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THE SPREAD OF FIRE IN BUILDINGS:
A STATISTICAL APPROACH

by

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SUMMARY

It is possible to obtain information on fire spread as affected by the attendance of the brigades from the statistics of the fires reported by the fire brigades. The long term implication for building regulations of these new uses of the statistical data may be fundamental since at present the requirements for the fire resistance of structures do not allow for the presence of the brigade - i.e. they are based on burn out under free burning. The paper describes the concepts employed, concepts which later will be refined by relating them to a probabalistic model of fire spread. Even without this, however, some interesting results can be obtained.

Firstly, the mean probability that a fire spreads out of a compartment in a non-residential building is about 0.02 min^{-1}, the order of magnitude to be expected where fire resistance is commonly 30 or 60 mins. Secondly, the probability that fires in these buildings built since 1950 spread out of the room of origin is virtually the same as for older buildings though there is a lower chance of spreading upwards and a higher chance of spreading sideways.

Also an effect of attendance time differences on the chance of spread has been found for at least one type of building.

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

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INTRODUCTION

Each year in the "U.K. Fire Statistics" there are data on the spread of fire in buildings under the categories listed in Table I. This paper attempts to employ some of these together with data for the control time, i.e. the time after arrival at which the "stop" message is sent, to explore their possible utility and significance.

The number of fires which spread beyond the building of origin, categories 10-17, (or were "unknown") was less than 5 per cent of the total in 1963, though the proportion is higher for agricultural, forestry, fishing, private sheds, garages, and construction. We shall not discuss these further here, where the immediate interest is in the spread within the building from room to room. Excluding fires in buildings containing only one compartment (category 6) and in categories 1, 2 and 3, where the fires generally do not affect the integrity of the structure what are the chances that fire spreads from the room of origin, in particular what are the chances of spreading upwards and sideways? The reason for posing these questions first is that these are perhaps the most readily answerable general questions regarding the spread of fire in a building, and from the point of view of the fire resistance of the structure the most important.

We cannot answer these questions explicitly from the data as given in "U.K. Fire Statistics", because data for multi and single-storey buildings are not given separately (though they are available and in later studies they will be used separately), but if we provisionally assume that the risks of spreading sideways and upwards in a single storey building, (upwards, through the roof) are, respectively, the same as in a multi-storey building, we can. The argument is as follows.

Consider categories 4, 5, 7 and 8 and let any set of numbers of fires for a particular category (occupancy, control time etc.) be A, B, C and D. Let A_1 be the number of fires confined to the room of origin in single-storey buildings, and A_2 the corresponding number in multi-storey buildings. Then

$$A_1 + A_2 = A$$

Let $\bar{p}_u$ be the probability, given that the fire has spread beyond the item first ignited, that it has spread upward by the time the fire is controlled and $\bar{p}_s$ the corresponding probability that it has spread sideways. We then have for single storey buildings

$$\frac{A_1}{C + A_1} = (1 - \bar{p}_u)\ (1 - \bar{p}_s)$$

The bar over $\bar{p}_u$ and $\bar{p}_s$ denotes all fire durations, i.e. the probability for all fires at the time of arrival of the brigade.

For multi-storey buildings we have

$$\frac{A_2}{B + D + A_2} = (1 - \bar{p}_u)\ (1 - \bar{p}_s)$$

$$\frac{B}{B + D + A_2} = (1 - \bar{p}_u)\bar{p}_s .$$

These four equations determine $\bar{p}_u$, $\bar{p}_s$, A_1 and A_2 and give

$$\frac{A_1}{A_2} = \frac{C}{B + D} = a$$

$$\bar{p}_u = \frac{D}{B + D}\ \left(\frac{B + C + D}{A + B + C + D}\right) \text{ and } \bar{p}_s = \frac{B(B + C + D)}{A(D + B) + B(B + C + D)}$$

the equations for A_1 and A_2 are equivalent to writing the obvious

$$(1 - \bar{p}_u)\ (1 - \bar{p}_s) = \frac{A}{A + B + C + D}$$

It should be noted that neither $\bar{p}_u$ nor $\bar{p}_s$ refer to the room of origin. It is not possible (see Appendix) to separate sideways and upwards spread out of the room of origin though clearly the chance of such spread is

$$\bar{P}_R = \bar{p}_u + \bar{p}_s - \bar{p}_u\bar{p}_s$$

and for small values of either $\bar{p}_u$ or $\bar{p}_s$ this is roughly $\bar{p}_u + \bar{p}_s$.

For some years the records give A_1 and A_2 separately and it is not then necessary to assume that fires break through the roof of single-storey buildings as readily as from one floor to another in multi-storey buildings.

Even then, however, the assumption that both $\bar{p}_u$ and $\bar{p}_s$ differ between single-storey and multi-storey buildings, would give four quantities, viz, two sets of $\bar{p}_u$ and $\bar{p}_s$, to be determined from three, the ratios formed from A_1, A_2, B and C. ($\bar{p}_u$ and $\bar{p}_s$ can be determined separately for multi-storey buildings but not for single-storey buildings; for there only $\bar{P}_R$ can be obtained).

At this stage of the investigation we shall assume only one pair of values for $\bar{p}_u$ and $\bar{p}_s$. Because the ratio A_1/A_2 estimates a ratio for which actual data exist a check has been made that there is good agreement for the data as a whole.

The probabilities $\bar{p}_u$ and $\bar{p}_s$

Table 2 shows the overall values of $\bar{p}_u$ and $\bar{p}_s$ for the 1965 data and the values for "agriculture, forestry and fishing" are obviously high, perhaps because the attendance times in rural areas are longer than those in urban areas. Differences between different occupancies are clearly of interest and may reflect differences in the type and amounts of fuel, construction and regulations etc., but these variations between occupancies incorporate variations in fire-fighting time as well. The differences in $\bar{p}_u$ from year to year are not marked, see Table 3.

