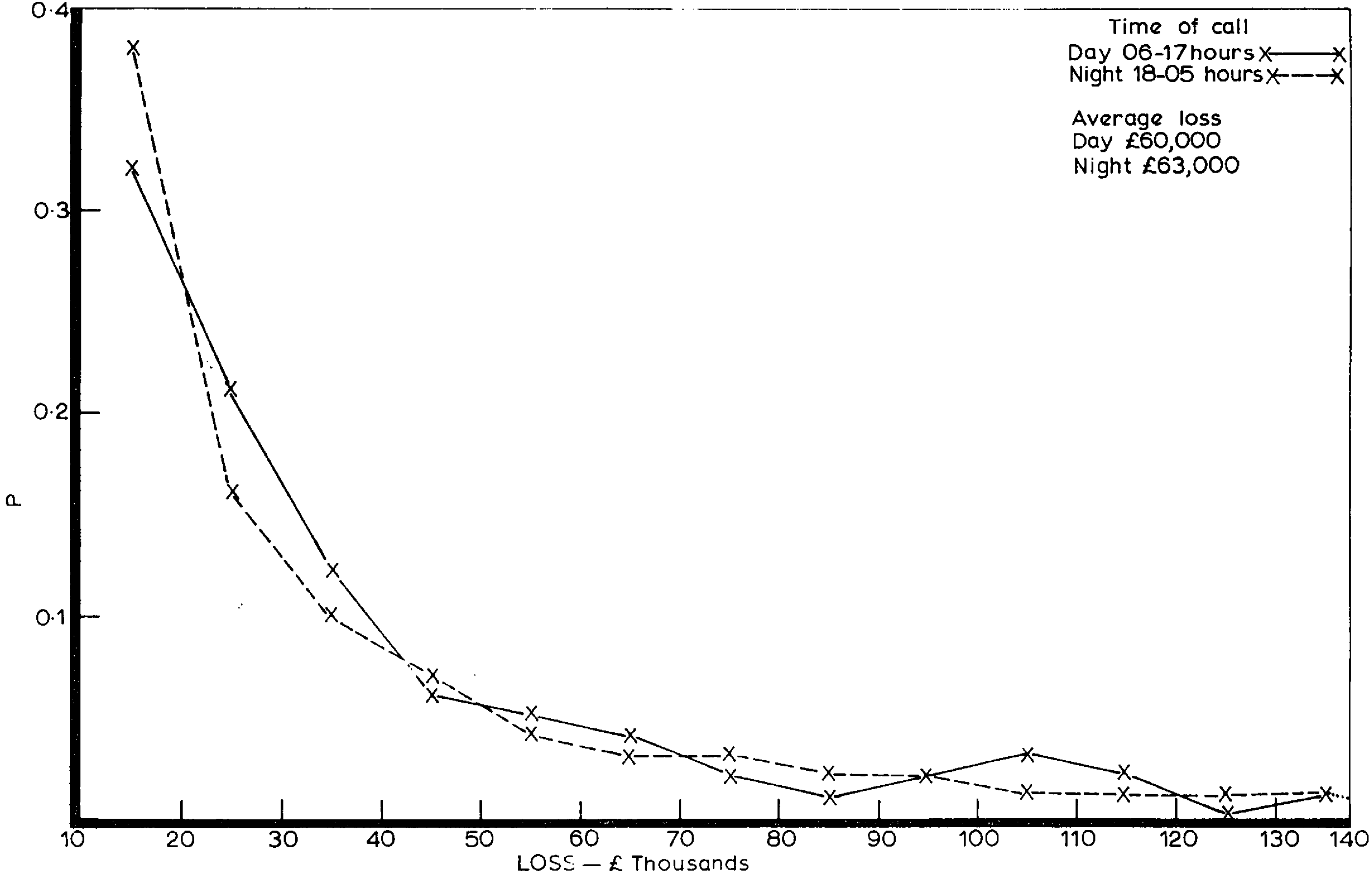

FIG. 6. DISTRIBUTION OF LOSSES IN DAYTIME AND NIGHT TIME FIRES