Fire Research Note
No 877

A RELATIONSHIP BETWEEN FIRE GRADING AND BUILDING DESIGN AND CONTENTS

by

Margaret Law

January 1971

FIRE
RESEARCH
STATION

SYMBOLS

A_F	Floor area	m^2
A_T	Area of compartment surfaces (excluding ventilation area) to which heat is lost	m^2
A_W	Ventilation area, window area.	m^2
A_{TT}	$A_T + A_W$	m^2
C	Thermal capacity of steel column	$J/^oC$
H	Compartment height	m
h	Window height	m
I	Intensity of radiation in plane of ventilation opening	W/cm^2
I_p	Maximum value of I	W/cm^2
k	Thermal diffusivity	cm^2/s
L	Total fire load	kg
M	Air supply (mass)	kg/s
N	Wall thickness	cm
Q	Air supply (volume)	m^3/s
R	Average rate of burning (80/30 value)	kg/s
R_i	Thermal insulation on steel column	min $^oC/J$
r	Ratio volume to surface area of fuel	cm
t	Time	min
t_f	Equivalent fire resistance time	min
α	Heat transfer coefficient	$Wcm^{-2\,o}C^{-1}$
λ	Thermal conductivity	$Wcm^{-1\,o}C^{-1}$
σ	Stefan Boltzmann constant = 5.69×10^{-12}	$Wcm^{-2\,o}K^{-4}$
θ_c	Temperature of upper thermocouple in compartment gases	^oC
θ_F	Average temperature of gases in fire compartment	^oC
θ_{PF}	Maximum value of θ_F	^oC
θ_s	Steel temperature	^oC
θ_t	Temperature in furnace (ISO curve)	^oC
θ_o	Temperature of heated surface of protected column	^oC
τ	Nominal fire duration = $\frac{L}{60R}$	min

The suffix 80/30 denotes an average value for the period during which the weight of fuel fell from 80 to 30 per cent of its original value.

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SUMMARY

This paper shows how temperature and rate of burning data from an international programme of experiments[1] on the behaviour of fully developed fires in compartments can be used to calculate, for each fire, the thermal properties of a protected steel column which just attains a critical temperature. It demonstrates how the time t_f for the same column to reach this temperature in the standard fire resistance test can be calculated. A correlation is then obtained for a range of scales, shapes, fire loads, ventilation areas and fuel thicknesses in the form $t_f = K \frac{L}{\sqrt{A_W A_T}}$ where L, A_W, A_T denote respectively fire load, window area and the sum of wall and ceiling area. The value of K varies slightly with fuel spacing. Data from other experimental fires in larger scale brick and concrete compartments, including those by Ödeen with forced ventilation, have been examined and give a somewhat lower value of K. Reasons for this are discussed. The calculations are compared with those of Kawagoe and Sekine, Lie, Pettersson and Ödeen, and the relation to Ingberg's early experiments is examined.

KEY WORDS: Building Correlation Fire grading Structural elements

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1. INTRODUCTION

A major aim of research into the behaviour of fully developed fires is to estimate the temperatures of building elements for a range of fire conditions, and in particular to determine whether certain critical temperatures will be attained which will cause structural or insulation failure. To achieve this it is necessary to know not only the properties of the building element but also the variation of temperature and rate of fuel consumption (rate of burning) with time. Such data have recently become available as a result of the international research programme[1] undertaken by the members of the Fire Research Working Party of the Conseil International du Batiment (CIB). This programme examined fully developed fires in single compartments $\frac{1}{2}$ m, 1 m and $1\frac{1}{2}$ m high, of various shapes with various areas of window opening and amounts and dispersions of fuel.

An analysis of the results indicates that a number of factors have a significant effect on the fire behaviour but it is by no means certain that they would have such a significant effect on structural behaviour. For example, a reduction in rate of burning increases fire duration but it can be associated with a decrease in fire temperature so that the net effect on structural temperature might be small.

This note makes a preliminary examination of the expected effects of fire behaviour on structural temperatures using these CIB data. Although based on a number of simplifying assumptions, the examination would be expected to indicate the correct form of these effects.

It has been common in the past to use areas under temperature-time curves as measures of fire behaviour. A better way of comparing the effects of the different fires is to compare the temperatures attained by a 'standard element' exposed to each fire in turn. However, if the main interest is in determining whether the element will or will not fail when exposed to a given fire, it would be more useful to know what the properties of the element must be in order to withstand failure in that fire. The standard method of measuring these properties is a fire resistance test, in which the furnace temperature is controlled to follow the ISO curve[2], and it would therefore be useful to relate the effects of fire behaviour to the effects of the fire resistance test.

Out of the wide variety of building elements it has been decided to consider, first, the temperature rise of a column surrounded by fire since the heat flow in such a column is simple to analyse. For additional simplification, a steel column protected with a light-weight insulating material is considered, failure being assumed when the steel reaches a critical temperature. A total burn-out condition is assumed, that is, the cooling portion of the temperature-time curve is taken into account when calculating the steel temperature.

The CIB experiments are described fully elsewhere[1] and summarised in Fig.1.

2. ESTIMATION OF FIRE RESISTANCE EQUIVALENT TO A GIVEN FIRE

2.1. Heating of column in fire and furnace

The relationship between the exposure time in the furnace, t_f, for a protected steel column to reach the same critical temperature as in a fire is derived below and takes the form

$$t_f = 0.0033 \, \tau^{0.84} \, (\theta_{PF} - 270) \qquad (1)$$

where τ is fire load divided by average rate of burning
and θ_{PF} is peak fire temperature
Equation (1) is derived as follows:

The steel temperature rise θ_s at time t is given by

$$\theta_s + R_i C \frac{d\theta_s}{dt} = \theta_o \qquad (2)$$

where θ_o is the temperature rise of the exposed surface of the protective material

R_i represents the thermal insulation provided by the protective material

C is the thermal capacity of the steel

The temperature θ_t of the ISO curve can be represented by[3]

$$\theta_t = 1200 - 550e^{0.01t_f} + 200e^{-0.5t_f} - 850e^{-0.2t_f} \qquad (3)$$

If we assume for the moment that the temperature of the exposed surface of the protective material follows the ISO curve, then we can substitute Θ_t for Θ_o in equation (2), integrate and obtain (Appendix)

$$\Theta_s = 0.91 \quad \Theta_t \ (1 - e^{-t_f/R_iC}) \qquad (4)$$

When a furnace is heated by non-luminous flames Θ_o will be significantly lower than Θ_t and equation (4) will need adjustment. For the purpose of comparing the effects of the fuel, compartment, etc however, equation (1) will be used. A real furnace would give a longer fire resistance time.

It has been shown[4] that in a building fire, which has radiant flames, the value of Θ_o can be close to the fire temperature Θ_F. An equation for the variation of Θ_F with time, similar to equation (3), has not been derived but earlier work suggests[5] that, to calculate maximum steel temperature, Θ_F can be represented by a constant temperature Θ_{PF} applied for a time τ, where Θ_{PF} and τ have already been defined for equation (1). Thus, integrating equation (2), substituting Θ_{PF} and τ for Θ_o and t, we obtain

$$\Theta_s = \Theta_{PF} \ (1 - e^{-\tau/R_iC}) \qquad (5)$$

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If Θ_s reaches the critical value for failure in the fire, then the equivalent furnace time can be found by substituting this same value for Θ_s in equation (4). For present design loads in the UK, a critical steel temperature of 550°C can be assumed and from equations (3), (4) and (5), putting Θ_s = 550°C, equation (1) can be obtained (Appendix). It is valid for τ = 10-120 min and Θ_{PF} = 600 - 1300°C. For higher design loads there are lower critical temperatures, say 400°C, but these make little difference (see Appendix) to the relationships to be described below.

2.2. Calculation of t_f for experimental results

For each experimental fire of the international programme, τ has been calculated simply by dividing the total fire load, L, by the measured average rate of burning R.

The summary data for the programme[6] do not give the measured values of Θ_{PF}, but two methods of deriving Θ_{PF} from the data can be devised:

Firstly, earlier work[7] suggests that the maximum temperature of the compartment gases is approximately 10 per cent higher than the average value over the 80/30 period and this average value is given in the summary data. Thus, basing the temperature of the compartment on the reading of the upper thermocouple in these experiments we have

$$\theta_{PF} \simeq 1.1 \; \theta_{c \; 80/30} \qquad (6)$$

and equation (1) becomes

$$t_f = .00363 \, \gamma^{0.84} \, (\theta_{c \; 80/30} - 245) \qquad (1a)$$

Thomas and Heselden[1] express some reservations about the use of θ_c to represent the fire temperature and suggest that temperatures based on radiation data are possibly more meaningful, particularly for non-cubical compartments. This use of radiation data has also been recommended in the past[8,9] and it has been shown[7] that it is valid to assume that the fire compartment is a black body radiator.

$$\text{ie.} \quad I = \sigma (\theta_f + 273)^4$$

where σ is the Stefan-Boltzmann constant.

Secondly, then, θ_{PF} can be expressed in terms of the radiation data which are also given as averages for the 80/30 period $I_{80/30}$. Earlier work[7] suggests that

$$I_{PF} \simeq \frac{4}{3} \; I_{80/30} \qquad (7)$$

and θ_{PF} has been estimated from the following

$$\frac{4}{3} \; I_{80/30} \simeq \sigma (\theta_{PF} + 273)^4$$

Equation (1) then becomes

$$t_f = 2.3 \, \gamma^{0.84} \left[(I_{80/30})^{\frac{1}{4}} - 0.78 \right] \qquad (1b)$$

Values of t_f calculated using equation (1b) are given in Table 1. For comparison, values for some earlier experiments in cubical compartments[10] are given in Table 2. Before discussing these values, it is necessary to examine the assumptions of equations (5), (6) (7) on which equations (1a) and (1b) are based and to compare equations (1a) and (1b).

2.3. Validity of calculations of t_f

Equations (5) (6) and (7) are based on measurements made in a compartment of 3.05 m scale, approximately 211 in shape in which most of the fires were well ventilated[5]. It does not obviously follow, therefore, that they are applicable, say, to the much deeper 441 compartment shape or when the rate of burning is restricted by the ventilation. Some temperature-time curves for both these compartments are illustrated in Figs 2 and 3.

Another way to estimate t_f is to take the temperature-time curve for the fire and calculate the value of R_iC which would give a maximum value for θ_s of 550°C. Substitution in equation (4) would then give t_f. This has been done for the 441, 1.5 m scale experiments by referring to the original data and taking the variation of θ_c with time for comparison with equation (1a) and taking the variation of I with time to derive a temperature-time curve for comparison with equation (1b). Similar calculations have been done for the earlier experiments[5]. Table 3 illustrates these and shows that all 4 methods are in remarkably good agreement except for two low values given by equation (1a), where θ_c was still rising after t_{30}. Values of t_f based on equation (1b) can therefore be discussed with some confidence.

3. THE VALUES CALCULATED FOR t_f

3.1. General correlation

Inspection of the values in Table 1 shows that variations of scale and stick thickness have little effect on t_f. Stick spacing, however, does have some effect and the values of t_f for 3-spacing tend to be lower.

As would be expected, for given fire load densities the compartment shape and amount of ventilation have significant effects, but these effects should be reduced by relating t_f to fire load per unit window area (L/A_W). However, while it is clear that L/A_W is a major controlling factor, there still remains an effect of compartment shape, with the shallowest compartment (211) having the largest values of t_f, and there also remains a ventilation effect, the full ventilation giving the largest values of t_f. Kawagoe's heat balance to determine temperature in the compartment[11] shows that an 'opening factor' $A_T/A_W\sqrt{H}$ has theoretical importance. (A_T is taken here as the surface area of the walls and ceiling only, since for the CIB experiments the heat loss to the floor is negligible). In terms of t_f, however, A_T/A_W would seem to be more appropriate, since H is of little significance, and the values in Tables 1 & 2 have therefore been examined in relation to A_T/A_W. The best relationship has been obtained with L/A_W modified by the factor $\sqrt{A_W/A_T}$. The values of t_f for 1-spacing are plotted against $L/\sqrt{A_W A_T}$ ($= L/A_W \times \sqrt{A_W/A_T}$) in Fig.4 and it will be seen there is a remarkably good correlation. Similar results are illustrated in Figs 5 and 6 for 3- and $\frac{1}{3}$- spacing. Modifying L/A_W in this way appears to have removed any ventilation effect so that, for the sake of clarity, no distinction has been made on the graph between the results for different ventilation factors. The effect of compartment shape has been very largely removed, but there is a tendency for the 121 shape to have higher values of t_f and the 211 lower values. The slopes of the lines drawn (by eye) though the points are 1.5, 1.3 and 1.1 min m^2/kg for $\frac{1}{3}$-, 1- and 3- spacing respectively and they are compared in Fig.6.