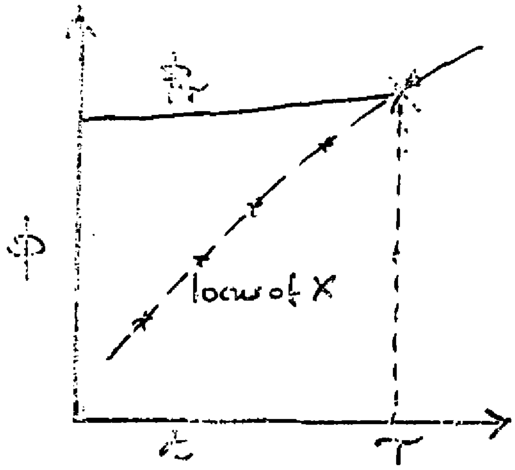
Allowance for control time variation

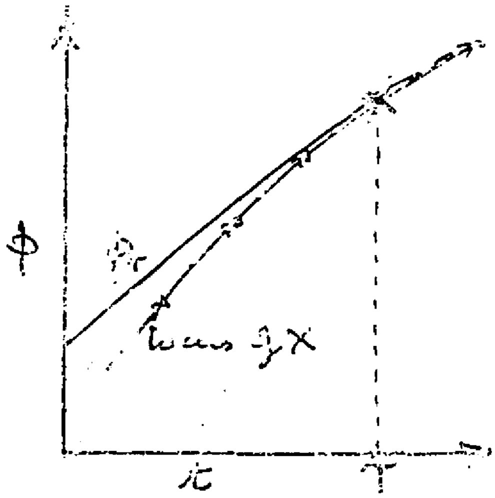
Values of A, B, C, D, for fires in non-residential buildings (categories 1-20) in 1963 have been classified according to the control time 'T' and these were grouped into intervals of 5 minutes. Values of $P_{R.T}$, $p_{u.T}$ and $p_{s.T}$ were then evaluated in the same way as for $\bar{P}_R$, $\bar{p}_u$ and $\bar{p}_s$ for each time interval. The results for $P_{R.T}$ are given in Fig. (1) and $p_{u.T}$ and $p_{s.T}$ are given in Fig. (2A) and (2B) for two large groups of occupancy.

The high correlation, close to a proportionality between $P_{R.T}$, $p_{u.T}$, $p_{s.T}$ and T up to at least 20 min is remarkable. When the number of fires becomes smaller at long times, the curves become irregular, but in the first 20-30 min one can define a value for a constant of proportionality.

One can obtain $P_{R.T}$, $p_{u.T}$ and $p_{s.T}$ rising with T, for two quite different reasons.

Consider the group of fires which the brigade fight for a particular time T. If it were possible to evaluate any one of these probabilities during the course of the fire fighting, i.e. for times $t < T$ we would obtain some relation of which Fig (3A) and Fig (3B) show extreme cases. It is difficult to conceive of a $p_{u.T}$ curve lying below the chain dotted line which is the locus of the end points X. The lines appearing in Figs. (1) and (2) are such loci.





If we review the meaning of a 'stop' message we can argue that the type of behaviour shown in Fig (3B) may be more realistic. Sending a stop message implies that no more resources will be needed. The fire is surrounded and is not spreading. Clearly these concepts have little relevance to Fig.(3A), which implies that the fire is not spreading significantly throughout the time the brigade is in attendance but the brigade is unable to send a stop message. Whichever interpretation is employed for the present, the slope of the chain dotted line at X is greater than the slope of the locus line expressing the growth of the fire so that the slopes in Figs (1) and (2) give upper limits to the growth of fire expressed as a probability rate.

Comparison of post 1950 industrial buildings and others

A rough comparison between old and new buildings has been effected by separately analysing data for those buildings built in 1950 or later - this date being chosen to include a high proportion of buildings built to post war building regulations. Fig (1) and Fig (4) show values of $p_{R,T}$, $p_{u,T}$ and $p_{s,T}$ for non-residential fires in 1963 reported as occurring in buildings dated as 1950 or later.

Values of $\bar{p}_u$ and $\bar{p}_s$ and the slopes λ_u and λ_s of the $p_{u,T}$ and $p_{s,T}$ curves are given in Table 4.

Table 4

Type and age of building	$\bar{p}_u$	$\bar{p}_s$	λ_u min^{-1}	λ_s min^{-1}
Non residential	0.16	0.09	0.015	0.007
" " (1950 and later)	0.11	0.12	0.012	0.012
Residential houses	0.07	0.045	0.011	0.006
" " (1950 and later)	-	-	0.0045	-

Data for 1963

The initial slopes of the curves in Fig.(1) are approximately the same as $\lambda_u + \lambda_s$ and little different for the two sets of non-residential buildings. The line in Fig. (1) has a slope of 0.02 min^{-1}.

Excluding the 5 per cent of fires that spread beyond the building - the extent of this spread may of course be trivial - and the 4 per cent or so which affect only exterior components or which are confined to common service spaces, the proportion of fires confined to the appliance or item from which heat first emanated is almost exactly the same in old and new buildings.

Table 5

Type and age of building	Fires confined to appliances (1963)	Total (1963)	Per cent of total
Non-residential buildings	4210	29980	14.0
" " (1950 and later)	898	6078	14.8

The confinement of a fire to the appliance of origin or source of heat is unlikely to be primarily dependent on the type of building save in so far as newer buildings may have different or newer appliances.

The value of $\frac{a}{a+1}$ (see p.2) estimates the fraction of multi-compartment single storey buildings involved in fire from the assumption that ρ_u and ρ_s are the same for single and multi-storey buildings. It is 30 per cent for all non-residential buildings of all ages and 56 per cent for post 1950 buildings which reflects the greater tendency to single storey production units, in modern construction . The data for 1963 do in fact separate fires between single and multi-storey buildings and the actual fractions of such single storey fires are 33 per cent and 56 per cent* which are sufficiently close enough to the above estimates not to contradict the assumption made earlier. Later studies will deal separately with single and multi-storey buildings and different occupancies.

The major difference between the spread statistics for buildings of all ages and those in post 1950 buildings is that the proportion of fires stopped in the room of origin, and floor of origin, are reduced in newer buildings but the proportion listed as stopped in single compartment buildings is almost correspondingly higher.

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*Including single compartment buildings as single storey raises the figures to 55 per cent and 78 per cent respectively.

This is presumably a reflection of a greater proportion of such buildings at risk. Larger compartments at risk mean a greater potential and real loss. However, the value of λ_u is lower and λ_s is higher for newer buildings than for older buildings. Their sum 0.022 to 0.024 min^{-1} is in fact slightly greater though not necessarily significantly so. These results imply that in newer buildings the chance of spread per unit time is roughly the same, though it tends to be more sideways than in older buildings and less upwards.

The interpretation of these results is made difficult by the ambiguity in the word 'room.' This is not necessarily the same as 'compartment' which is reserved for an area enclosed by fire resisting construction. If such a compartment were divided by a non fire-resisting partition a fire on one side of the partition could burn through it and be classed as spreading beyond the room of origin, but with or without the partition the same fire might be confined to the compartment. A greater value of p_s may be no more than a consequence of a greater tendency to use such partitions. Fires with high values of p_u are very likely to be larger than those with low p_u, but the same is not necessarily so for differences in p_s. Also these values reflect changes in the proportion of single to multi storey buildings in recent years.

Considerations of fire resistance

If T_f is the minimum fire resistance period in a compartment and T_g is the growth time to flashover we should expect that if a fire is not controlled by the brigade it spreads out of a compartment with a probability rate $1/(T_f + T_g)$ or greater if a high proportion of doors are left open. T_g is of order 10 min and if T_f taken is 30 min this rate is 0.025 min^{-1}. If T_f is 60 min the rate is 0.014 min^{-1}. The sum for all non-residential buildings is 0.023 min^{-1} which is to the order of magnitude expected and which reinforces the significance attached to this parameter. It is of course not yet possible to assess this way what contribution the brigade make in reducing this risk of spread prior to controlling the fire.

