Fire Research Note No 901

THE FIRE RESISTANCE REQUIRED TO SURVIVE A BURN OUT

by

P. H. THOMAS

November 1970

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SUMMARY

A CIB research programme on the duration and temperatures of fully developed compartment fires has been completed. Data have been obtained for a wide variety of shapes, amounts and dispersion of fuel, scale and ventilation conditions. Estimates of the fire resistance t_f required to survive these fires have been made and are closely proportional to

$$\frac{L}{\sqrt{A_W A_T}}$$

where L is the amount of fuel

A_W is the window area (or its equivalent)

A_T is the area of the internal surfaces over which heat is lost.

cont'd/

DEPARTMENT OF TRADE AND INDUSTRY AND FIRE OFFICES' COMMITTEE
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The constant of proportionality depends on the porosity of the fuel bed. Many published large scale experimental fires have also been examined and a similar law applies but the constant of proportionality is somewhat less than those for the CIB experiments. The relationship between this form of t_f and Ingberg's correlation of fire resistance with fuel per unit floor area (L/A_F) is discussed and it is suggested that Ingberg's correlation will over-estimate fire resistance requirements when

$$\frac{A_W A_T}{A_F^2} > \frac{1}{3} \text{ approx.}$$

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INTRODUCTION

Fires can be confined to a part of a building if the walls, floors and ceiling have an adequate degree of fire resistance. The space so protected is known as a fire compartment and partitions, ceilings and floors having no effective fire resistance are neglected in defining this space. The specification of these fire resistance requirements in most regulations can be traced back to the work of Ingberg[1] in the late 1920s (see also the review by Robertson and Gross)[2], who derived requirements for offices and record rooms specified in terms of the amount of fuel (or its thermal equivalent) per unit of floor area (fire load density). They were designed to provide full protection, that is to resist a complete burnout in the compartment. A UK report[3] published in 1946 gave values which do not differ greatly from those of Ingberg, but the data were expressed in somewhat broader terms. However, current UK regulations[4] do not now specify the fire resistance requirements in terms of fire load density but in terms of particular types of buildings classified according to their purpose and size. Perhaps some fire load density is implicit in these specifications, but other considerations have been included.

The requirements are sometimes reduced; perhaps in an implicit recognition that "burn-out" is unlikely when the fire brigade can attend quickly and there is no serious life risk and they are sometimes increased to introduce a "safety factor", as example, in tall buildings, although in principle the duration and severity of a fire confined to a compartment will be no greater in a tall building than in a low one. Such reductions or extension of the requirements are in general ad hoc, as there is at present no formal way in which probability considerations of incidence, of the frequent failure of a fire to develop beyond a small stage or the mitigating effects of sprinklers and fire-fighting etc can be introduced into the specification of fire resistance requirements. A later paper by Baldwin[5] deals with some recent research in this area where "experience" is being examined statistically from the reports of Fire Brigades. Here we shall only be concerned with specifying these requirements for the structure to survive a burn-out and we shall not be referring to other considerations of life safety (which can be dependent on the rapidity of fire growth and hence on the flammability of materials, means of escape & smoke control), nor with estimating the fire resistance of a given element or structure, only with what is required to resist a burn-out.

REQUIREMENTS FOR PREDICTING FIRE RESISTANCE TO WITHSTAND BURN OUT IN A COMPARTMENT

(1) Broadly speaking one needs a <u>temperature-time relation</u> $\theta(t)$ which defines the thermal input to the structural element. The variations in the heat transfer coefficients and in the methods of measuring temperature between one furnace and another pose serious, perhaps insoluble, problems for standardization but they are less than the variations between fires due to different compartment shapes, window openings, etc. in buildings.

(2) Given descriptions of the compartment, its construction and thermal properties, and of its contents, one can, in principle, write a heat balance equation from which the temperature-time variation could be evaluated if one knew the <u>rate of heat release</u> as a function of time. Although one can attain acceptable accuracy in heat transfer calculations, one is forced to assume, even in the latest methods for the calculation of fire resistance that temperatures are uniform within the compartment. Complex fuel and compartment geometries would present serious problems if one took any other course. The

mathematical fluid flow and chemical reaction equations involve a description of turbulence in a variable density field so that for practical purposes one can only deal with simple approximations.

(3). The rate of heat release in a building fire can be expected to depend on:

(i) the type of fuel and its geometrical distribution both in relation to itself and the compartment;

(ii) the availability of air to the fuel (its porosity) and to the compartment (openings, windows etc);

(iii) the thermal and gaseous environment which can affect the burning of fuel and the efficiency of combustion.

Because of the interdependency between the rate of heat release and the fire itself (feedback) and the weakness in our data on pyrolysis, turbulence etc one can appreciate that an entirely analytic approach must be difficult, to say the least.

PRESENT STATUS OF KNOWLEDGE OF FIRE BEHAVIOUR

It has been established that there are a wide variety of conditions where the rate of burning R and of heat release Q are dependent primarily only on the air supply through the windows. This air supply can be calculated and, for a room full of gas at a uniform temperature having one window, is closely given by a formula[6]

$$\text{Air flow} = k_1 A_W \sqrt{H} \qquad (1)$$

where $k_1 = 0.5\ \text{kg/m}^{5/2}\ \text{sec}$

A_W is window area m^2

H is window height m

Modifications for other window geometries can be calculated.

It has been conventional to take the rate of burning as:

$$R = k_2 A_W \sqrt{H}$$

For these conditions one could solve the heat balance equation and derive the temperature time variation for a given fire. Kawagoe and Sekine[7] and Odeen[8] have followed this procedure.