3.2. Stick thickness and spacing

Although the values of t_f in Table 1 are, in general, slightly larger for the thinner sticks, the difference is probably of little significance. The effect of spacing is more significant and the differences are mainly attributable to different rates of burning, t_f in any case being less sensitive to variations in $I_{80/30}$ than γ (equation (1b)). In general the values of $I_{80/30}$ for 3-spacing are similar to or slightly less than those for 1-spacing, so that when they are combined with higher rates of burning, giving shorter values of fire duration, they produce lower values of t_f. On the other hand, with $\frac{1}{3}$-spacing, the reduced $I_{80/30}$ compared with 1-spacing is more than compensated for by a longer fire duration.

The differences in t_f caused by variations in spacing should be considered in the context of information about the amount and distribution of fire loads in real buildings, which are discussed later in this paper. It is interesting to note that in Thomas and Heselden's[1] statistical analysis it was necessary to exclude the $\frac{1}{3}$-spacing results because of their greater variability and more complicated interaction terms, but that in terms of fire resistance they present a pattern of behavior which is consistent with the 1- and 3- spacing results.

4. COMPARISON WITH LARGER SCALE DATA

One of the interesting features of the analysis for the compartments of Tables 1 and 2 is that scale appears to have no significant effect on the value of t_f. Thomas and Heselden[1] show that for the experiments with small openings, temperature depends on $(\text{scale})^{0.2}$ and fire duration on $(\text{scale})^{-0.35}$. Combining these in equation (1) suggests that t_f would decrease slightly, but not significantly with scale. To test this, values of t_f have been derived from temperature-time curves for a number of compartments, most of them approximately double the largest scale of the experiments of Table 1; these values are given in Table 4 and are illustrated in Fig.7 which shows that they are somewhat lower than predicted from the CIB results, although it is clear that there is a powerful correlation with $\frac{L}{\sqrt{A_W A_T}}$. (For these data, A_T includes floor area to allow for heat loss to the floor surface). A number of factors might explain the difference between the two sets of results, the most obvious being the different wall materials.

4.1. Effect of wall materials

We might expect that the CIB results for the 211 compartment with 4, 1 stick thickness and spacing would be closest to those for the 2.5, 1.2, 1 compartment of Tests A with 4.5, 1 stick thickness and spacing. With this latter building it was estimated that less than 30 per cent of the heat flowed into the walls and ceiling[4] and the effect of increasing the insulation, by using a 2.5 cm thickness of mineral wool lining, was small. Nevertheless, the values of $I_{80/30}$ for tests A are significantly lower than for the CIB tests, as shown in Table 5.

Heat transfer coefficients, α , from fire to walls can be estimated. For the CIB experiments, under steady state conditions, assuming heat loss by radiation and natural convection from the external surface, α is approximately $0.8\lambda/N$ where λ is thermal conductivity and N thickness. For the walls of the large scale compartments, assuming they are thick enough to be semi-infinite solids, with the heated surface at a constant temperature θ_F, the heat flux at the heated face at time t is $\lambda\,\theta_F/\sqrt{\pi kt}$, where k is thermal diffusivity, so that α is $\lambda/\sqrt{\pi kt}$ at time t and has an average value of $2\lambda/\sqrt{\pi kt}$ for the period 0 to t. Calculated heat transfer coefficients are given in Table 6 and it will be seen that the values for building A are not much larger than for the CIB compartments.

From CIB tests with different types of asbestos board, Thomas and Heselden[1] show that a change in λ/N of over 100 per cent resulted in a change in θ_c of about 5 per cent and in I of about 24 per cent, and concluded that the fires were not very sensitive to changes in the conductance of the wall.

The effect of variation of λ of the wall material was estimated by Kawagoe and Sekine[11], who calculated a heat balance for rooms with λ of 5.85 and 11.7×10^{-3} W cm^{-1} $^oC^{-1}$ and k of 5.55×10^{-3} cm^2/s; they related a 'fire duration time' of $L/5.5\, A_W\sqrt{h}$ min and a 'temperature factor' of $A_W\sqrt{h}/A_{TT}$ where A_{TT} is the area of floor, ceiling and walls including window, to an "equivalent testing time" in the furnace, t_f. The resultant values for a $1\frac{1}{2}$ m, 441 shape and the shape for tests A are shown in Table 7; these values show that halving the thermal conductivity increases the value of t_f by 15-30 per cent which suggests more sensitivity to the wall material than found in the CIB experiments of Tests A.

4.2. Effect of window height

In the CIB experiments the window height h and the scale H are the same, whereas for the larger scale experiments h is smaller than H. If we say that fire resistance is a function of fire duration and fire temperature and we assume that rate of burning depends on $A_W \sqrt{h}$ then we could write

$$t_f = F\left(\frac{L}{A_W\sqrt{h}} \times \sqrt{\frac{A_W\sqrt{h}}{A_T}} \right) = F\left(\frac{L}{\sqrt{A_W A_T}} \times \frac{1}{h^{\frac{1}{4}}} \right)$$

Since in the CIB experiments there is no variation of t_f with h we would need to write

$$t_f = F\left[\frac{L}{\sqrt{A_W A_T}} \times \left(\frac{H}{h}\right)^{\frac{1}{4}} \right]$$

The factor $(H/h)^{\frac{1}{4}}$ would make the large scale results diverge from the CIB ones, but in any case there is no indication from the results for Tests C, D and E, where H/h was varied, that this factor has any noticeable effect on the correlation.

Since the lower portions of the windows in the CIB experiments were blocked by the wood cribs it could be said that the effective window height h was less than the compartment height H. The difference between h and H would become relatively less important with increasing scale, and for 1- spacing 40 kg/m^2 fire load density, for example, the value of $L/\sqrt{A_W A_T}$ would be increased by not more than 6 per cent. It has not been found possible to achieve a combination of the factors $L/A_W \sqrt{h}$ and $A_T/A_W \sqrt{h}$ which gives as satisfactory a correlation as $L/\sqrt{A_W A_T}$.

The effect of variation of window height on rate of burning and temperature was studied on model scale by Gross and Robertson[16], in a 121 shape, 1.45 m scale compartment, with an opening either full-height "vertical" or full-width "horizontal". From their reported measurements of R and $\theta_{80/30}$ and other data kindly supplied by Mr. Gross, values of t_f and $L/\sqrt{A_W A_T}$ have been calculated and are shown in Fig.8. Details of the experiments are given in Table 8. It will be seen that there is no systematic effect due to the variation of h. There is good agreement with the line for the CIB 3-spacing results except for the experiment with $L/\sqrt{A_W A_T} = 85$. It is possible that θ was still rising at t_{30}, as observed for some of the CIB experiments (see section 2.3) which would result in an underestimation of θ_{PF} and hence of t_f.

4.3. Effect of number of windows

The CIB test compartments had single window openings. A number of the large scale tests had two or more windows either on the same wall (Tests A and C) or on adjacent or opposing walls (Tests D) but the effect of the number and position of the windows appears to be not significantly different from the effect of a single window (Tests B, E and the first one of D). None of these test compartments had one window above the other.

4.4. Comparison with controlled air supply experiments

Ödeen[17] carried out experiments in a tunnel 9 m long x 3 m wide x 2.2 m high ($A_T = 75\ m^2$) supplying air with a fan. The wood fuel was described by r the ratio of volume to surface area. From his radiation measurements, temperature time curves and hence values of t_f have been derived. There is of course no value of A_W we can use directly, but an equivalent one can be estimated as follows. The inlet flow of air N, for a window of area A_W and height h is given by[18]

$$N = 0.50\ A_W \sqrt{h} \quad \text{kg/s}$$

If the volume of air supplied by fan in Ödeen's experiments is Q m^3/s then

$$1.25Q = 0.50 A_W \sqrt{h} \quad \text{kg/s}$$

where the density of air is 1.25 kg/m^3

With a nominal value for h of 1m we obtain

$$A_W = 2.50Q$$

$$\frac{L}{\sqrt{A_W A_T}} = \frac{L}{\sqrt{2.50Q \times 75}} = 0.073 \frac{L}{\sqrt{Q}}$$

(The value of $L/\sqrt{A_W A_T}$ varies as $h^{\frac{1}{4}}$ so that it is not very sensitive to the value of h).

Values of t_f, are given in Table 9 for those experiments where the fire temperature exceeded 550°C, and plotted against $0.073\ L/\sqrt{Q}$ in Fig. 9. Despite the scatter of points, due at least in part to the varying geometry of the fuel, there is remarkably good agreement with the line derived for the other large scale experiments.

5. COMPARISON WITH OTHER CALCULATIONS

As already mentioned, Kawagoe and Sekine[11] established a relationship between building design and fire resistance based on a heat balance. The standard temperature-time curve and the fire curve were equated in terms of the area above 300°C. They allowed for the cooling part of the temperature-time curve in estimating t_f. In a later paper Kawagoe[19] omits the cooling curve, suggesting that it introduces too large a safety factor. The earlier correlation is more directly comparable with our own and will be discussed here. Kawagoe and Sekine assume that the rate of burning is given by $5.5\ A_W\sqrt{h}$, but Thomas and Heselden show[1] that this is a gross approximation for the CIB experiments where higher values have been measured for the higher values of $A_T/A_W\sqrt{h}$. For well ventilated fires, e.g. some of tests A, the rate of burning would be controlled by the fire load, not $A_W\sqrt{h}$. Some comparisons of Kawagoe and Sekine values with experimental ones have already been given in Table 7 and variation of their values of t_f with $L/\sqrt{A_W A_T}$ is shown in Fig.10 for a value of h = 1 m. ($L/\sqrt{A_W A_T}$ varies approximately as $h^{\frac{1}{4}}$ and is therefore not very sensitive to the value of h). Because of the differences in calculating t_f and the limitation of the assumption for rate of burning, it is not too surprising that the curves of Fig.10 are somewhat different from the line for the large scale experiments. An interesting feature of their correlation is that there appears to be no flattening off of the values of t_f for large $L/\sqrt{A_W A_T}$.

A similar correlation is given by Lie[3], based on Kawagoe and Sekine's work. Kawagoe's later correlation[19], as mentioned, gives much shorter values of t_f (approximately half), based on the assumption that the cooling curve can be ignored. Clearly such an assumption has a greater order of significance than any effects of scale or fuel spacing discussed here.

Pettersson and Ödeen[20] also work out a heat balance based on a rate of burning of $5.5\ A_W\sqrt{h}$ and show how temperatures of insulated metal structures can be calculated in terms of the fire load and the "opening factor" $A_W\sqrt{h}/A_{TT}$. Data provided for an opening factor of 0.02 $m^{\frac{1}{2}}$ yield a value for $t_f\sqrt{A_W\ A_T}/L$ of approximately 1.0, assuming a failure temperature of 550°C and h = 1.0 m. These data do not allow for the cooling curve of the fire, otherwise the values of t_f would have been greater. A later publication[21] does include the cooling curve but does not give directly the corresponding values of t_f.

6. EFFECT OF WIND ON VALUES OF t_f

As I has been found to increase much less with wind speed than rate of burning[1], a wind would be expected to reduce t_f. Experiments in still air, assuming a total burn out, would therefore be expected to give maximum severity for internal members.

7. RELATION TO CONVENTIONAL FIRE GRADING

The classic work of Ingberg[22] in the early 1920s is still the foundation of much modern fire grading; his results are summarized for instance in the Post-war Building Study[23] published in the UK in 1946. It is only proper therefore, to explore any correlation between his data and the CIB data.

Unfortunately a direct comparison is difficult because it is not certain what ventilation areas were used. Ingberg's tests were made in rooms in which the ventilation was provided by windows fitted with pivoted shutters whose positions were adjusted, sometimes during a test, "to give what was deemed to be the proper amount of air for maximum fire conditions within the room." In addition to the shutters there was an adjustable chimney vent.