The 'duration' of fires and the probability of control

Figs (5) and (6) show details of the data on fire duration for those fires which spread beyond the item first ignited.

It should be noted that after the region 5-15 min the curves become less steep and almost linear. This time corresponds roughly to the period for which first aid appliances and hose-reels from the water tender are used. Such appliances are used on about 80 per cent of fires in buildings.

This shows that the chance of sending a "stop" message falls, perhaps due to the greater relative effectiveness of first aid appliances on small fires than of larger jets on large fires.

It is therefore possible that the change of slope which corresponds to a change in the probability of "stopping" the fire per unit time is associated with this major procedural change in fire fighting.

In the region 15-45 min, where the curves are almost linear the mean chance of sending a stop message is given by the slope in Fig (5) as about 0.05 min^{-1}. The form of this distribution and the existence of such a linearity is of course partly a function of the distribution of buildings at risk.

The limiting slope at long times in Fig (6) measures (for fires in the room of origin) the chance of a "stop" message being sent added to the chance of a fire leaving the room of origin by spreading. The chance in a time δT of controlling a fire which has spread beyond the room of origin is not necessarily the same as that for a fire which has not spread. Fire fighting effort increases as more resources are called so it is not possible to argue that the chance of a stop decreases simply because the fire is bigger. This question will be pursued elsewhere. If provisionally we assume the chances of sending a "stop" are the same then the difference in the slopes between Fig (5) and Fig (6) represent the probability of spread per min. out of the room of origin. This latter quantity can therefore be calculated as very roughly 0.025 min^{-1} which is very close to the value obtained from $\lambda_w + \lambda_s$, possibly fortuitously so.

The larger a fire becomes, the more walls and ceilings and doors there are for it to penetrate and the greater the chance that one of these is weak. Thus it is possible that the chance of spread increases as the fire becomes larger. If this is so and the chance of control remains the same or decreases, a "threshold" condition may be crossed so that it becomes highly probable that the fire will become much larger and will probably be only limited by the building itself. Such ideas have often been expressed in the past. It may now become possible to give some quantitative guidance on them.

The effect of attendance time

One of the more obvious possible influences on fire behaviour is the variation of attendance time, and Fig (7) shows that at least for single storey non-residential building there is such an effect. The vertical scale is the probability that a fire which is alight at time T after the arrival of the brigade will be confined to the room of origin. (Fires where the fire is out on arrival have been excluded). The data were subdivided into almost three equally sized groups; arrival up to 3 mins, arrival at 3-6 mins and arrival at 6 or more minutes. There is clearly some difference in the probability of spread for these three groups. The lower points in each curve are based on very few data so are liable to more statistical variation than the upper values based on more data. The three groups of fire do not however necessarily correspond to similar fires. High risk areas tend to have a higher first attendance and lower attendance times than low risk areas, so this simple separation of the data may reflect differences other than only in the attendance time. If fires were fought from the time they were initiated the chance of ultimate spread would be very low. It is somewhat of a speculation to extrapolate back these lines along the negative time axis but such a procedure suggests that the mean time at which fires are initiated is roughly 15-20 min at the most before the time of call. Clearly this is an arguable procedure and the data need more detailed analysis and discussion in relation to a proper model before any such procedure could be justified. When this sub-division of the data is done for particular occupancies there may not always be so obvious an effect of attendance time. A somewhat better approach might be on the following lines.

The intercepts on the zero time axis are the probabilities of spread irrespective of fire duration and are obtained from the total number of fires in each category. These totals appear in Table 6.

Table 6A

Extend of fire spread (Single storey)

Attendance time	Item first ignited (Appliance)		Room of origin		Building		Total	
0-3 min	382	0.21	1134	0.62	302	0.17	1818	1.0
4-6 min	422	0.21	1156	0.58	402	0.20	1986	1.0
6 min	314	0.19	906	0.55	440	0.26	1660	1.0

Table 6B

Extent of fire spread (multi storey)

Attendance time	Item first ignited (appliance)		Room of origin		Floor		Building		Total	
0-3 min	1136	0.20	3258	0.58	436	0.08	808	0.14	5638	1.0
4-6 min	692	0.20	2076	0.58	236	0.07	552	0.15	3556	1.0
6 min	278	0.14	1026	0.53	124	0.06	512	0.27	1940	1.0

The small numbers are the proportion (probabilities) for each category. There is a noticeable difference between the data for multi-storey and single-storey buildings in that the chances of spread are little different between the 0-3 and 4-6 min categories for multi-storey building, perhaps because the difference in risk offsets more the difference in attendance time. Equally one might argue that the predetermined attendance times for single storey buildings insufficiently compensate for variations in risk category. This topic will be included in later studies.

Also the chance of a fire having spread beyond the appliance or item first ignited in single storey buildings is much the same for all attendance times. It is perhaps better to pool these with the fires confined to the room of origin than to omit them - though their small number would not alter Fig.(7) much. It is reasonable to assume that all fires are originally confined to the room of origin or to the appliance and therefore the combined probability of not spreading beyond the room of origin is plotted versus attendance time in Fig.(8), taking the weighted mean attendance times for each group as 2 min, 4 min and 7 min. From these data the chance of being confined is estimated as being unity at an attendance time of 6 min. 6 min is therefore an effective mean time of growth up to the mean call time, if growth is measured by a probability per unit time. This result may clearly only apply to the fires examined here which are mainly small ones.

This procedure and this interpretation are clearly not possible for the data in Table 6B for multi-storey buildings. An analysis will have to be made of a smaller more homogeneous category to confirm whether this approach has any general validity.

It is not without interest however that the rate of increase in the probability of spreading beyond the room, measured by the slope in Fig. 8 is 0.024 min^{-1}, which is similar to previous estimates. The closeness of these figures apparently indicates that prior to being controlled fire spread in single storey buildings in the presence or absence of the fire brigade is little different. However the evidence given here is scanty and insufficiently analysed for such a conclusion to be adhered to firmly. The subject is introduced here merely to illustrate that fire brigade reports might enable some quantitative conclusion on this topic to be reached.

Conclusions

It appears that there are certain probabilities associated with fire spread and fire control, for which measures can be obtained. These probabilities are of considerable operational significance and their evaluation for various categories of fire, types of construction, attendance time etc. is an important task. In particular the probabilities of spread and of stopping the fire per unit time evaluated for various occupancies and types of fire fighting from year to year should provide a valuable additional method of quantifying fire behaviour. The few results discussed here are given mainly as an illustration of what use might be made of the data on spread given by the existing fire reports. They encourage one to pursue this approach with the aid of a "probabalistic" model of fire spread and fire fighting.