For example, in an air controlled fire we have, in its simplest, idealised form

$$Q \propto k_1 A_W \sqrt{H} \propto ((k_1 + k_2) A_W \sqrt{H} C \bar{\theta}_c + \bar{h} A_T \bar{\theta}_c) \qquad (2)$$

where $\bar{h}$ is an average heat loss coefficient between the fire inside and the ambient condition outside

A_T is the effective surface area over which heat is lost to the walls, ceiling etc.

C is the specific heat of the hot gases leaving the compartment

θ_c is a mean temperature of the gases in the compartment

k_1 is a calculated constant and k_2 is experimentally determined (conventionally 0.1 $kg/m^{5/2}s$)

Since R is usually small compared with the air flow

θ_c is mainly a function of $\dfrac{A_T}{A_W\sqrt{H}}$ and $\bar{h}$.

When the window opening is large enough in relation to the compartment wall area, for the hot gases to occupy only part of the compartment, the air flow is no longer determined in the same way and the rate of heat release is determined more by the availability of fuel (fuel controlled) than by that of the air (air controlled)[9,10].

THE CIB RESEARCH PROGRAMME ON FULLY DEVELOPED FIRES

The pioneering work on fully-developed fires by Ingberg was followed by more detailed studies in several countries, notably by Fujita[6] and Kawagoe[11] in Japan. However in view of the paucity of available information and the world wide nature of the problem it was agreed in 1958 between a number of laboratories participating in the Conseil International du Batiment Working Party W14 that a programme of experiments suggested by Mr D I Lawson, Director of the Joint Fire Research Organization, England, to investigate the influence of various factors on the development of fire should be undertaken on a co-operative basis. At that time most experimental data referred to approximately cubic compartments and to air controlled fires and the use of models of different shapes with various sizes of window openings was a feature of these CIB experiments.

The factors affecting the duration and temperature of fully-developed fires are so numerous and fire experiments so variable that the programme could not be carried out in full scale compartments. On the other hand it is impossible to model in one fire the effects of more than very few factors. The procedure adopted was to carry out a graded series of experimental fires at a number of small scales so that the relative importance of various features could be found.

EXPERIMENTAL DETAILS

The variables examined were as follows.

SHAPE OF COMPARTMENT

It is convenient to designate the shape of a rectangular compartment by a three figure code representing the three principal dimensions of width, depth and height, relative to height (see Fig. 1). Thus a 211 compartment measured 2 units wide, 1 unit deep and 1 unit high. The four shapes of compartment examined were 211, 121, 221 and 441.

Each laboratory constructed its own fire compartment and in order to obtain consistency between laboratories the materials and methods of construction were standardised as far as possible using asbestos based materials for walls etc. For most experiments these were of order 10 mm thick.

SCALE

The scale of the compartment was taken as the compartment height. Scales of $\frac{1}{2}$, 1 and $1\frac{1}{2}$ m were employed.

VENTILATION OPENING

The ventilation opening was rectangular, extended from floor to ceiling and occupied one quarter, one half, or the whole of the front of the compartment.

FUEL

Fire load densities of 20, 30 and 40 kg/m^2 were used; these represent the range of fire load density that would be encountered in normal occupancies, excluding warehouses.

Cribs of wood were used for the fuel because they provided a reproducible fuel bed whose properties could be varied systematically (see Fig. 2). The wood sticks forming the cribs were 1, 2 or 4 cm thick with horizontal spacings between the sticks of $\frac{1}{3}$, 1 or 3 stick thicknesses.

Different laboratories used different species of wood with densities in the range 390-510 kg/m^3. Many, but not all, of the laboratories were able to condition the wood fuel to a constant moisture content.

The linear dimensions of the cribs were 5/6 of those of the floor of the compartment. The fires were lit so that they grew rapidly; attention being confined to the fully developed fire.

MEASUREMENTS AND ANALYSIS.

Measurements made during each test were standardized; the main ones being

(i) the loss in weight of fuel, from which the rate of burning could be derived

(ii) the temperature of bare thermocouples placed within the compartment

(iii) the intensity of radiation at a point in front of the ventilation opening. This gives a measure of the radiation hazard to neighbouring buildings and can be used to calculate an effective mean black body temperature.

A full report of the work in detail will be published by CIB[12].

The analysis made so far has been for various time averaged values. Rates of weight loss R, two temperatures one near the ceiling, θ_c, the other near the floor θ_f and the radiation emitted I_o from the opening, are the most important; all averaged over the most active period of burning, from 80 per cent initial weight to 30 per cent of the initial weight.

SUMMARY OF RESULTS

The main conclusions are as follows:

(1) The effect of fuel thickness on temperature and rate of burning is slight and probably negligible for practical purposes particularly in air controlled fires.

(2) The effect of scale, shape and window area can mostly be accounted for in simple correlations to be described below.

(3) The influence of porosity of the fuel (the relative spacing between sticks in crib fuel) on temperature and on rate of burning is not negligible even when allowance is made for its effect on fuel height. Its effect is less when the spacings are small.

Figures 3 to 6 show a selection of results. Some of the scatter can be associated with changes in shape, fuel load/floor area and porosity; here only the effects of the primary variables $\frac{A_T}{A_W\sqrt{H}}$ and $A_W\sqrt{H}$ are shown. Figure 4 shows temperatures calculated from the radiation data.

In the CIB experiments the floor was better insulated than the ceiling and walls and correlations of data using an A_T excluding the floor are marginally preferable to those with A_T including the floor.

It is to be noted that:

(a) there is a region of $\frac{A_T}{A_W\sqrt{H}}$ (8-15 $m^{-\frac{1}{2}}$ approximately) where the mean temperature is highest. Above a certain high value of $\frac{A_T}{A_W\sqrt{H}}$ (50-100 $m^{-\frac{1}{2}}$) the mean temperature could be too low to produce failure at, say 500°C and perhaps even to sustain a fire with flaming combustion.