It seems reasonable to assume that the adjustments made by Ingberg were designed to produce maximum temperatures, and an analysis of the CIB data[1] suggests that for these conditions the 'opening factor' $A_T/A_W\sqrt{h}$ would have lain in the range 5–20 $m^{-\frac{1}{2}}$.

For the smaller of Ingberg's two test rooms (in which most of the experiments were performed) we estimate

$$A_T \simeq 110\ m^2$$

$$\sqrt{h} \simeq 1.2\ m^{\frac{1}{2}}$$

giving $A_W = 4.5 - 18.5\ m^2$

Mr Gross has kindly supplied some additional details of this room and from these it appears there were probably 5 (but possibly 7) shuttered windows measuring 1.04 m x 1.49 m and a door (probably closed) measuring 0.94 m x 2.24 m. It is probable therefore that A_W was less than 7.8 m^2 and would not have exceeded 13.0 m^2. An estimate of the additional contribution of the 0.2 m x 0.2 m chimney shows that this makes negligible difference to these upper estimates of A_W. For the purposes of comparison between Ingberg's and the CIB test data we shall assume $A_W \simeq 5\ m^2$ or 1 m^2 per window.

Ingberg's relation between fuel content and t_f (which was derived from areas under temperature-time curves) may be represented, for values of L/A_F up to 150 kg/m^2 by

$$t_f = 1.25 \frac{L}{A_F} \quad \text{min} \qquad (8)$$

To compare this with the CIB data we put

$$t_f = K \frac{L}{\sqrt{A_W A_T}} \quad \text{min}$$

$$= K \frac{L}{A_F} \times \frac{A_F}{A_T} \left(\frac{A_T}{A_W} \right)^{\frac{1}{2}} \quad \text{min}$$

The value of A_F is 42 m^2 giving

$$t_f = 1.8\ K \frac{L}{A_F} \quad \text{min}$$

combining this with equation (8) yields a value of 0.7 for K, which may be compared with the value of 1.3 for the CIB data and 0.95 for the larger scale compartments of Fig.7. The value of K = 0.7 would be larger if our estimate of A_W were larger but clearly it is only a little less than the value for the other large scale tests.

For L/A_F above 150 kg/m^2 Ingberg suggests that t_f should increase more steeply than given by equation (8), and for 250 kg/m^2 this would give $t_f = 1.45\ L/A_F$. The experiments with these higher values of L/A_F were carried out in a larger room for which there is even less precise information available about the number of windows and which appears to have had a significantly larger chimney vent since this was introduced to simulate an open stair or elevator shaft. The higher figure of t_f would increase the estimate of K to 0.8 for higher values of L/A_F. We can conclude that Ingberg's result for higher fire loads suggests that the relationship already obtained can be linearly extrapolated to longer fire durations and is broadly consistent with the more general correlation being discussed in this paper.

8. DISTRIBUTION OF FIRE LOADS IN BUILDING

A number of surveys of fire loads in office buildings have been or are being carried out. Witteveen[24] for example, gives data for nine office buildings and suggests that an acceptable risk is to base fire grading on a value of fire load density which has only a 20 per cent probability of being exceeded. For his data this gives a value of 24 kg/m^2. If $L/\sqrt{A_W A_T}$ is taken as the controlling factor then the probability of a given size of windows would need to be taken into account as well.

Some preliminary results for two modern office buildings in the UK[25] give, in addition to fire load densities, the distribution of the values of L/A_W, W/D and D/H. Values of $L/\sqrt{A_W A_T}$ have been computed and their distribution is shown in Fig.11. The lines for the CIB data and the large scale data are also shown. The comparison suggests that in a system of fire grading, differences in fuel thickness and spacing and differences in scale could have less importance than differences in room shape, window area and fire load. There is the added complication of deciding what constitutes the fire compartment; this may not be the room itself, if its walls have little or no fire resistance, but may be the whole of one floor of a building.

9. FURTHER WORK

9.1. Experiments

Discussion of the results suggests that further large scale experiments should if possible examine the following: effect of variation of window height in relation to compartment height, effect of thermal properties of walls, effect of increased depth of compartment, say 141 shape.

9.2. Mode of failure

A failure temperature for steel of 550°C is valid for present design loads but could be reduced to 400°C if loads are increased. Fortunately, a reduction to 400°C makes negligible difference to the relationships derived here (See Appendix). However, columns may be made of reinforced concrete (where failure is due to over-heating of the reinforcement) or be of steel encased in load bearing concrete so that heat flow in concrete needs to be analysed to establish suitable relationships between t_f and fire behaviour. Further research into the effects of restraint may show a range of failure temperature and the effects of such variations on correlations will need to be examined.

Very low fire loads or very low ventilation rates can give cool fires which never attain critical temperatures. For very low or very high values of $L/\sqrt{A_W A_T}$, therefore, it will be necessary to estimate the maximum temperature which will be attained to see whether failure conditions are possible.

A wall or floor can fail either structurally or because the unheated face reaches too high a temperature. Calculations will need to take account of both these modes of failure and to allow for cooling to the atmosphere.

9.3. Heating of structure in furnace

Equation 1 assumes a 'perfect' furnace, with the heated surface of the specimen following the ISO curve, and it therefore underestimates t_f. For each furnace an adjustment will be necessary to take account of the heat transfer coefficient. In addition, as explained in 9.2, calculations will be needed for concrete columns and for walls and floors.

10. CONCLUSIONS

a) The CIB fires have been related to the fire resistance time, t_f, in terms of the failure temperature of a protected steel column.

b) The main factor affecting the relationship is $L/\sqrt{A_W A_T}$ where L is fire load, A_W area of ventilation opening (window) and A_T area of walls and ceiling (excluding window)

c) In these experiments scale and stick thickness have negligible effects on t_f

d) Closer relative stick spacing gives larger values of t_f, mainly due to longer fire duration. The values of $t_f\sqrt{A_W A_T}/L$ obtained are 1.1, 1.3, 1.5 min m^2/kg for 3-, 1-, $\frac{1}{3}$- spacing respectively.

e) There is negligible difference between the values of t_f calculated for a failure temperature of 550°C and the values for a failure temperature of 400°C. Errors will only arise for very low fire loads or very small ventilation openings when critical temperatures may not be obtained.

f) Values of t_f for experiments in large scale brick or concrete compartments, approximately double the scale of the largest CIB compartments, are also strongly correlated with $L/\sqrt{A_W A_T}$ (where A_T includes floor area) but the average value of $t_f\sqrt{A_W A_T}/L$ is approximately 0.95 min m^2/kg. This lower value appears to be due to a lower compartment temperature or to a much greater effective spacing. The relation between the relative spacing of fuel in cribs and other forms of fuel encountered in other tests and in real fires makes it necessary to 'match' test data with real fires in some empirical manner, here this has been chosen to be the evaluation of $t_f \sqrt{A_W A_T}/L$.

g) In the large scale experiments there were differences in wall material, in window height related to compartment height and in fuel thickness and spacing, but it has not been possible to demonstrate how much these factors account for the lower values of $t_f \sqrt{A_W A_T}/L$ compared with the CIB experiments. Further experimental work on large scale, preferably with deep compartments, would be valuable.

h) Results obtained by Ödeen with forced air supply are shown to be consistent with the large scale experiments.

i) The distribution of $L/\sqrt{A_W A_T}$ for rooms in 2 modern office buildings is reported. Some of the variations in fire resistance discussed here may not be significant compared with variation in the value of $L/\sqrt{A_W A_T}$

j) Rate of burning increases more with wind than temperature does, so that maximum values of t_f are likely to be found in still air conditions.

k) The heat flow in other types of structural element needs to be examined.

l) Adjustments to the calculations will be needed to allow for the variation of the heat transfer coefficient with the type of furnace.

m) It is demonstrated that the maximum temperature attained by a protected steel column in these fires can be calculated by assuming the column is exposed to a constant temperature. θ_{PF}, equal to the maximum fire temperature, for a time τ, equal to fire load divided by average rate of burning. It is preferable to estimate θ_{PF} from radiation measurements rather than temperatures of thermocouples in the compartment gases.

n) Over the whole of the practical range of t_f, the fire resistance of a protected steel column, or any element with thermal impedance which fails at a critical core temperature, is given by $t_f \sqrt{A_W A_T}/L$ = constant. The best value of the constant is 0.95 min m^2/kg for those experiments whose records permit its evaluation.

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APPENDIX

1. Temperature rise of steel in furnace test

$$\theta_s + R_i\, C \frac{d\theta_s}{dt_f} = \theta_t \qquad (2)$$

$$\theta_t = 1200 - 550e^{-0.01t_f} + 200e^{-0.5t_f} - 850e^{-0.2t_f} \qquad (3)$$

Substituting for θ_t in equation (2) and integrating, gives

$$\theta_s = 1200(1 - e^{-t_f/R_iC}) - \frac{550}{0.01\ R_iC-1}(e^{-t_f/R_iC} - e^{-0.01t_f})$$

$$+ \frac{200}{0.05\ R_iC-1}(e^{-t_f/R_iC} - e^{-0.05t_f}) - \frac{850}{0.20\ R_iC-1}(e^{-t_f/R_iC} - e^{-0.20t_f}) \qquad (1A)$$

Values of θ_t and θ_s/θ_t for different values of t_f, computed from equations (3) and (1A), are given in Table 1A. It will be noted that for a given value of t_f/R_iC, θ_s/θ_t is almost constant. Thus equation (1A) can be replaced by

$$\frac{\theta_s}{\theta_t} \simeq 0.91\ (1 - e^{-t_f/R_iC}) \qquad (4)$$

where θ_t is given by equation (3).

2. Failure of steel column in furnace test and fire test.

Assuming that failure occurs when θ_s = 550, then from equations (4) and (5)

$$1 - e^{-t_f/R_iC} = \frac{605}{\theta_t} \qquad (2A)$$

$$1 - e^{-\tau/R_iC} = \frac{550}{\theta_{PF}} \qquad (3A)$$

Substituting for θ_t from equation 3, values of t_f corresponding to a range of values of τ and θ_{PF} have been calculated by eliminating R_iC from equations (2A) and (3A). They are plotted in Fig. 12. The straight lines drawn through the curves have the equation

$$t_f = 0.0033\,\tau^{0.84}\,(\theta_{PF} - 270) \qquad (1)$$

This equation is a valid approximation for θ_{PF} = 600 - 1300°C and for τ = 10 - 120 min.

2.1. Effect of variation of failure temperature

If larger design loads are used, the failure temperature will be lower than 550°C. For a failure temperature of 400°C the following equation can be derived

$$t_f = 0.00285 \, \gamma^{0.84} \, (\theta_{PF} - 170) \qquad (4A)$$

The biggest differences between equations (1) and (4A) is for low values of θ_{PF}. For $\theta_{PF} = 600°C$, t_f from equation (1) is 11 per cent less than t_f from equation (4A). However, if such a low value of θ_{PF} is due to a low fire load, the value of t_f is likely to be low and the absolute value of the difference is not likely to be significant. If the low value of θ_{PF} is due to a small A_W, it will be necessary in any case to check that the critical temperature could be attained. For $\theta_{PF} = 1300°C$, t_f from equation (1) is only 6 per cent greater than t_f from equation (4A). Thus values of t_f from equation (1) are not normally very sensitive to the assumed failure temperature for steel.