Acknowledgments

I should like to thank Mr. Fry, Mr. Langdon-Thomas, Mr. Baldwin and Mr. Ramachandran for the helpful discussions I have had with them, and Mrs. Day and Mr. North for obtaining the data and calculating the results.

Table 1

Non residential buildings fires (1963)

Spread category	Category Title	
1	Exterior components	1 056
2	Appliance (item from which heat emanated)	4 210
3	Common service spaces	364
4	Room of origin	12 440
5	Floor of origin	844
6	Building of origin (single-compartment)	6 548
7	Building of origin (multi-compartment single-storey)	1 166
8	Building of origin (multi-compartment multi-storey)	1 912
9	Building of origin (multi compartment storeys unknown)	14
10	Unknown	12
11	Adjoining buildings	566
12	Separate buildings	408
13	Other hazards	258
14	Adjoining and separate buildings	48
15	Adjoining buildings and other hazards	32
16	Separate buildings and other hazards	90
17	Adjoining and separate buildings and other hazards	12
	Total	29 980

Table 2

Extent of spread by occupancy

Industry hazard in which fire started	Category	$\bar{f}_a$	$\bar{f}_i$
Agriculture, forestry, fishing	1	0.59	0.37
Mining and quarrying	2	0.07	0.24*
Food, drink, tobacco	3	0.29	0.10
Chemicals and allied industry	4	0.15	0.18
Metal manufacture, engineering and allied industry	5	0.16	0.05
Textiles	6	0.16	0.12
Clothing, footwear, leather, fur	7	0.26	0.09
Bricks, pottery, glass, cement etc.	8	0.07	0.19
Timber, furniture etc.	9	0.36	0.13
Paper printing and publishing	10	0.16	0.02
Other and unknown manufacturing industry	11	0.24	0.10
Construction	12	0.13	0.24
Gas, water and electricity	13	0.11	0.06
Transport and communication	14	0.18	0.09
Distributive trades - retail	15	0.15	0.08
Distributive trades - other	16	0.29	0.33
Financial, professional, scientific and miscellaneous services	17	0.14	0.08
Places of public entertainment and ancillary services	18	0.17	0.14
Catering hotels etc.	19	0.12	0.06
Public administration and defence	20	0.14	0.07
Residential houses	21	0.07	0.05
Residential flats and maisonettes	22	0.08	0.07
Non institutional dwellings as part of other occupancies (including farm houses)	23	0.14	0.09
Private sheds and garages	24	0.15	0.19*
Undefined, derelict and unoccupied	25	0.15	0.09

Not all differences are significant

*Too few data for results to be meaningful.

Table 3

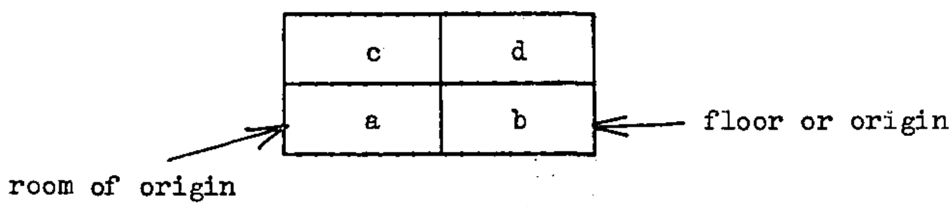
Variation in $\overline{\beta}_u$ from year to year

Type of building	1963	1964	1965
Residential houses	0.070	0.064	0.072
Construction industry	0.129	0.114	0.131
Non-residential	0.161	0.164	0.171

APPENDIX

The probabilities $\bar{p}_u$ and $\bar{p}_s$ and the probabilities of spreading from the room of origin

$\bar{p}_u$ and $\bar{p}_s$, whether referring to fires that last a particular time or to all fires irrespective of the duration of the fire (in which case $\bar{p}_u$ and $\bar{p}_s$ are replaced by p_u and p_s respectively) refer to spread at any time in the course of the fire, and so p_u includes upward spread from rooms other than that where the fire originated. If we assume that all rooms have the same chance as each other of spreading fire upwards (or wideways) we can consider the schematic representation of the building as



We exclude fires spreading beyond the building.

The zone "b" "c" and "d" may each contain more than one room but we have no knowledge of the number. The approach on these lines was suggested by Mr. Ramachandran.

The chance of fire spreading from a to c is denoted by f_u , and from a to b (or c to d) as f_s . The chance of spreading from b to d is denoted by f_{uf} and downward spread is excluded.

Then the probability of a fire remaining in a is $(1 - f_u)(1 - f_s)$ or being confined to a and b is $f_s(1 - f_u)(1 - f_{uf})$ and to a, b, c and d is $f_u + f_s f_{uf}(1 - f_u)$

Hence

$$p_u = f_u + f_s f_{uf}(1-f_u)$$

$$(1-p_s)(1-p_u) = (1-f_s)(1-f_u)$$

$$p_s(1-p_u) = f_s(1-f_u)(1-f_{uf})$$

$$f_s = \frac{p_s}{1-(1-p_s)f_{uf}}$$

$$f_u = p_u - \frac{p_s f_{uf}(1-p_u)}{1-f_{uf}}$$

Then if $f_{uf} \ll 1$

$$f_s \approx p_s$$

$$f_u \approx p_u$$

and the asymptotic slopes of p_s and p_u versus T are the same as those of f_s and f_u respectively. However, additional information is required before f_u and f_s and f_{uf} can be separately evaluated.