(b) Radiation may be as good or better than the temperature as a measure of fire severity.

(c) The slope of the lines in Figs 3 and 4 for large values of $\frac{A_T}{A_W\sqrt{H}}$ can be used to estimate an effective value of $\bar{h}$ from equation (2) of about 7 $W/m^2\ {}^oC$ i.e. 1.7×10^{-4} cal $cm^{-2}s^{-1}{}^oC^{-1}$ which is in reasonable agreement with calculations.

(d) There is no sharp discontinuity in the value of $\frac{R}{A_W\sqrt{H}}$ i.e. k_2. The general agreement between various research bodies that k_2 is about 0.1 $kg/m^{5/2}$ s for ventilation controlled fires (small openings) is, it is suggested, the result of the general tendency to use cubic or near cubic test rooms. Indeed, if the value of $\frac{R}{A_W\sqrt{H}}$ for all these CIB experiments with windows $\frac{1}{4}$ of the facade are averaged, the result is close to 0.1 $kg/m^{5/2}$s but the higher values obtained in some tests do appear to follow a real trend.

In the region where $\frac{A_T}{A_W\sqrt{H}}$ is small it is strictly improper to plot $\frac{R}{A_W\sqrt{H}}$ against $\frac{A_T}{A_W\sqrt{H}}$ since R does not depend on $A_W\sqrt{H}$ but on a complex property of the fuel bed.* The graph simply shows the data in

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*For example in the fully vented regime R increases more than proportionally to the increase in surface area when this is effected by changing the spacing and less than proportionally when it is effected by an increase in fuel quantity (at constant specific surface).

this way so as to put all the data together to show that $\frac{R}{A_W \sqrt{H}}$ does not have an upper limit at 5-6 kg/min $m^{5/2}$ nor is there any obvious sharp discontinuity with the opening factor for those experiments.

THE REQUIREMENTS FOR FIRE RESISTANCE

In principle, once the temperature time conditions of exposure are given the failure time could be calculated as a structural problem. We can therefore estimate the fire resistance, as measured in a furnace, which is required of a structural element so that it just survives the fire. This equivalence is in principle depending on loading and construction, but here we are seeking a furnace exposure time nominally equivalent to the thermal exposure from a fire. Earlier attempts to do this were based on the form of the temperature-time curves of the real fire and the furnace and equal areas under the curve i.e. $\int \theta \, dt$ were taken. Here we have assumed a particular structural element, namely a single protected steel member with variable insulation, assuming 400 or 550°C as a failure temperature, but instead of using the complete curve of the temperature variation with time we have used suitably defined mean values. A few detailed calculations have been made with the full curves and these give almost the same results as does an approximate method with the mean values. We have thus calculated for each experimental condition an effective equivalent duration of exposure to the ISO temperature time curve. The details of the method of doing this will be described elsewhere[13]. The difference between 400°C and 550°C was not important in the present context. The values t_f for the CIB data are shown in Fig. 7 and lie close to

$$t_f \propto \frac{L}{A_W} \left(\frac{A_W}{A_T}\right)^{\frac{1}{2}} \qquad (3)$$

$$= K \frac{L}{\sqrt{A_W A_T}}$$

The use of variables like $A_W \sqrt{H}$ implies that a term deriving from H could appear but equation (3) does in fact correlate the data from $\frac{1}{2}$ to $1\frac{1}{2}$ m scale on a pragmatic basis. (Some well understood scale effects, e.g. the H in the term $A_W\sqrt{H}$ are compensated by others not so well understood - at least to the accuracy in Fig. 7. Also at higher values of $\frac{A_T}{A_W\sqrt{H}}$ than examined here the temperature could fall to or below the critical temperature and the apparent universality of the relation would be lost. The value of K however does vary significantly with the spacing between the sticks in the crib, and we have to ask what is the equivalence between cribs and real fuel system. It appears advisable to treat this parameter empirically and having found that

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

depends only on the crib design, at least for a given structure, we ask if this K is reasonably constant for fires with real fuel systems and, perhaps more realistic wall and ceiling constructions, and, if so, seek its best value. Accordingly, full scale test data for a variety[11,14,15,16,17,18,19] of experimental structures have been assembled by Miss Law in Fig. 8 from which one obtains a good correlation* with a constant K only slightly less than for the CIB data.

Because R varies strongly with L at low values of $\frac{A_T}{A_W\sqrt{H}}$, K is dependent on L at low values of $\sqrt{\frac{L}{A_W \quad A_T}}$ but t_f is then small anyway and variations matter less.

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*Equation (1) and a nominal value for H of 1 m were used to obtain an effective A_W for Odeen's data which were for forced ventilation. For all the data t_f was obtained from the whole $\theta(t)$ curve. In the correlation of full scale data the floor area is included in A_T since, unlike the CIB experiments, no special measures were taken to insulate the floor nor did the fuel always cover the floor.

Ingberg's data for his smaller test room and for wood furniture are plotted in Fig. 10 on the basis that one could assume that his adjustments of the windows to produce "maximum severity" put his data in the region of high mean temperature. I am indebted to Mr Gross of the Bureau of Standards (U.S) for tracing some details of the room in which these tests were done. Even so difficulties remain. A_T for the smaller test room (including the floor) was about 150 m^2. A_W for fully open windows would be 7.8 m^2 and the chimney vent would make little difference to this. The windows were partially shut but an effective value of less than 5 m^2 would make $\frac{A_T}{A_W \sqrt{H}}$ unrealistically large for the maintenance of high temperatures. In the absence of some of the temperature time data we have used Ingberg's upper and lower estimates of t_f based on equivalent areas under the temperature curves. One finds that over the range of fire load examined K was approximately 0.7 and perhaps 0.8 at the highest fire loads when Ingberg's effective fire resistance was over 4 hours. These considerations imply that

(1) the classic Ingberg relation between fire load per unit floor area and fire resistance may be regarded as a particular case of a more general relation;

(2) the proportionality between t_f and $\frac{L}{\sqrt{A_W A_T}}$ may be extrapolated to values higher than shown in Fig. 7 and 8 (provided $\frac{A_W}{A_T}$ is not too small to give high temperatures).