Table 1. Predicted equivalent fire resistance time t_f for CIB experiments

Quarter ventilation

Shape	$\frac{L}{A_F}$ kg/m²	Scale m	t_f min, Stick thickness & spacing 2, 1	4, 1	1, 3	2, 3	2, $\frac{1}{3}$	$\frac{L}{A_W}$ kg/m²	$\frac{L}{\sqrt{A_W A_T}}$ kg/m²
211	20	0.5	24	20	24	24	23	80	20.5
	20	1.0	26*	23	21	23	25	80	20.5
	20	1.5	24	22	22	20	28	80	20.5
	30	1.0	35	49+			38	120	31
	30	1.5	34	34	34	32	44	120	31
	40	1.0	49*	48			72	160	41
	40	1.5	48	50	41	38	68	160	41
121	20	0.5	50	44	41	40	47	160	29
	20	1.0	41*	45	38	40	56	160	29
	30	1.0	64	58	58	56	75	240	43
	40	1.0	88*	75	72	70	97	320	57.5
221	20	0.5	38	34	44	41	41	160	33.5
	20	1.0	39*	33	35	31	46	160	33.5
	30	1.0	60	50	51	48	71	240	50
	40	1.0	79*	62	71	60	88	320	66.5
441	20	0.5	66					320	57.5
	20	1.5	64					320	57.5
	30	0.5	113					480	86
	40	1.5	152					640	115

Half ventilation

211	20	0.5	21	18	18	15	18	40	15
	20	1.0	26					40	15
	30	1.0	35					60	22.5
	40	1.0	43		25	27		80	30
121	20	0.5	30	31	28	29	41	80	20.5
	20	1.0	33					80	20.5
	30	1.0	50					120	31
	40	1.0	62					160	41
221	20	0.5	33	26	31	32	37	80	24
	20	1.0	34					80	24
	30	1.0	48					120	36
	40	1.0	61					160	48
441	10	1.5	26					80	20.5
	20	0.5	50					160	41
	20	1.5	50					160	41
	30	0.5	74					240	62
	40	1.5	118					320	82.5

+ probable error in I

* from mean value of 8 or more readings of I and R

Table 1 continued

Three quarter ventilation

Shape	$\frac{L}{A_F}$ kg/m^2	Scale m	t_f min — Stick thickness & spacing 2, 1	4, 1	1, 3	2, 3	2, $\frac{1}{3}$	$\frac{L}{A_W}$ kg/m^2	$\frac{L}{\sqrt{A_W A_T}}$ kg/m^2
211	40	1.0				21		53.5	25.5
441	10	1.5	29					53.5	17

Full ventilation

Shape	$\frac{L}{A_F}$ kg/m^2	Scale m	2, 1	4, 1	1, 3	2, 3	2, $\frac{1}{3}$	$\frac{L}{A_W}$ kg/m^2	$\frac{L}{\sqrt{A_W A_T}}$ kg/m^2
211	20	0.5	16	14	12	11	11	20	11.5
	20	1.0	18*	+	14	15	+	20	11.5
	20	1.5	16	+	16	14		20	11.5
	30	1.0	24	21	16		18	30	17.5
	30	1.5	23	19	21	17		30	17.5
	40	1.0	34*	25	17	20	23	40	23
	40	1.5	30	26	26	18		40	23
121	20	0.5	25	26	21	21	+	40	15
	20	1.0	25*	23	19	21		40	15
	30	1.0	35	34	25	26	+	60	22.5
	40	1.0	44*	41	30	31	+	80	30
221	20	0.5	26	18	20	20	27	40	18
	20	1.0	24*	19	23	19	23	40	18
	30	1.0	37	29	29	23	40	60	27
	40	1.0	47*	40		26	53	80	36
441	20	0.5	36					80	30
	20	1.5	39					80	30
	30	0.5	48					120	45.5
	30	1.5	62**					120	45.5
	40	1.5	88**					160	60.5

+ $\theta_{PF} < 600^\circ C$

* from mean value of 8 or more readings of I and R

** from θ_c , see Table 3

Table 1A. θ_t and θ_s/θ_t from equations (3) and (1A)

t min	θ_t °C	θ_s/θ_t t/R_iC 0.25	0.5	1.0	1.5	2.0	3.0
30	835	0.18	0.34	0.555	0.715	0.83	0.89
60	910	0.19	0.345	0.56	0.705	0.80	0.89
120	1035	0.19	0.345	0.555	0.685	0.79	0.885
240	1150	0.19	0.35	0.565	0.695	0.80	0.89
360	1185	0.20	0.36	0.585	0.72	0.81	0.91
Equation (4)		0.20	0.355	0.575	0.705	0.78	0.865

Table 2

Predicted equivalent fire resistance time - t_f - for cubical compartments[10]

Full ventilation $\frac{L}{A_F} = \frac{L}{A_W}$

Shape	$\frac{L}{A_F}$ kg/m²	Scale m	Stick thickness and spacing	t_f min	$\frac{L}{\sqrt{A_W A_T}}$ kg/m²
111	29	0.9	5.1, 3	14	14.5
	27	"	" "	12	13.5
	24	"	" "	12	12
	36.5	0.6	5.1, 3	17	18
	33	"	" "	15	16.5
	28	"	" "	15	14
	23.5	"	" "	16	11.5

NB θ_{PF} derived from I_{PF}

τ derived from R90/20

Table 3

Methods of calculating t_f

Compartment	Ventilation	$\frac{L}{A_F}$ kg/m^2	From I t_f - min Curve	From I t_f - min Eqn (1b)	From θ_c t_f - min Curve	From θ_c t_f - min Eqn(1a)
CIB	¼	20	66	64	64	50+
		40	*	152	154	121+
	½	10	28	26	28	20
		20	50	50	47	46
		40	101	118	102	107
	¾	10	26	29	25	28
	Full	20	40	39	40	37
		30	-	-	62	63
		40	-	-	88	92
A	⅛	60	*	81	87	90
	¼	15	*	17	20	20
		30	*	36	35	36
		60	*	58	19	67
	½	30	*	27	24	28
		60	*	46	47	47

Compartment CIB : 441, 1.5 m scale

" A : 2.5 1.2 1, 3.05 scale, brick[5]

* curves not available

+ θ_c still rising after t_{30}

Table 4. Predicted equivalent fire resistance time t_f for larger scale brick or concrete compartments, calculated from temperature-time curves

Tests	H (m)	$\frac{W}{H}$	$\frac{D}{H}$	A_W (m^2)	h (m)	$\frac{L}{A_F}$ (kg/m^2)	$\frac{L}{\sqrt{A_W A_T}}$ (kg/m^2)	t_f (min)	Notes
A	3.05	2.5	1.2	2 x 5.6	1.83	30	24	24	
						30	24	26	a
						30	24	23	a
						30	24	24	a,b
						60	48.5	47	
				2 x 2.8	1.83	15	17	20	
						30	33.5	35	
						30	33.5	39	a
						30	33.5	36	a
						30	33.5	35	a,b
						60	67	69	
				2 x 1.3	1.83	60	97	87	
B	2.40	1.0	1.0	5.76	2.40	25	11.5	12.5	a
						38	17	20	a
C	2.60	1.1	1.2	2 x 1.63	1.52	49	35	30	
						49	35	30	
				2 x 1.79	1.68	34	23.5	26	
						61	42	37	
				2 x 2.60	2.44	49	28	24	
						49	28	22	
						49	28	25	
						61	35.5	39	
D	2.5	1.2	1.2	1.67	1.80	45	45.5	34	
	3.0	1.3	1.3	2 x 2.70	1.5	50	40	22	g
	2.6	1.4	1.0	2.52	1.4)	64	44.5	38	c,h
		1.0	1.4	1.26	1.4)				
	2.5	1.7	1.4	2 x 2.40	1.46	44	38	50	g
	2.7	1.5	1.5	1.80	1.0)	31	30	24	g
				1.80	1.1)				
	2.6	2.0	2.0	4 x 1.7	1.7	46	47	43	g
	3.8	1.05	1.05	2 x 6.15	2.2	50	25.5	24	d,g
	~1.2	~2.5	~2.8	2 x 0.64	0.75)	24	25	29	e,g
				0.21	0.50)				
				1.28	0.98)				
	~1.2	~2.5	~2.8	2 x 0.64	0.75)	40	48.5	67	f,g
				0.21	0.50)				
				0.48	0.75)				
E	3.13	1.1	1.2	2.58	2.18	15	14	15	
						30	28.5	26	
						60	57	53	
				1.06	0.90	30	44	41	
				4.24	2.18	30	22.5	21	

Notes for Table 4

Tests	Notes
A	JFRO compartment containing steelwork[5]. Brick walls with vermiculite plaster, concrete ceiling Wood cribs 4.5 cm sticks, 1-spacing Note (a) t_f from equation 1b (b) compartment lined with mineral wool slabs
B	JFRO Webster cube[12] Brick walls and ceiling Wood cribs 2.5 cm sticks, 3-spacing Note (a) t_f from equation 1b
C	JFRO Tower block[13] Brick walls plastered, concrete ceiling Wood cribs 5 cm x 10 cm sticks and 2.5 cm x 7.5 cm sticks Fibre insulating board on walls and floor
D	Japan, Kawagoe[14], various buildings Concrete walls & celing "Waste timbers" for fuel Note (c) plastered ceiling (d) lightweight concrete (e) plastered finish (f) high moisture content of fuel (g) windows in two walls, opposing (h) windows in two walls, adjacent
E	Metz[15] Brick walls, concrete ceiling Wood cribs 7 cm x 4.5 cm sticks 7 cm apart

Table 5. Comparison of results for 211 CIB Compartment and for Tests A Compartment, both quarter ventilation

Tests	Scale m	Stick thickness & spacing	$\frac{L}{A_F}$ kg/m^2	$\frac{L}{\sqrt{A_W A_T}}$ kg/m^2	$I_{80/30}$ W/cm^2	τ min	θ_c °C
CIB	1.5	4, 1	20 30 40	20.5 31.0 41.5	15.4 23.2 22.0	11.9 16.6 26.0	1027 1145 1145
A	3.05	4.5, 1	15 30 30 30 30 60	17.0 33.5 33.5 33.5 33.5 67	3.3 11.8 13.8* 15.1 13.1 15.3	21.4 23.4 21.6 23.0 23.0 37.7	665 930 1010* 985 1015 1120

* walls & ceiling lined with mineral wool slab

Table 6. Heat transfer coefficient α from fire to walls & ceiling

Material	α - Heat transfer coefficient 10^{-4} Wcm^{-2} C^{-1}		
	t = 15	30	45 min
CIB $1\frac{1}{2}$ m, 4+1	4.6	4.6	4.6
CIB, asbestos millboard	12.5	12.5	12.5
Vermiculite plaster	13.8	10.0	8.0
Mineral wool	2.5	2.1	1.7
Refractory concrete	35.5	26.0	20.5
Brick	51.0	36.0	29.2

Table 7. Fire resistance time calculated by Kawagoe and Sekine[11] for two values of λ

Compartment	Ventilation	$\frac{L}{A_F}$	$\lambda = 5.85 \times 10^{-3}$ t_f-min	11.7×10^{-3} t_f-min	Experimental t_f-min
441, 1½ m	¼	20 40	59 -	45 -	64 154
	½	10 20 40	~ 41 55 91	~30 46 73	28 47 102
	Full	20 30 40	~ 62 70 79	~48 61 69	40 62 88
Tests A	¼	15 30 60	~44 55 86	~32 49 74	20 35 69
	½	30 60	~70 83	~55 72	24 47

Table 8. Predicted equivalent fire resistance time t_f for experiments of Gross and Robertson[16]

H = 1.45 m

121 shape

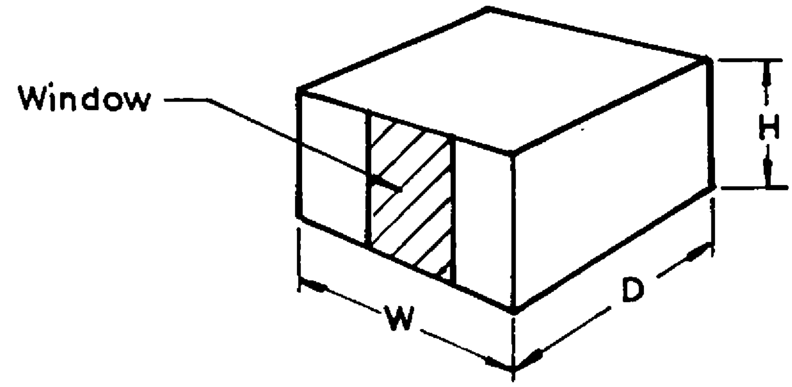
(7.5, 3) stick thickness and spacing (fibre insulating board)

A_W m^2	h m	$\frac{L}{A_F}$ kg/m^2	$\frac{L}{\sqrt{A_W A_T}}$ kg/m^2	t_f min
0.151	0.104	12	29.5	43
0.260	0.178	13.5	25	55.5
0.297	0.205	13.5	24	52
0.391	0.270	16	24.5	39.5
0.602	0.416	18.5	23	39.5
0.0565	1.45	21	85	59.5
0.0736	"	13	45	54
0.166	"	18	42	42.5
0.166	"	17	40	43
0.166	"	7.5	17.5	28
0.261	"	12	22.5	27
0.413	"	21.5	32	36.5
0.818	"	12	13	25
0.818	"	21	23	28.5
0.818	"	29.5	30	22.5
1.226	"	21.5	19	28
2.120	"	30.5	21	36