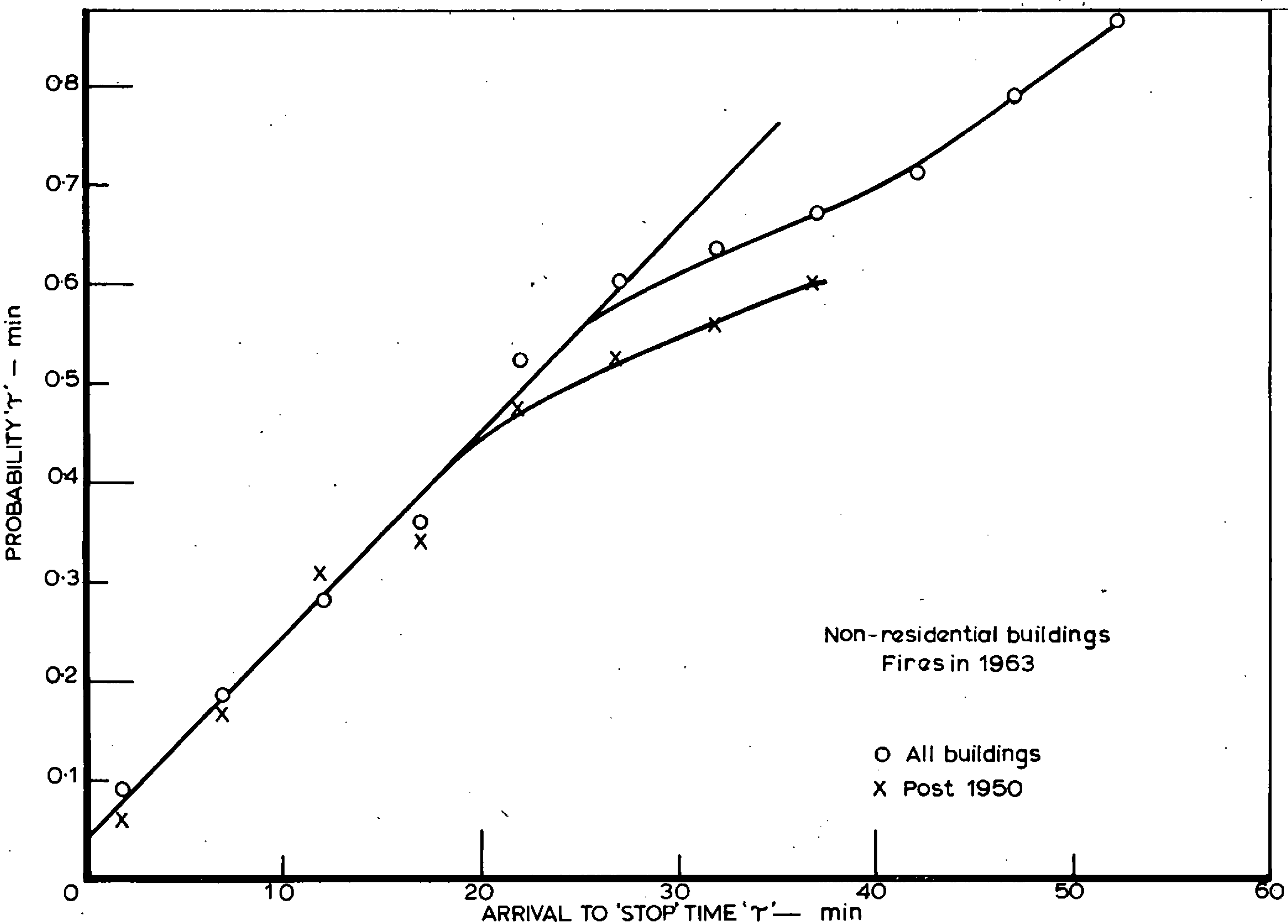


FIG.1. PROBABILITY OF SPREADING OUT OF ROOM OF ORIGIN FOR FIRES LASTING TIME - τ

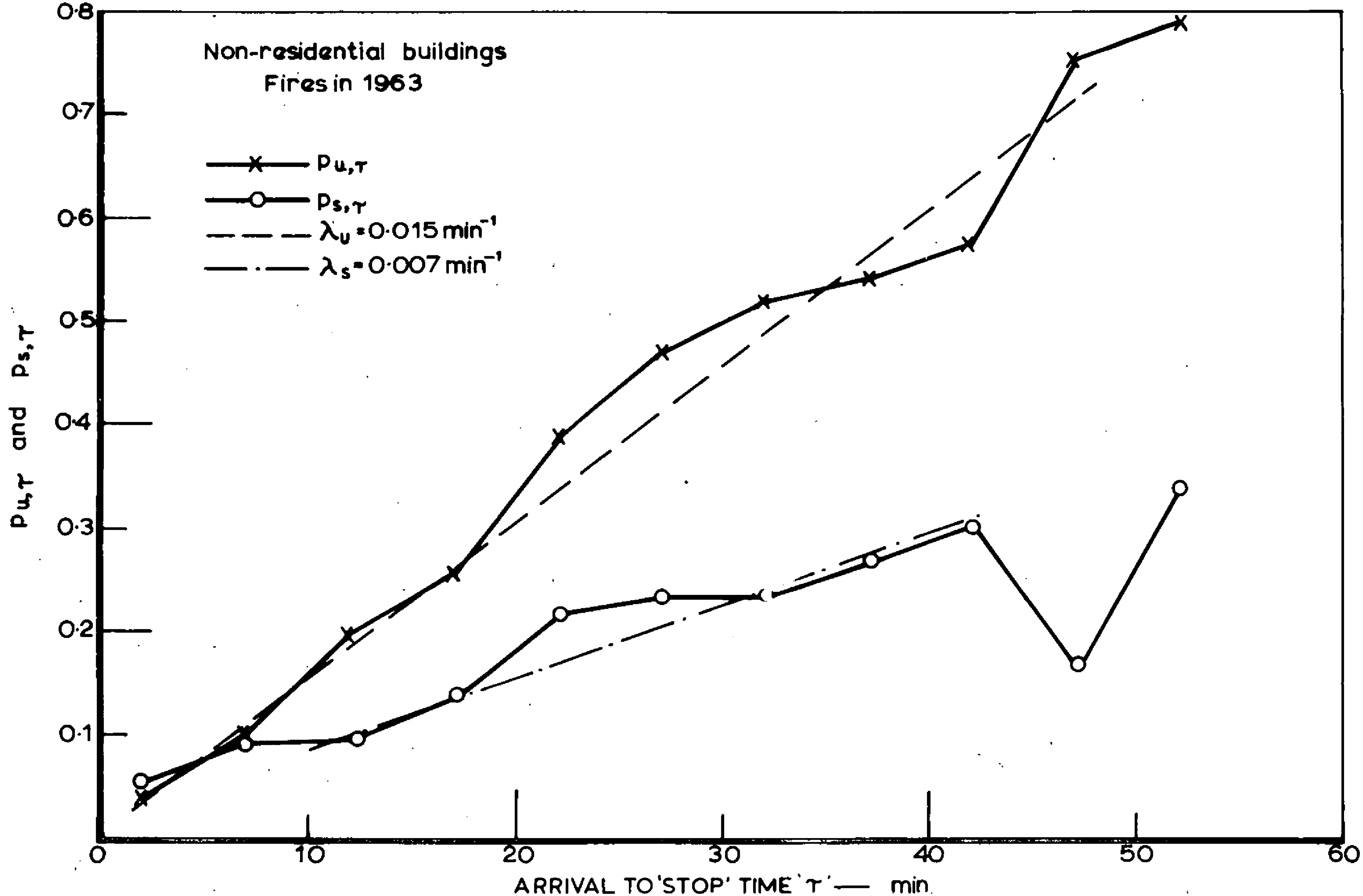


FIG. 2 a. PROBABILITIES OF SPREAD FOR FIRES LASTING A GIVEN TIME