Kawagoe and Sekine's calculations have been used to estimate values of t_f. Those obtained by the earlier method[7] are shown in Fig. 10. Here too the use of $\frac{L}{\sqrt{A_W A_T}}$ brings the calculated curves closer together. The later method[20] disregarding the "cooling period" of the fire produces values of t_f considerably less.

DISCUSSION

(1) Despite the attempts made to get uniform and repeatable conditions, the variability assigned to random error in $R_{80/30}$ is at least $\pm$ 10 per cent which may be acceptable for regulatory purposes but it demonstrates that attempts to refine calculations better than this (which is possible for certain parts of the problem) may be unwarranted at the present time.

(2) The restriction of the CIB experiments to compartments with walls and ceilings having little effective thermal capacity and to fuels in the form of cribs means that some matching has been necessary between these experiments and other experimental fires which may be more realistic in some ways but study fewer variations of other factors.

(3) There is a range of $\dfrac{A_T}{A_W\sqrt{H}}$ where the mean temperatures are highest. It lies roughly from 8 to 15 $m^{-\frac{1}{2}}$.

(4) Current regulations which implicitely follow Ingberg's basis, viz

$$t_f \propto \frac{L}{A_F}$$

would be expected to over-estimate the required fire resistance when

$$\frac{A_W \ A_T}{A_F^2} > \tfrac{1}{3}$$

and under-estimate it when this ratio is small, i.e. $< \frac{1}{3}$ (Some regulations do demand higher values of t_f for large area compartments).

(5) In practice one may not always need full fire resisting protection. Some allowance may be permissible for the rapid arrival of the fire brigade, automatic detection or the absence of a life risk over a long period as in small readily evacuated buildings. Control over the flammability of materials may then be more relevant. The omission of the 'cooling period' in computing t_f, as has been discussed by Kawagoe, is one such method

but at present there is no quantitative way of introducing such relaxations on a scientific basis. One should try to seek correlations of life loss or structural damage property loss with current regulations or design and these may be assisted by knowledge that one can express fire severity in terms of $\frac{L}{\sqrt{A_W A_T}}$.

(6) If a study of fire incidents involving structural damage were undertaken the severity of such damage might be correlated with values of $\frac{A_W A_T}{A_F^2}$ as well as $\frac{L}{A_F}$. If so one has practical grounds for raising standards in those situations and relaxing them when $\frac{A_W A_T}{A_F^2}$ is large. If no such correlation can be found one must ask if it is because there is in general considerable over-design or whether these scientific studies are refined enough to justify much change.

CONCLUSIONS

(1) Within the limits of present experimental accuracy and well within those required for regulatory purposes if not for engineering design, the fire resistance required for confining a fire throughout its whole duration, 'burn out', is in effect proportional to

$$\frac{L}{\sqrt{A_T A_W}} \quad \text{i.e.} \quad \frac{L}{A_F}\left(\frac{A_F}{\sqrt{A_W A_T}}\right)$$

and regulations which do not recognize the role of windows, or comparable openings, and the shape of the compartment which is implicit in the ratio $\frac{A_W A_T}{A_F^2}$ even if adequate in practice cannot be seen to be so and may therefore appear to the engineer as incomplete or incorrect.

(2) Methods of calculation, of which those by Kawagoe and Sekine are representative, lead to results which are consistant with the relationships given here.

(3) Although the differences resulting from their approximation that $\frac{R}{A_W\sqrt{H}}$ is a known constant over the whole range of conditions may not lead to significant error in predicting fire resistance there are problems, such as estimating the length of flame emerging from windows, where a more accurate representation of burning rate is necessary and the results summarised here are more appropriate, especially when the windows are a large fraction of the facade.