Table 9. Predicted equivalent fire resistance time t_f derived from Ödeens experiments[17]

Test	L kg	Air supply Q m^3/s	Fuel ratio r cm	t_f min	$\frac{0.073L}{\sqrt{Q}}$
2	675	2.0	1.0	41	35
3	"	1.0	"	46	49
4	"	0.7	"	36	59
5	"	1.5	"	47	40
7	"	1.0	1.7	48	49
9	"	1.0	0.6	35	49
10	270	1.0	0.6	~13	20
14	945	1.0	1.6	66	69
15	1350	2.0	1.4	93	70
16	405	0.7	0.4	29	35

Compartment



W — width

D — depth

H — height

A_W — window area

A_F — floor area = W x D

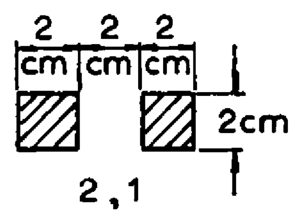
A_T — areas walls and ceiling = $W \times D + 2 \times (W+D) H - A_W$

$\frac{A_W}{W \times H}$ — ventilation

Code for shape : numbers give in order width, depth and height relative to height

e.g. for H = 1m , 211 means W = 2 m, D = 1m

Fuel



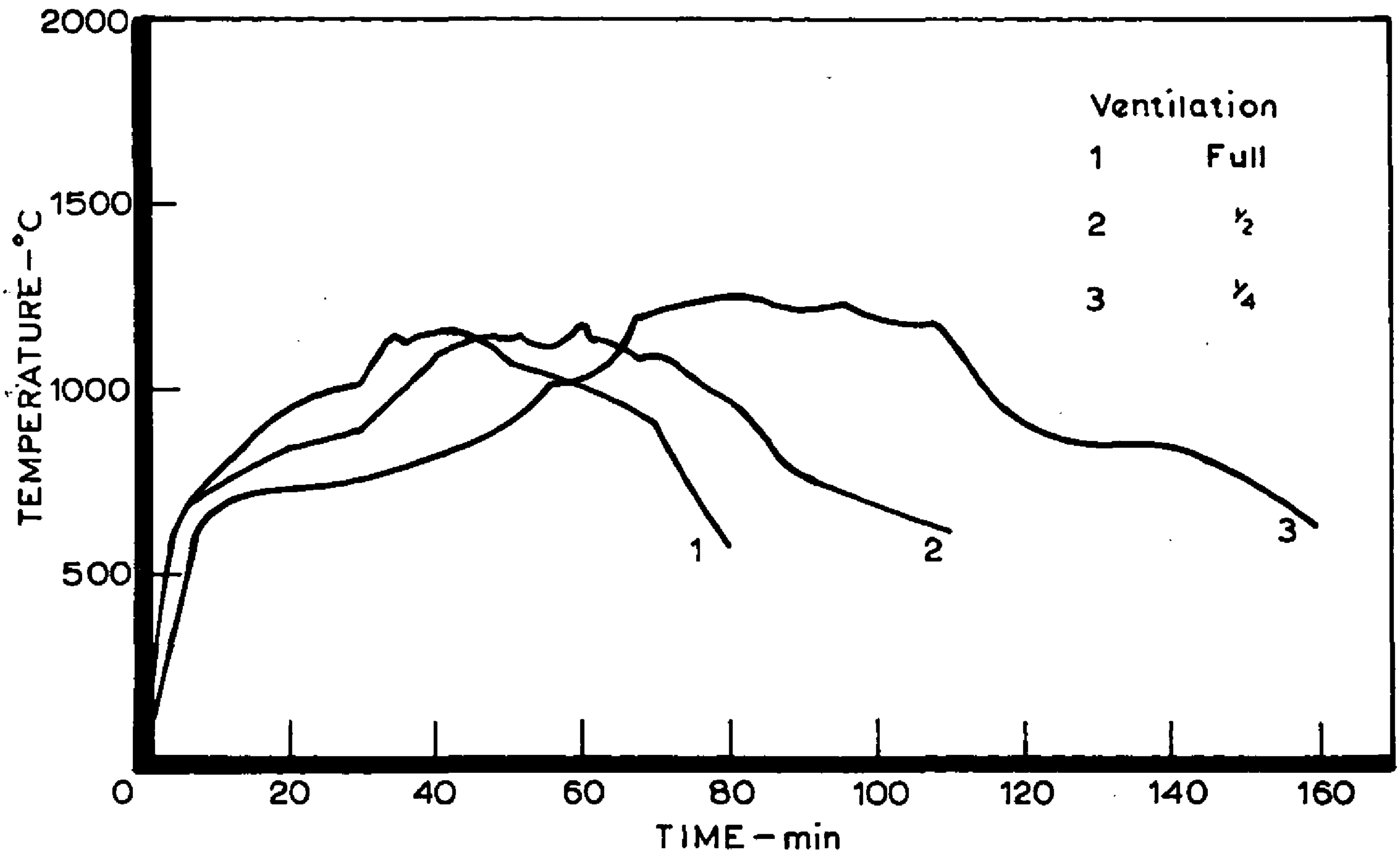
L — fire load = total weight of fuel

Code : numbers give in order stick thickness in cm and relative stick spacing

Range of variables

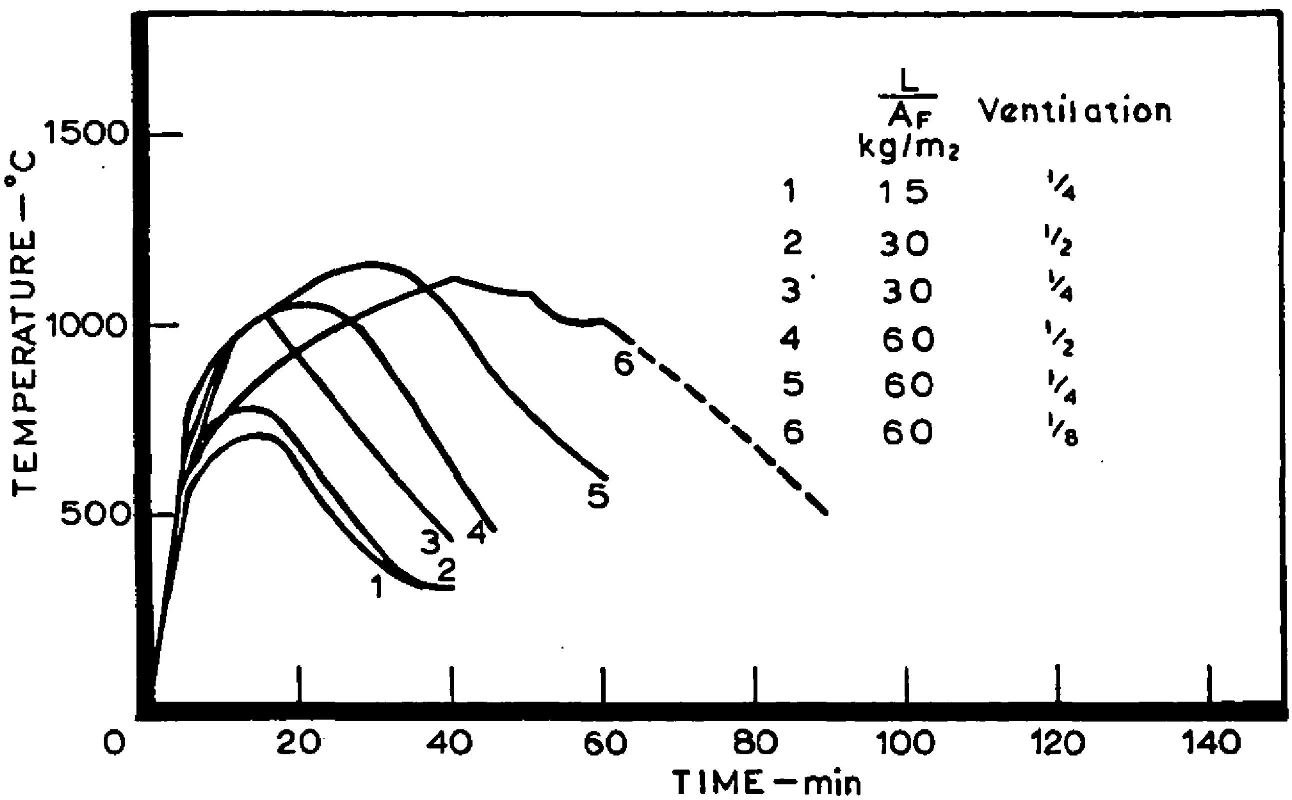
H m	Ventilation	Shape	Stick thickness and spacing	$\frac{L}{A_F}$ kg/m²
0·5	¼	211	2,1	10
1·0	½	121	4,1	20
1·5	¾	221	1,3	30
	Full	441	2,3	40
			2,⅓	

FIG.1 VARIABLES FOR CIB EXPERIMENTS



441 compartment 1·5m scale $\frac{L}{A_F}$ = 40 kg/m²

FIG. 2 TEMPERATURE OF UPPER THERMOCOUPLE - θ_c IN CIB EXPERIMENTS



Shape 2·5, 1·2, 1 3·05 m scale

FIG. 3 AVERAGE TEMPERATURE OF COMPARTMENT GASES IN LARGE SCALE BRICK COMPARTMENT[5]