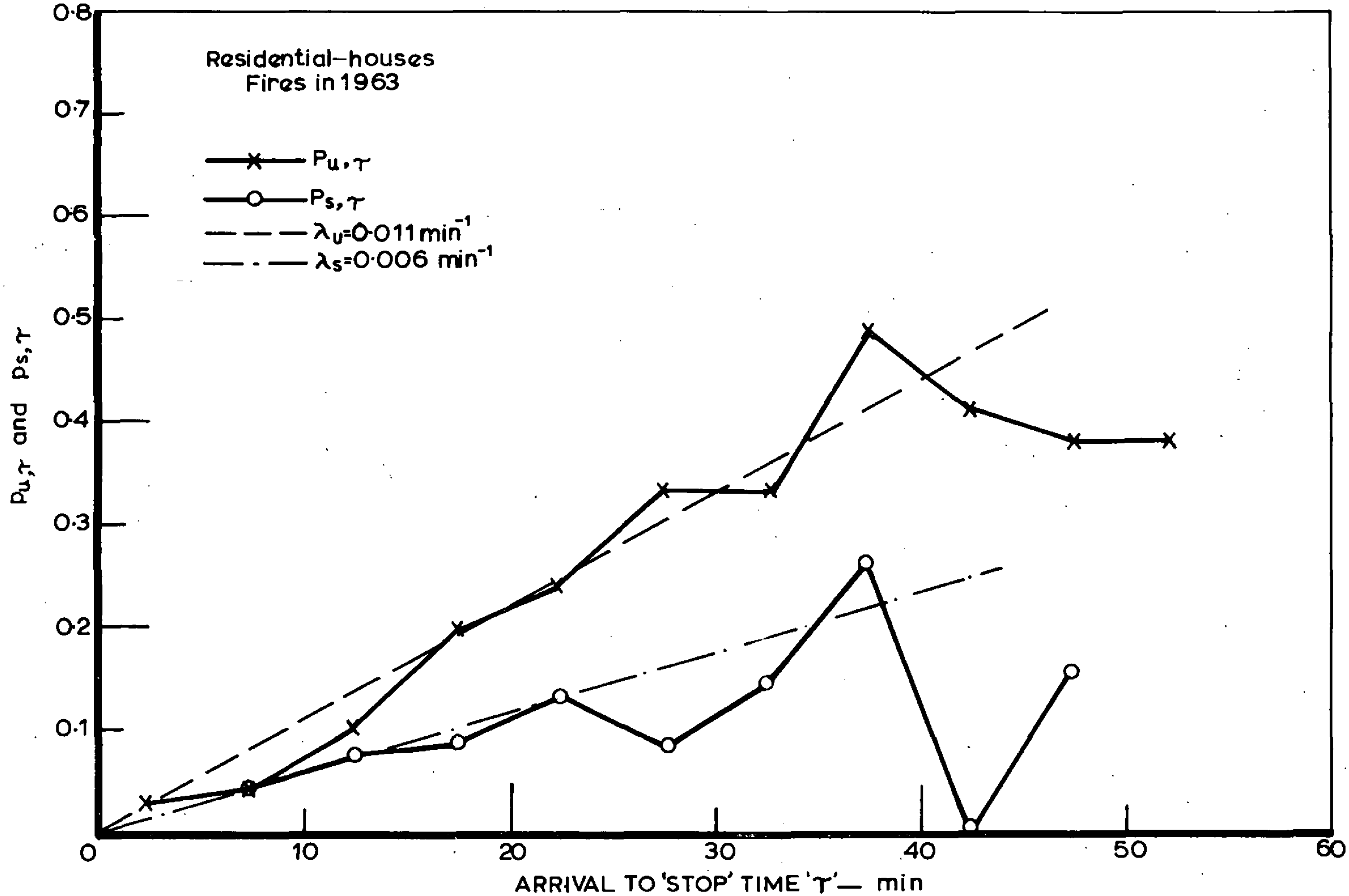


FIG 2.b. PROBABILITIES OF SPREAD FOR FIRES LASTING A GIVEN TIME

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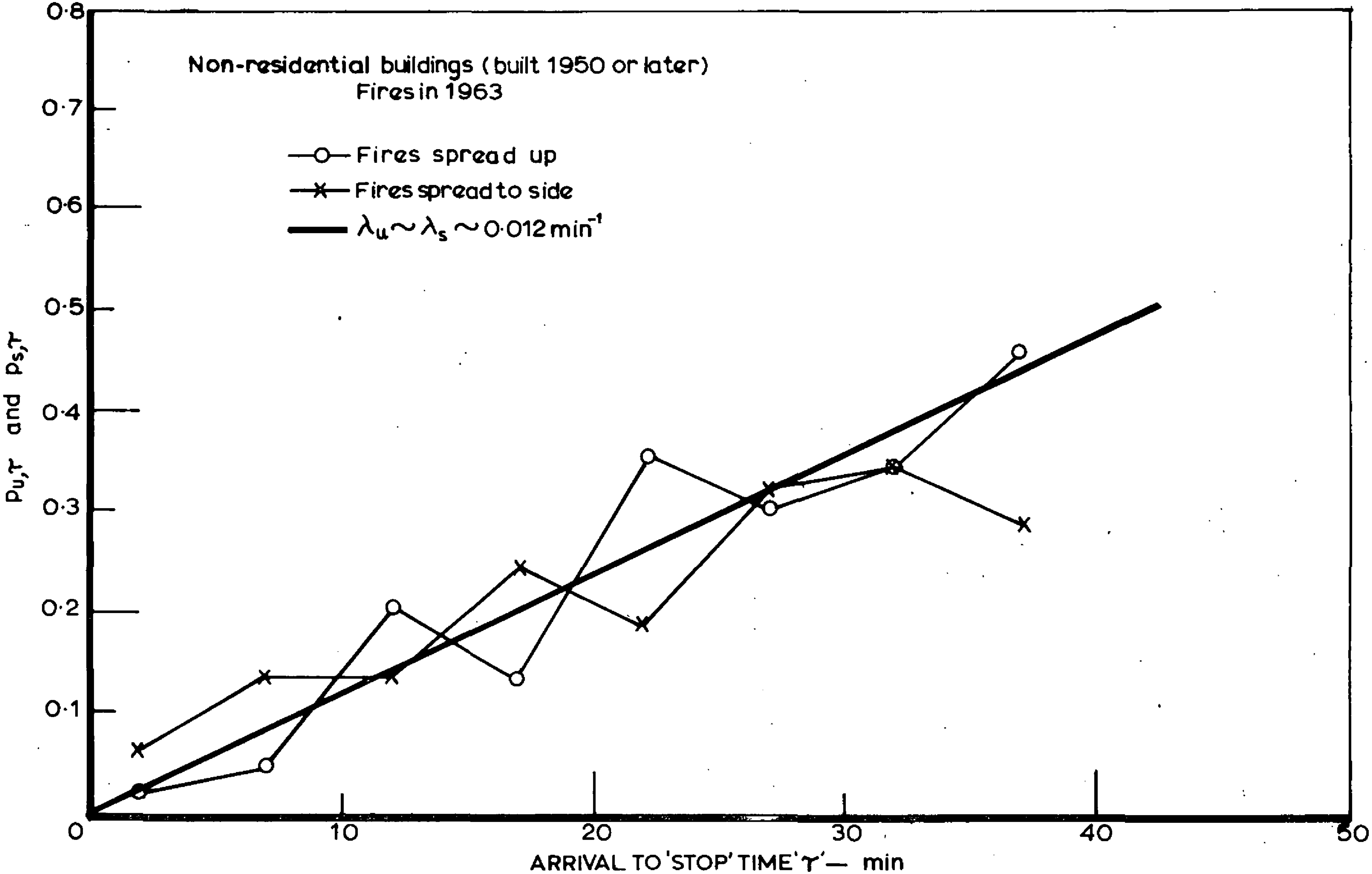