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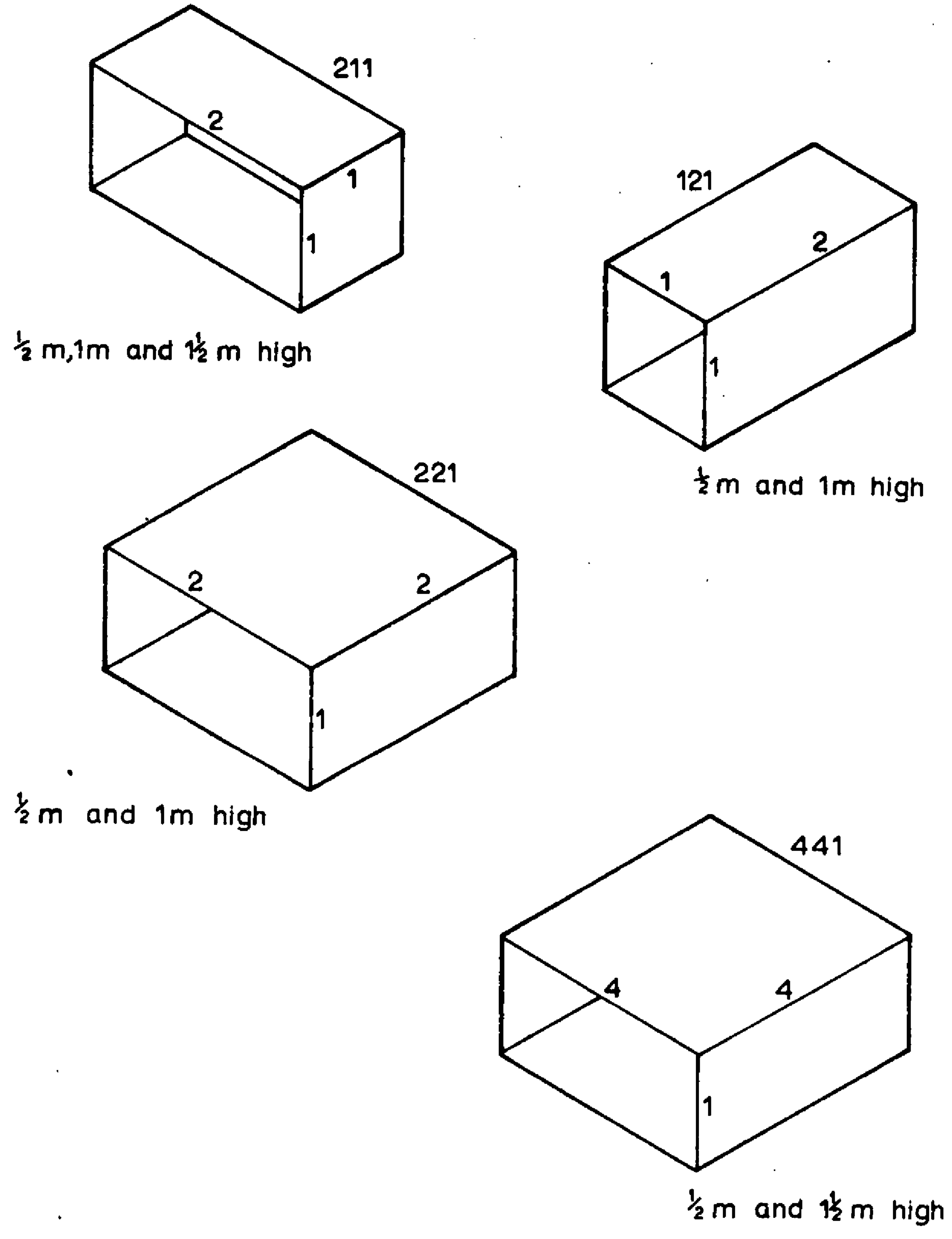
I am indebted to many colleagues both at the Fire Research Station and in those laboratories participating in the co-operative research for many helpful discussions. Because several aspects of this research have yet to be fully analysed the views expressed and the way the data have been used are solely the responsibility of the author.

In particular I am grateful to Miss Law who obtained the values of t_F and devised the methods of so doing.



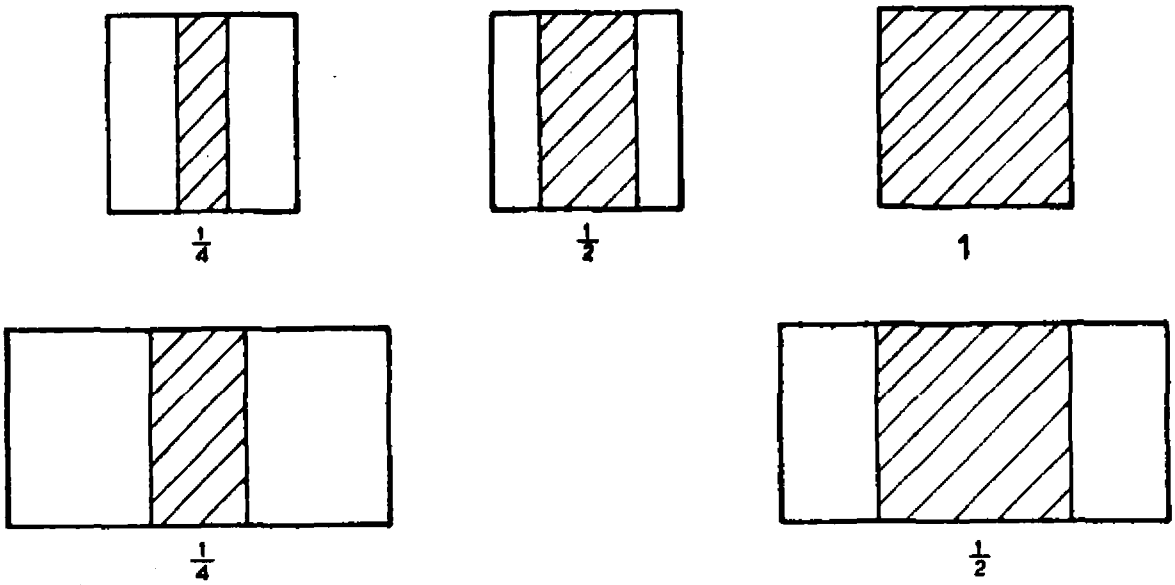
Shape

The code describing shape gives in order the compartment width, depth and height, relative to the height.

Scale: This is the height of the compartment.

FIG. 1a. KEY TO CODES FOR THE EXPERIMENTAL CONDITIONS

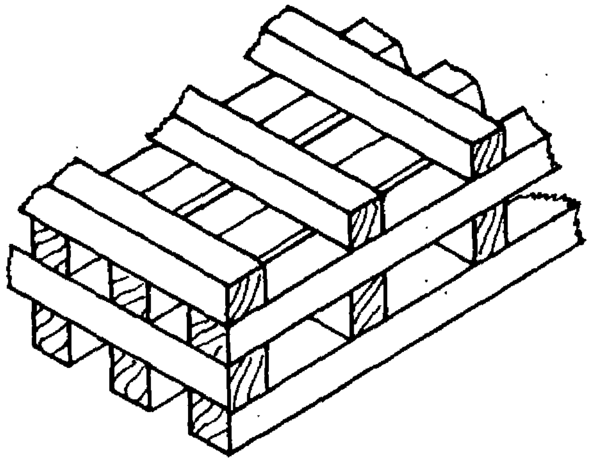
FR.901 10,043



Ventilation

Fraction of the area of the front of the compartment left open.