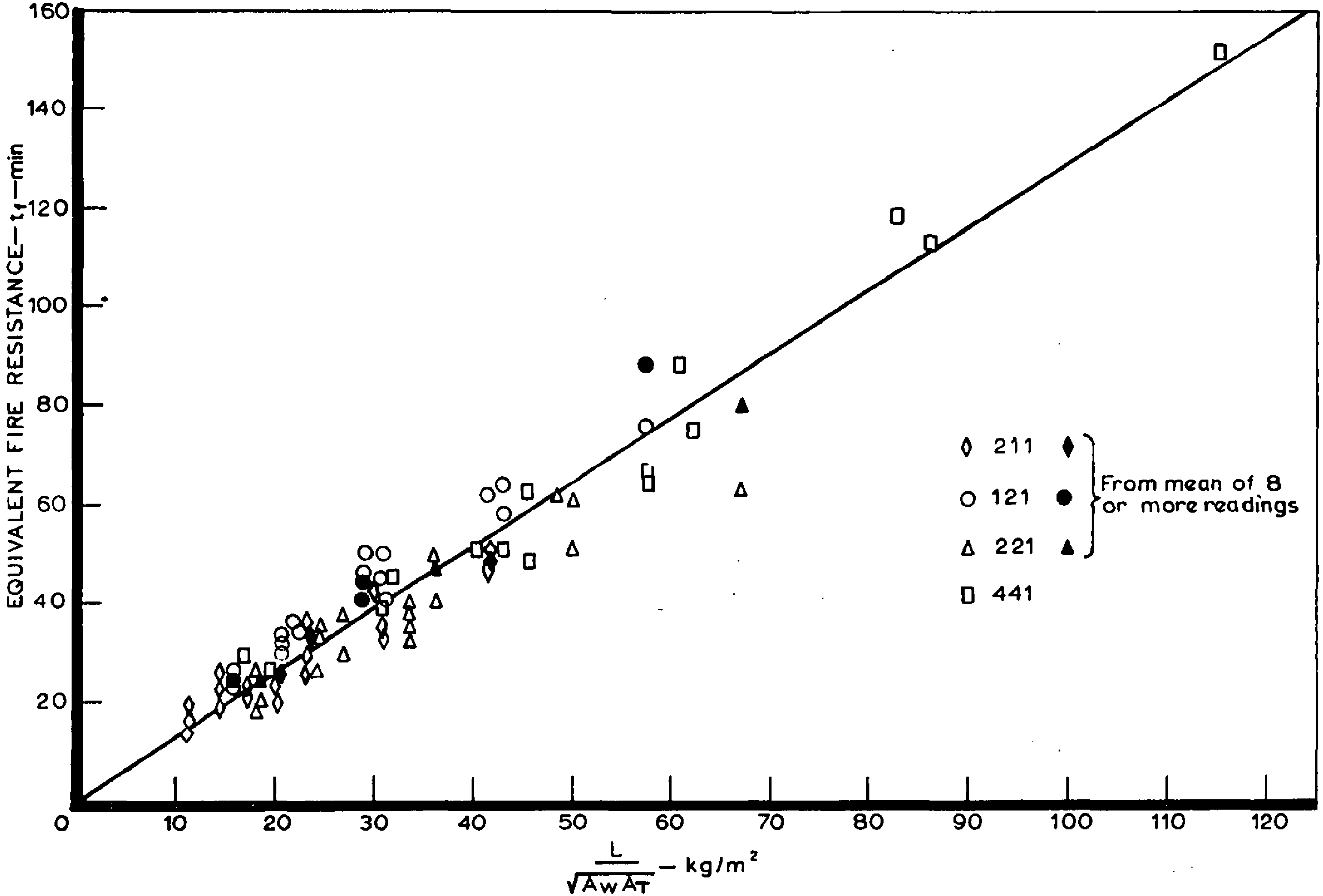


FIG.4 EQUIVALENT FIRE RESISTANCE FOR CIB DATA 1–SPACING

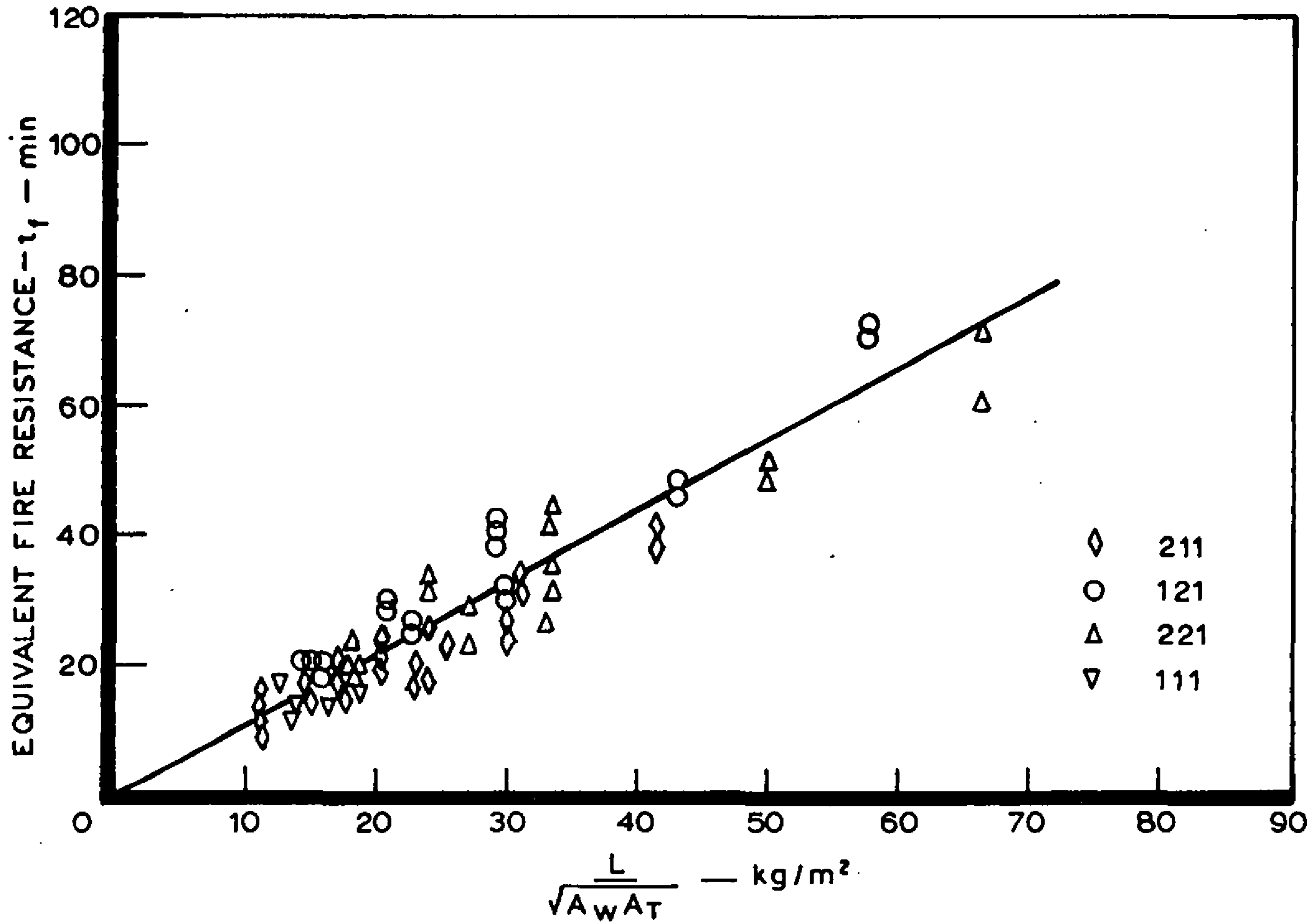


FIG.5 EQUIVALENT FIRE RESISTANCE FOR CIB DATA 3–SPACING

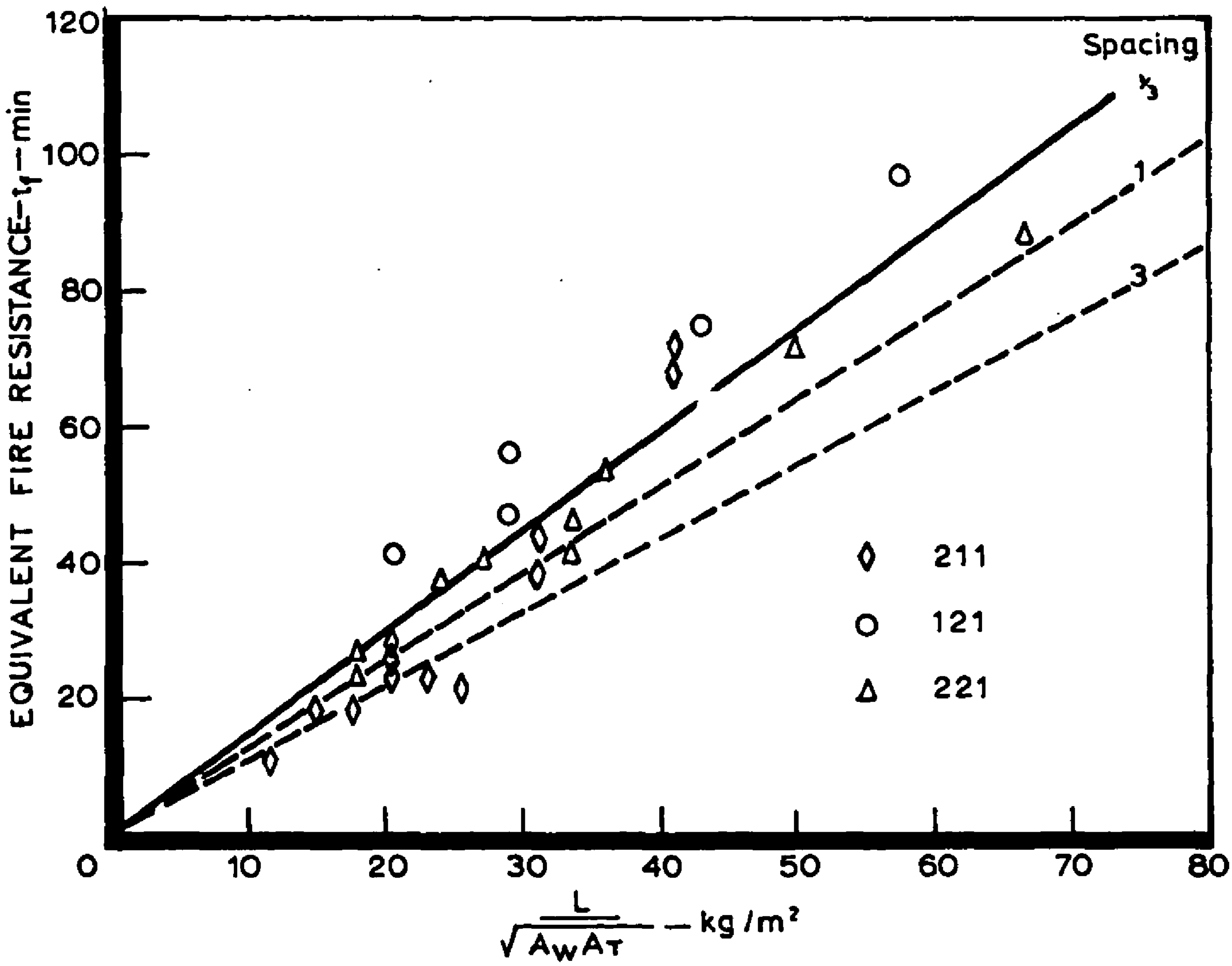


FIG. 6 EQUIVALENT FIRE RESISTANCE FOR C I B DATA 1/3—SPACING

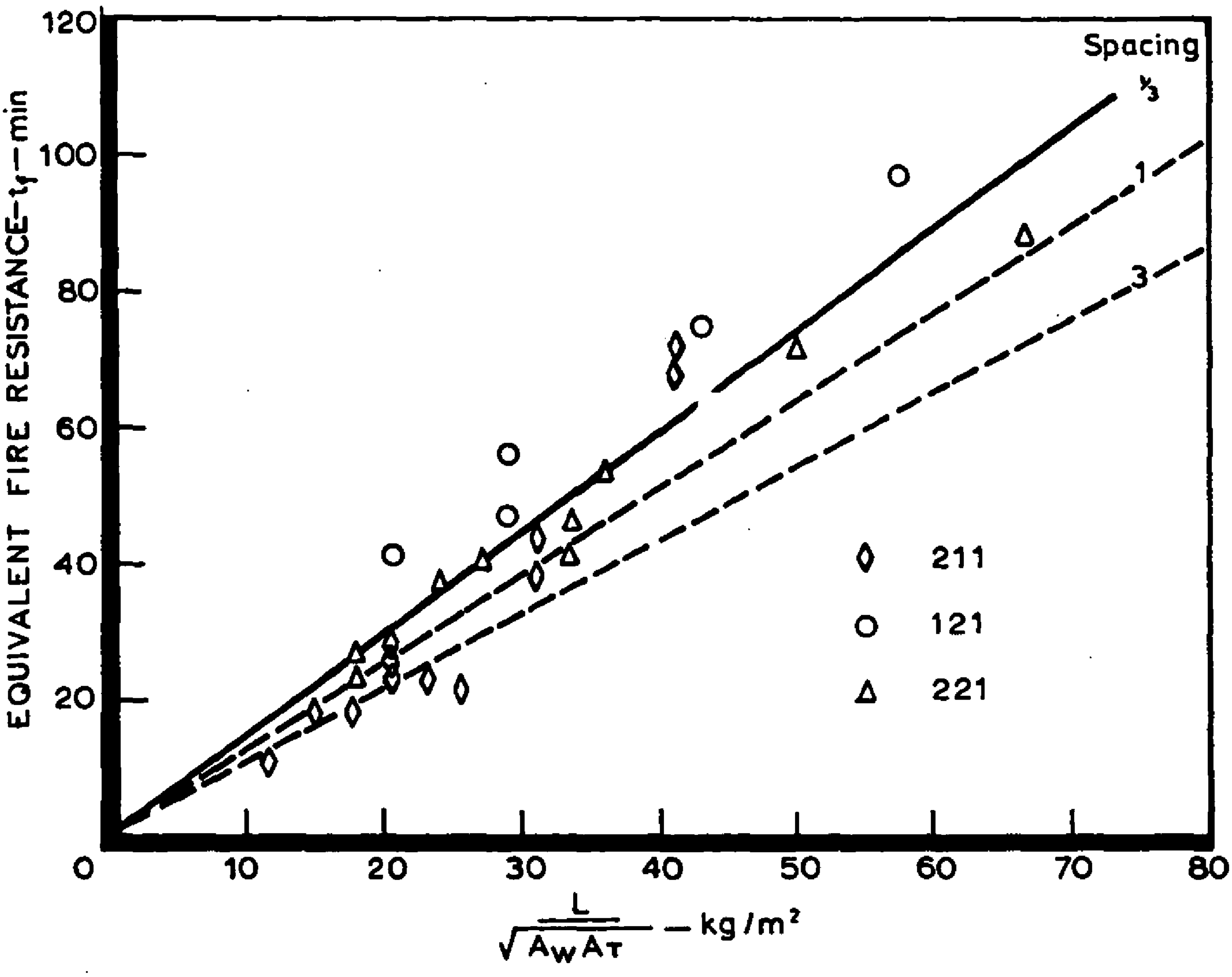


FIG. 6 EQUIVALENT FIRE RESISTANCE FOR C I B DATA ⅓—SPACING