FIG.4. PROBABILITIES OF SPREAD IN NEW BUILDINGS FOR FIRES LASTING A GIVEN TIME

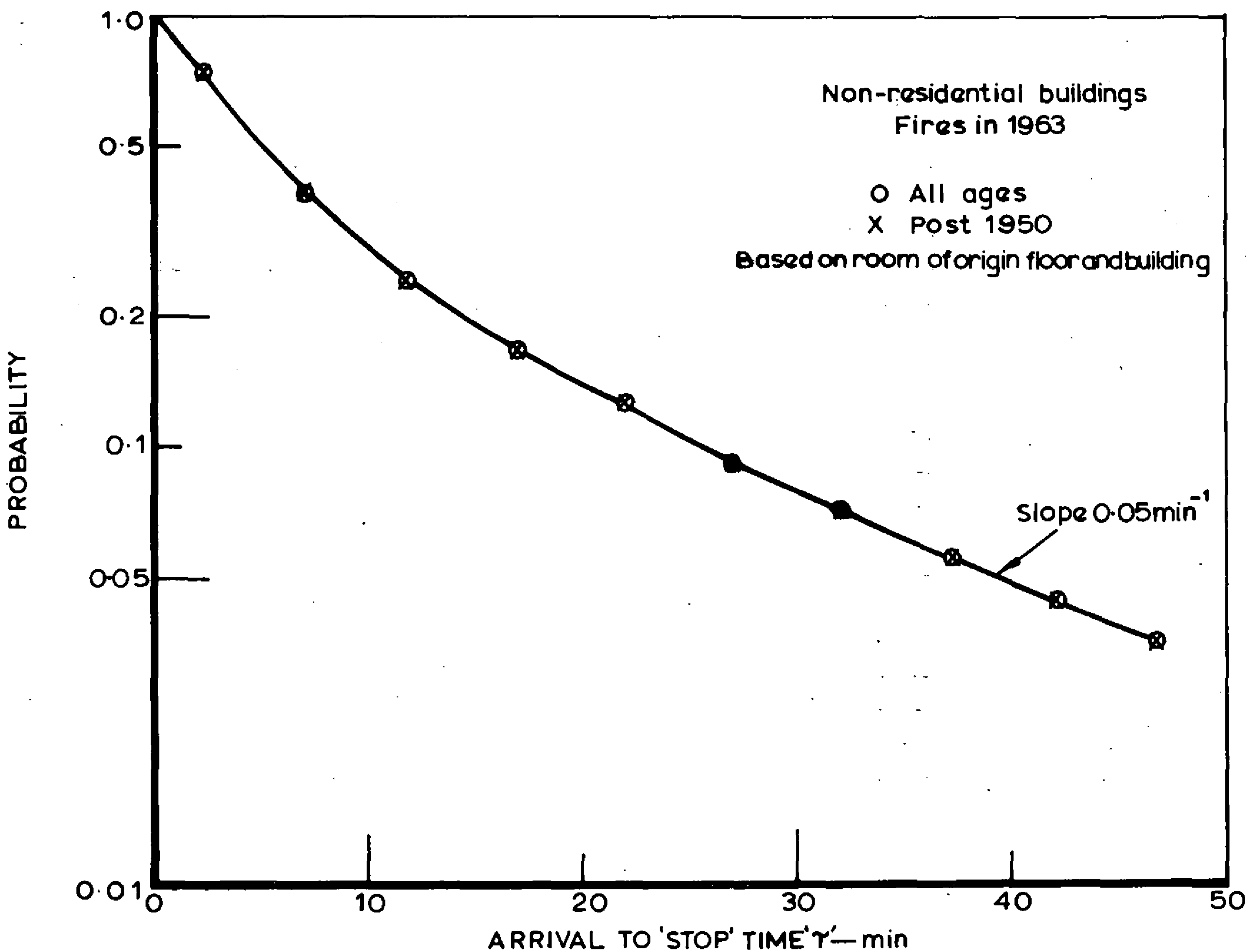

FIG.5. PROBABILITY OF FIRE REMAINING 'UNSTOPPED'