FIG. 1b. KEY TO CODES FOR THE EXPERIMENTAL CONDITIONS



CRIB-ARRANGEMENT OF SQUARE SECTIONAL WOOD STICKS

Stick thickness and spacing

The first figure in the code is the stick thickness in cm, the second is the spacing between sticks expressed in stick widths. Thus 4,1 stands for 4cm thick sticks 1x4 = 4cm apart:

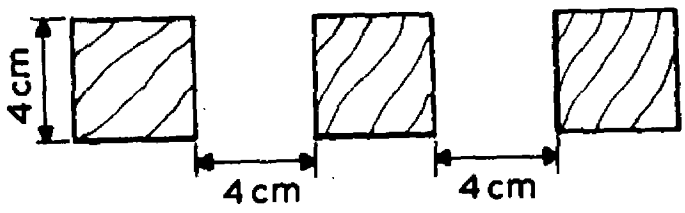
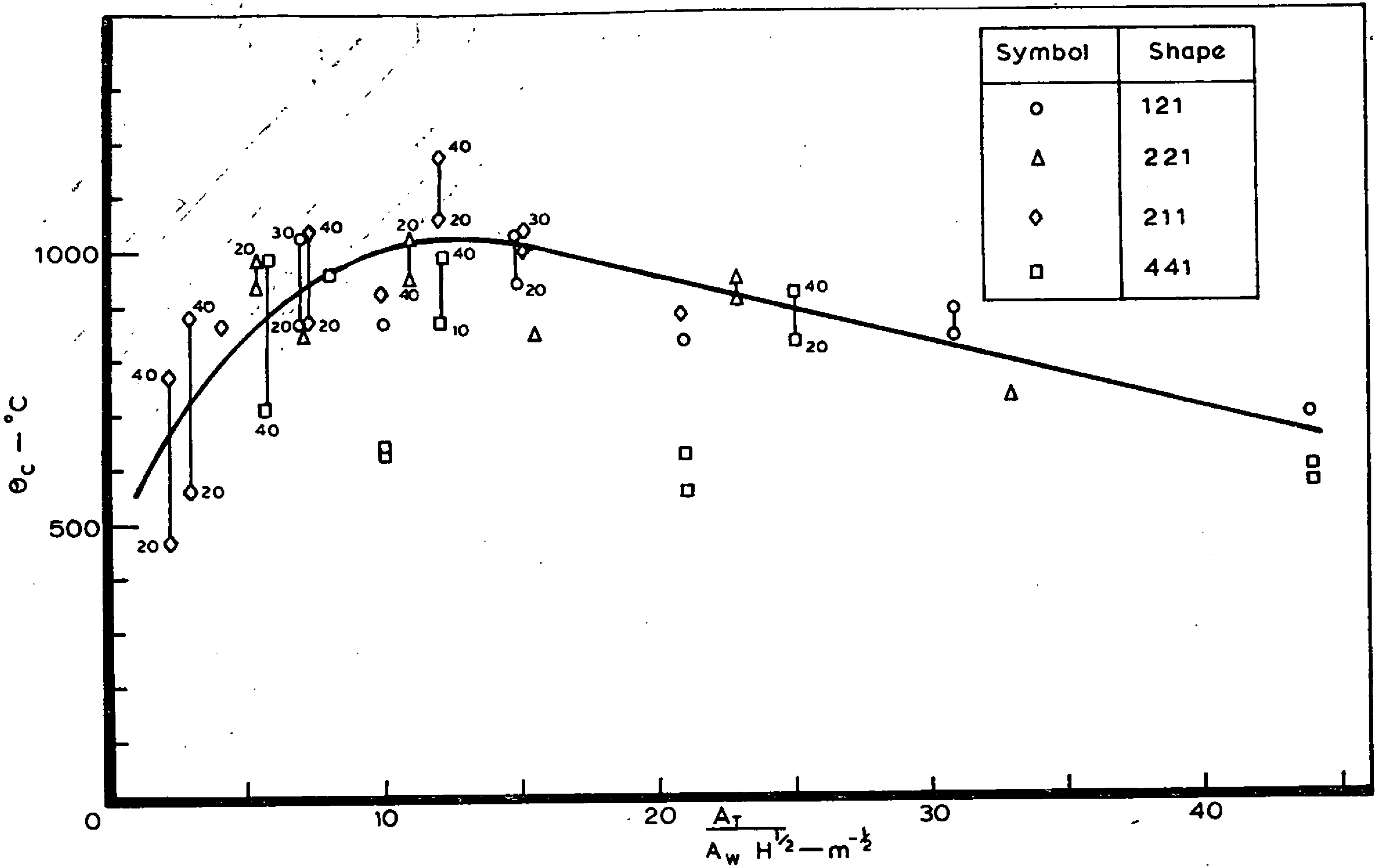


FIG. 2. CRIB DESIGN

FR 901 10,046



A excludes floor and opening Numbers are fire load densities (kg/m) at ends of range of temperatures

FIG. 3. MEAN TEMPERATURE DURING STEADY BURNING PERIOD ($\theta_{C\,80/30}$)(2,1 fuel)