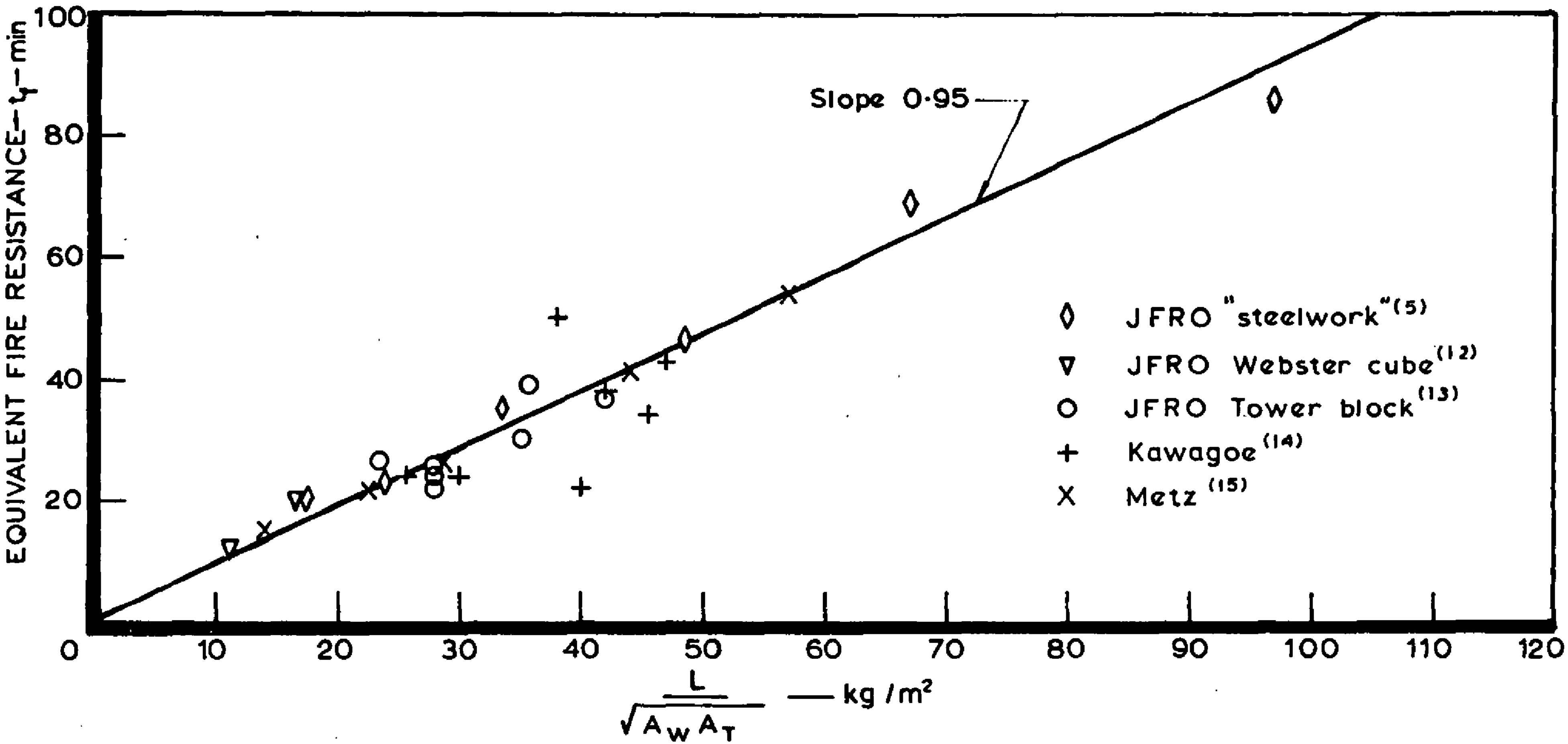


FIG.7 EQUIVALENT FIRE RESISTANCE DERIVED FROM DATA FOR LARGE SCALE BRICK OR CONCRETE COMPARTMENTS

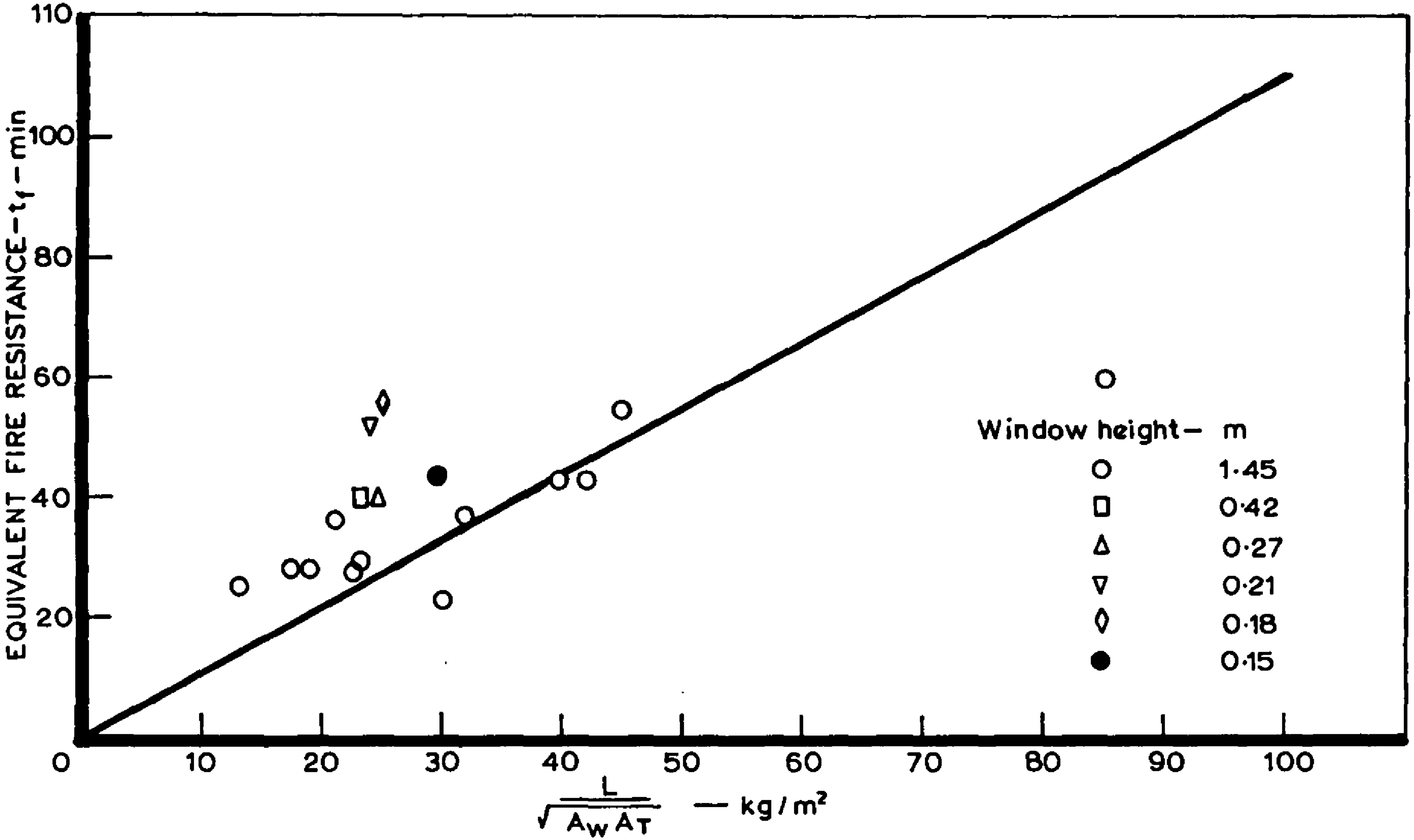


FIG. 8 EQUIVALENT FIRE RESISTANCE DERIVED FROM GROSS AND ROBERTSON 1·45m SCALE EXPERIMENTS (16)

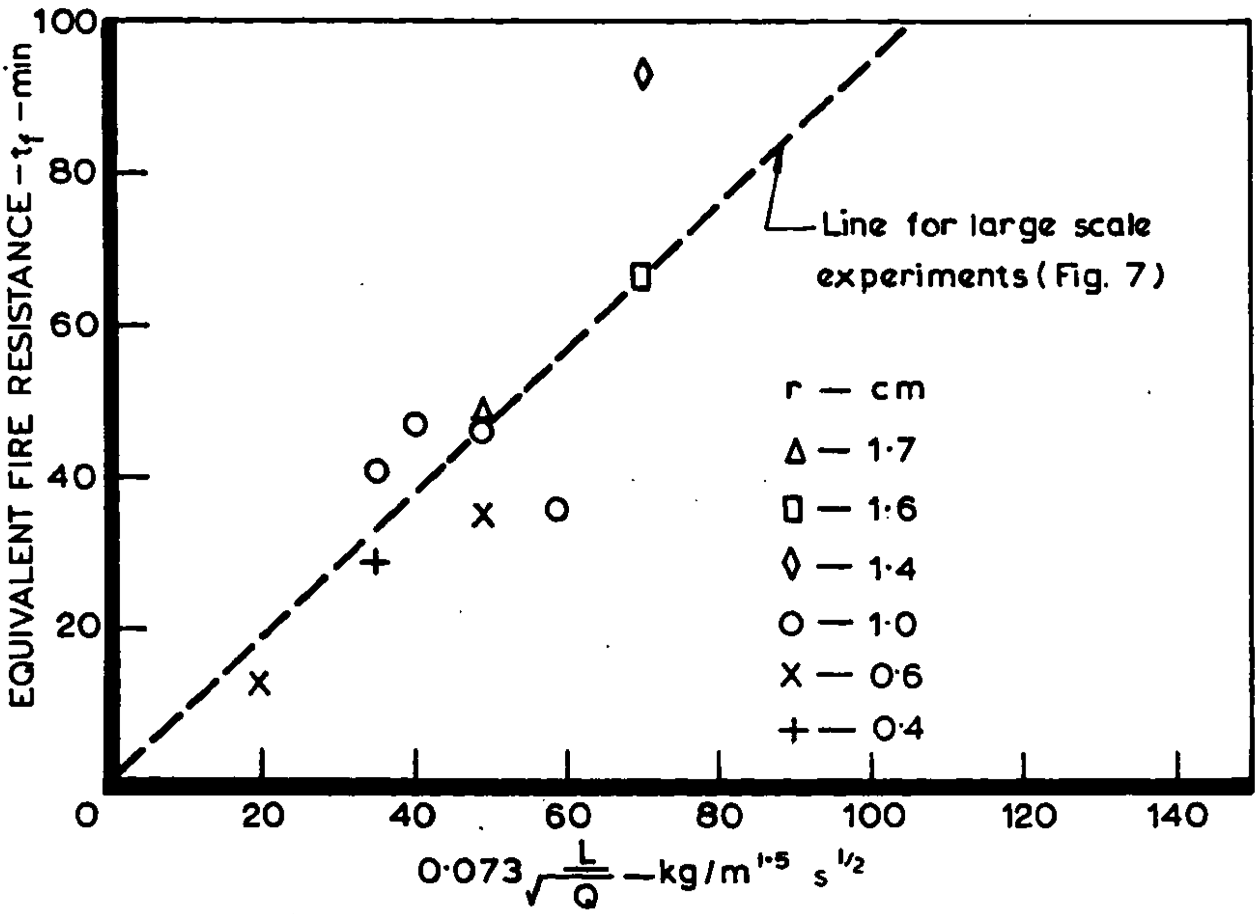


FIG.9 EQUIVALENT FIRE RESISTANCE DERIVED FROM ÖDEEN'S EXPERIMENTS [17]