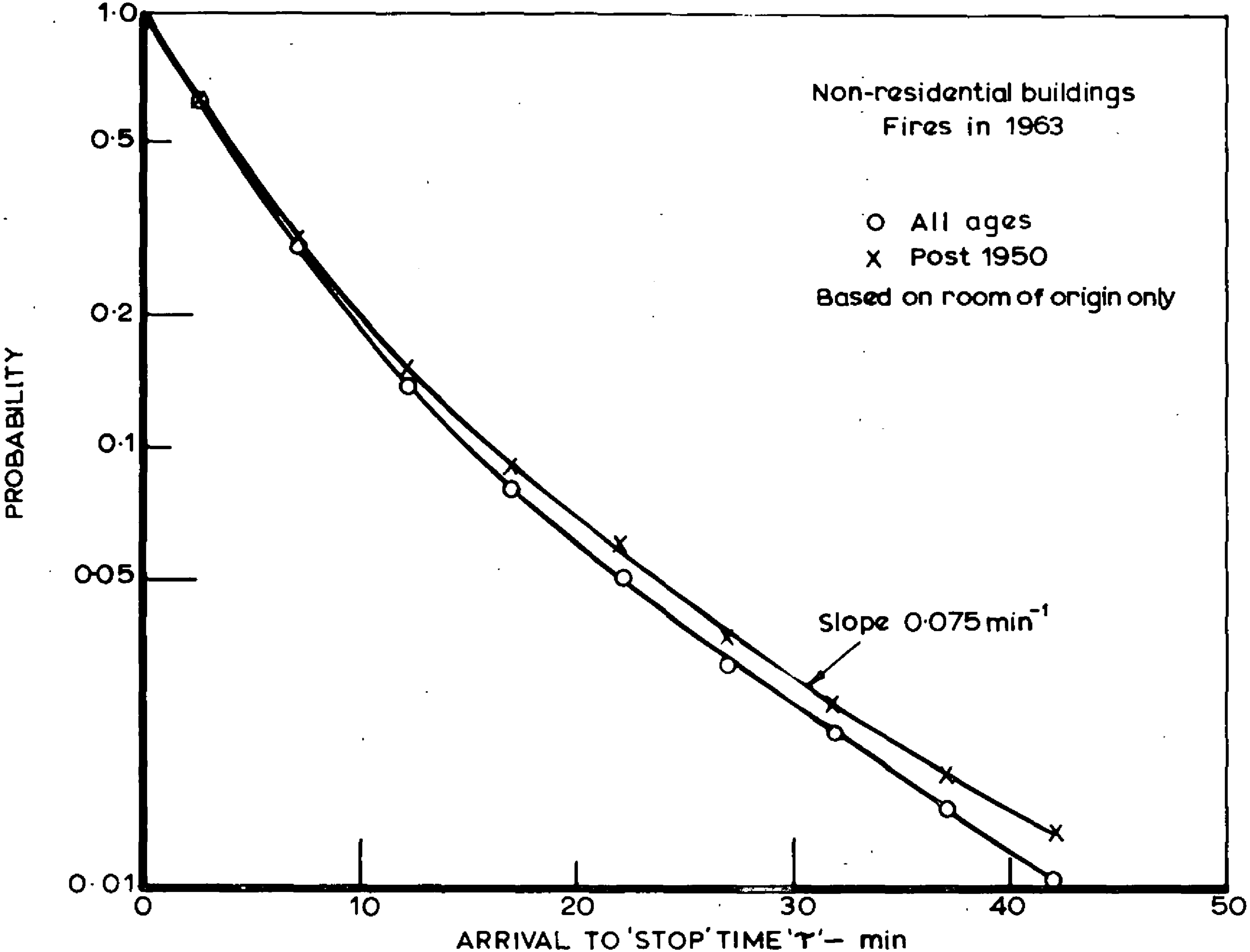

FIG.6. PROBABILITY OF FIRE REMAINING UNSTOPPED IN ROOM OF ORIGIN

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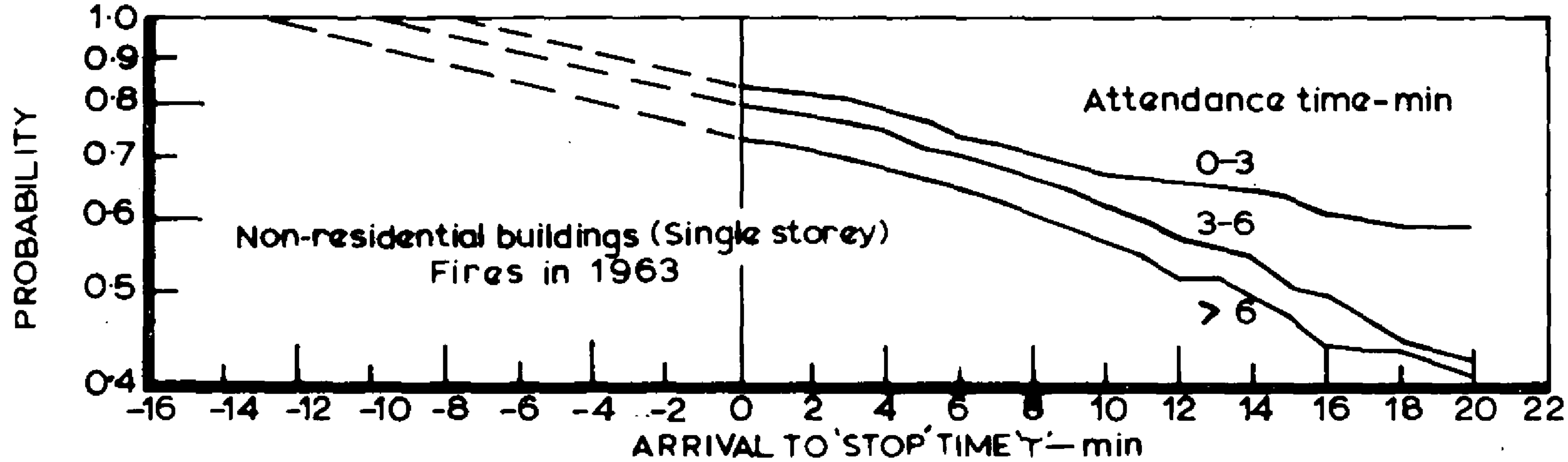

FIG.7. PROBABILITY OF EVENTUALLY BEING CONFINED TO ROOM OF ORIGIN OR ITEM FROM WHICH HEAT EMANATED

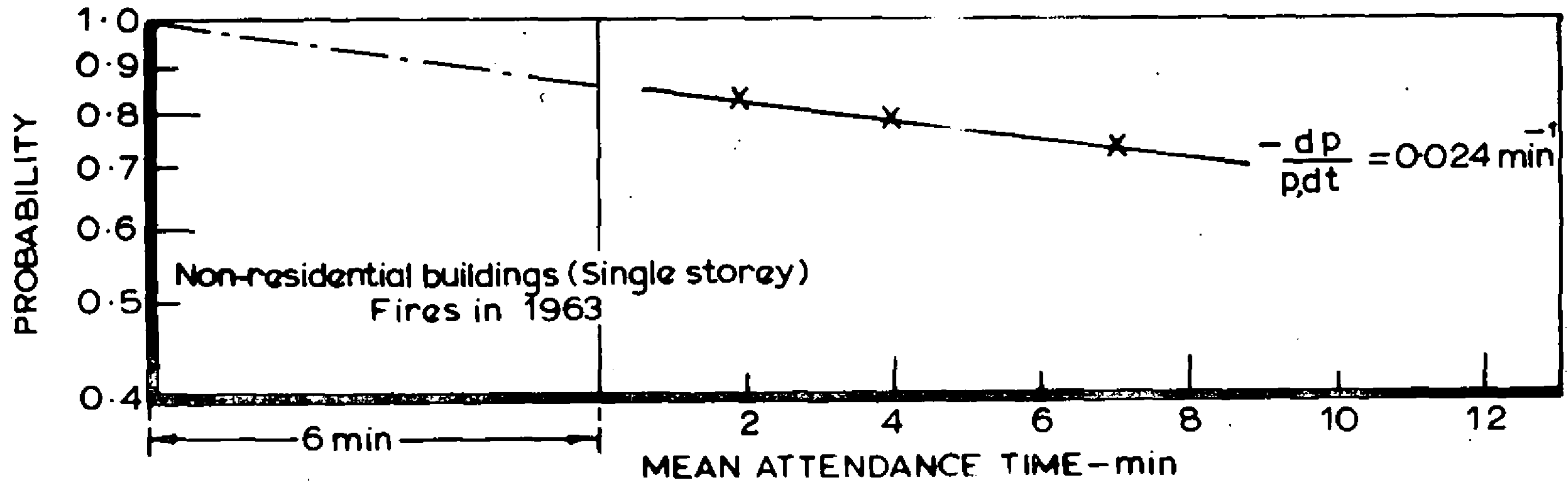

FIG.8. PROBABILITY OF EVENTUALLY BEING CONFINED TO ROOM OF ORIGIN OR ITEM FROM WHICH HEAT EMANATED