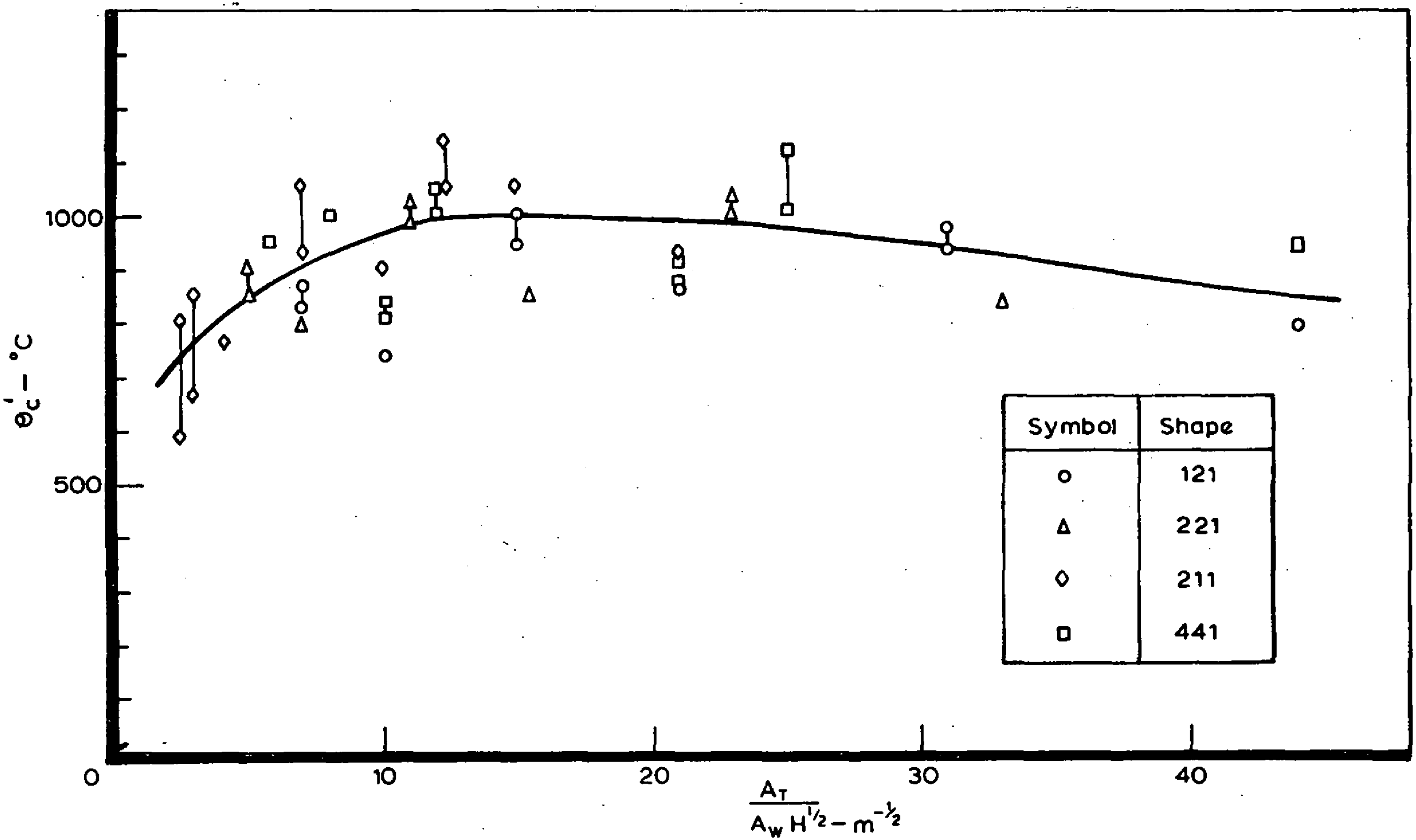


FIG. 4. MEAN TEMPERATURE DURING STEADY BURNING PERIOD (θ_c' 80/30)
DERIVED FROM I_0 (2,1 fuel)