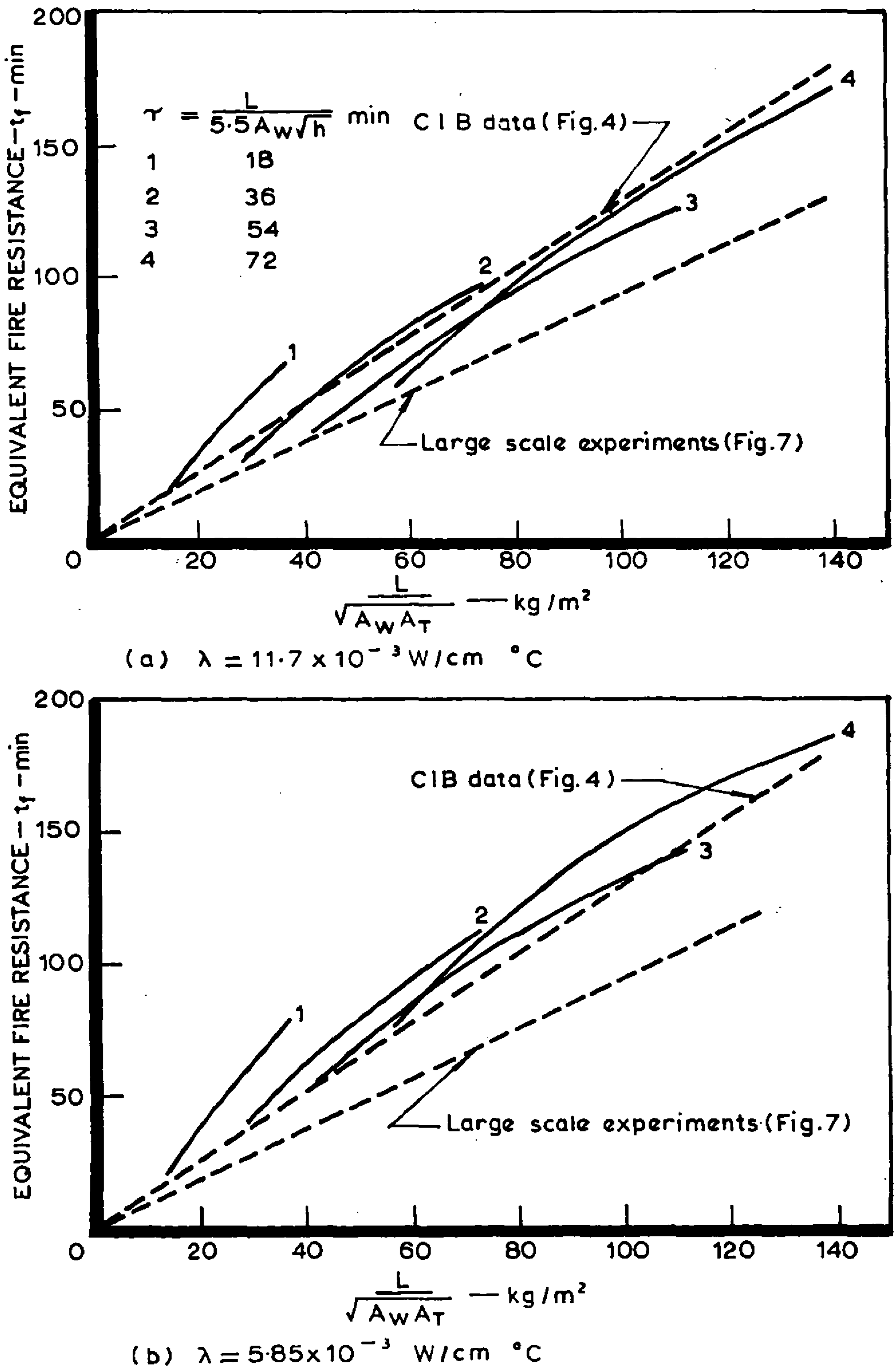
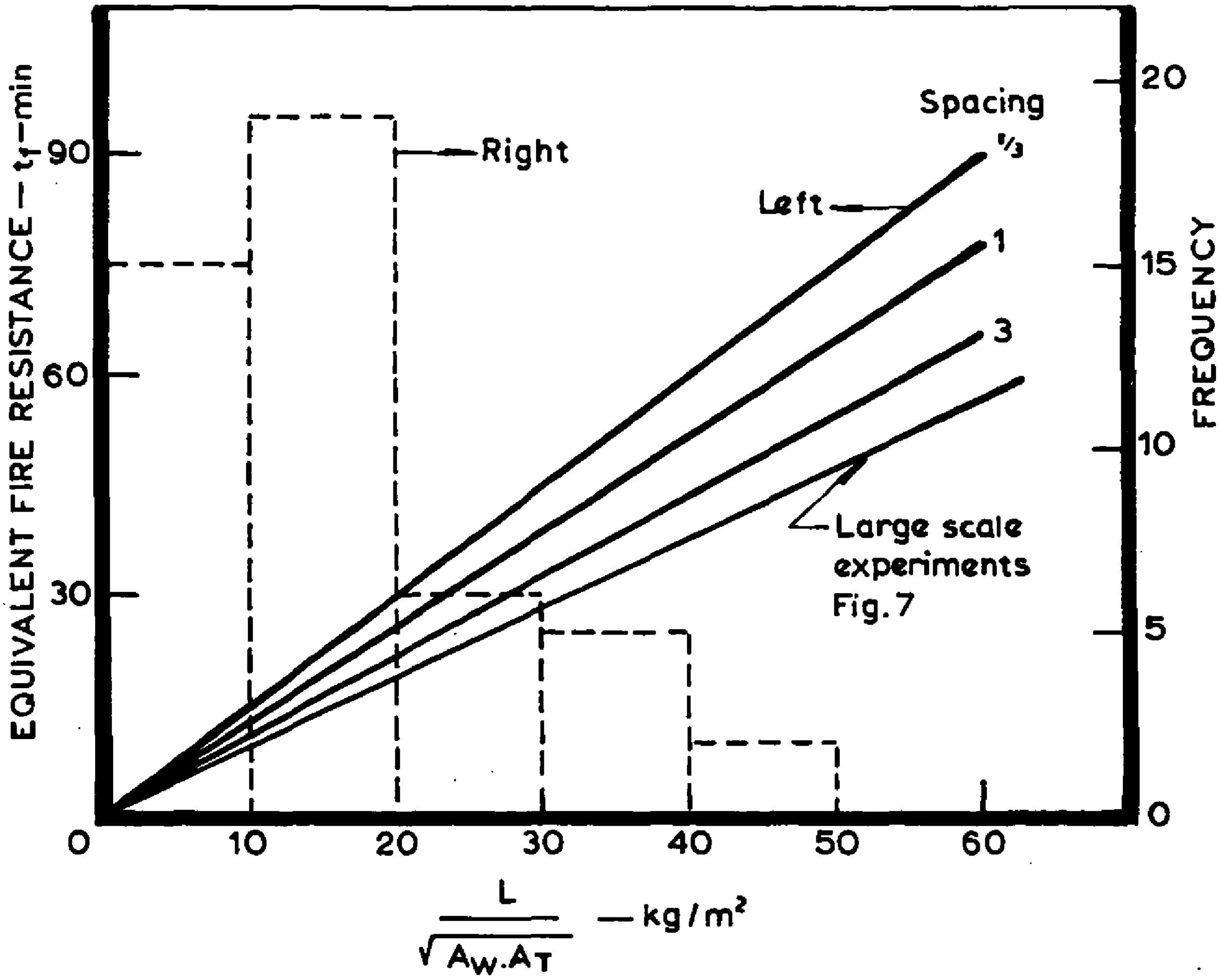


FIG.10 KAWAGOE AND SEKINE CALCULATIONS[11] OF FIRE RESISTANCE REQUIREMENTS (FOR h = 1m)



The straight lines show the variation of t_f (left hand scale) with $\frac{L}{\sqrt{A_W A_T}}$ for the three values of relative stick spacing

Superimposed, in dashed outline, is the frequency (right-hand scale) of offices with $\frac{L}{\sqrt{A_W A_T}}$ falling in a given range

FIG. 11 VARIATION OF FIRE RESISTANCE AND FREQUENCY OF OFFICES WITH $L/(A_W A_T)^{1/2}$

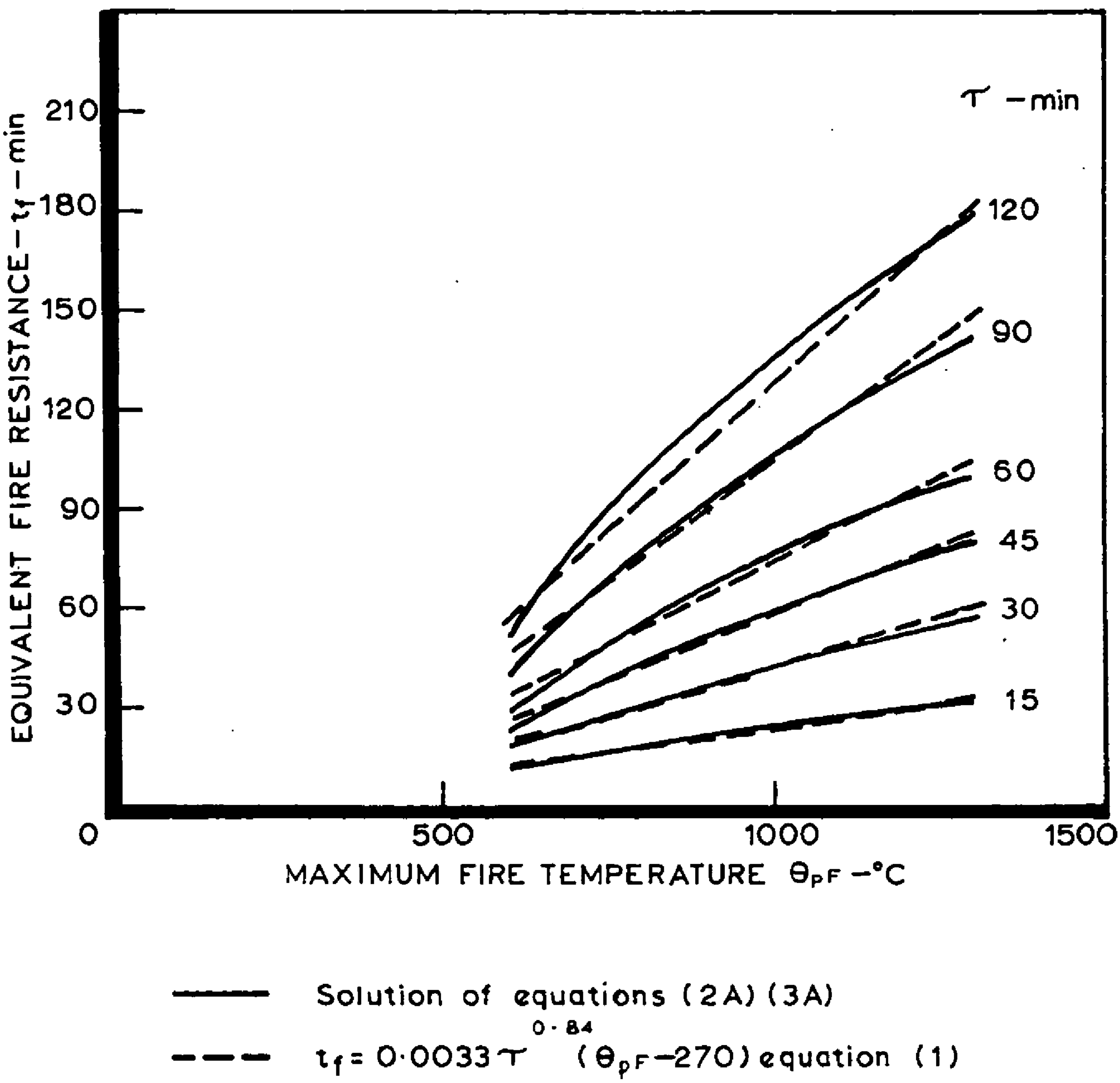


FIG.12 CALCULATED RELATIONSHIP BETWEEN FIRE RESISTANCE AND FIRE BEHAVIOUR