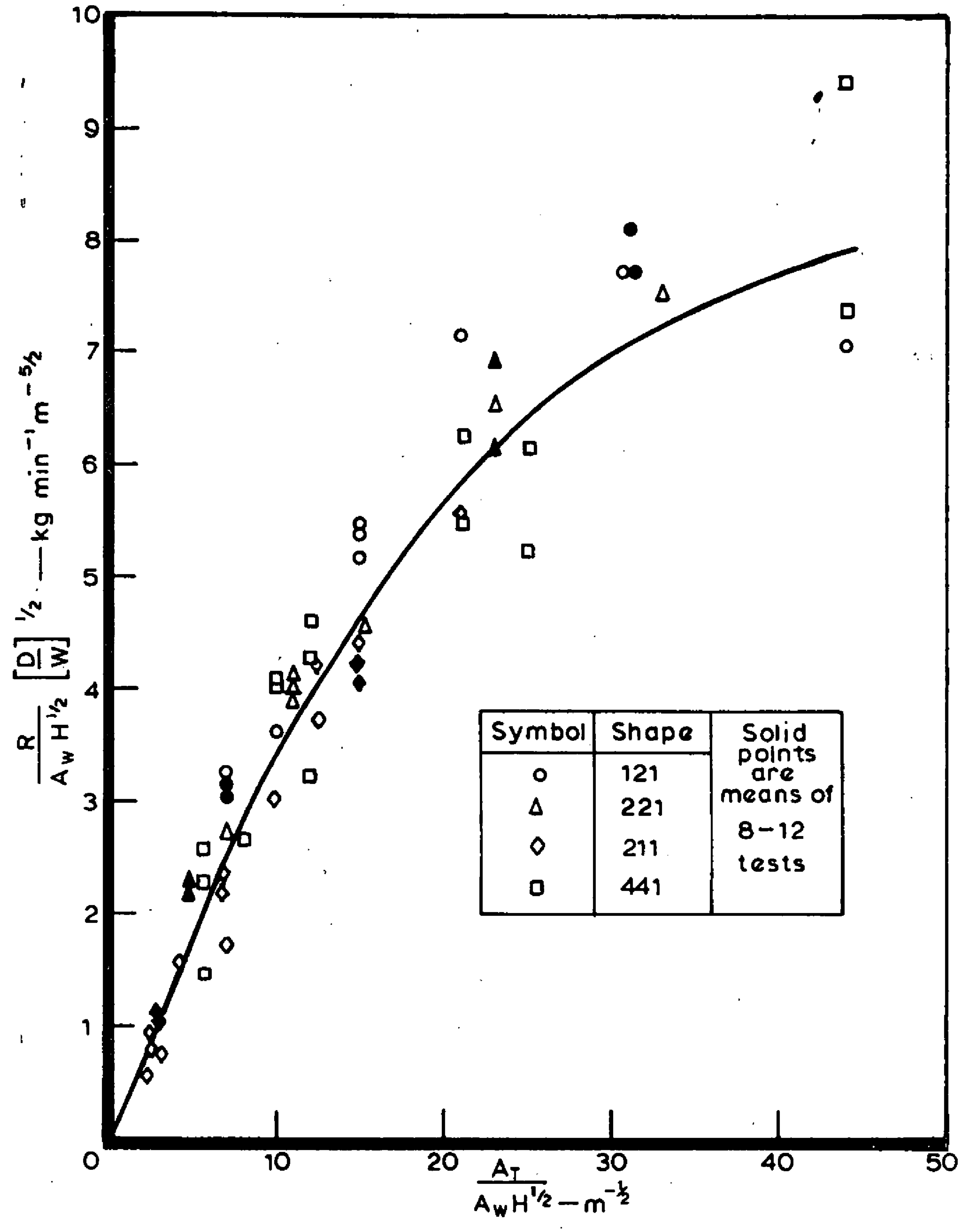


FIG. 5. EFFECT OF COMPARTMENT & WINDOW DIMENSIONS ON RATE OF BURNING (2,1 fuel)

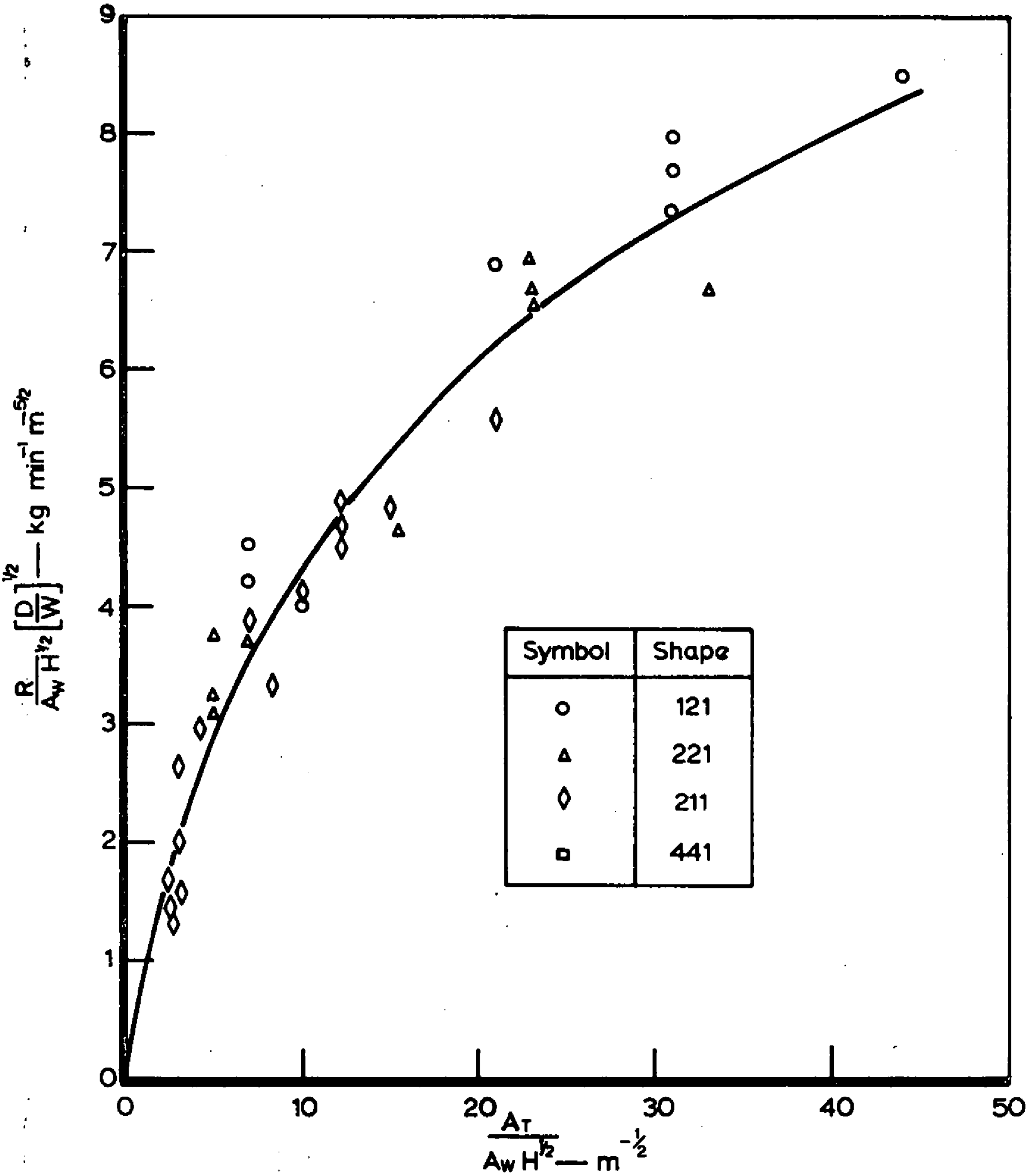


FIG. 6. EFFECT OF COMPARTMENT & WINDOW DIMENSIONS ON RATE OF BURNING (Mean of 1,3 and 2,3 fuel)

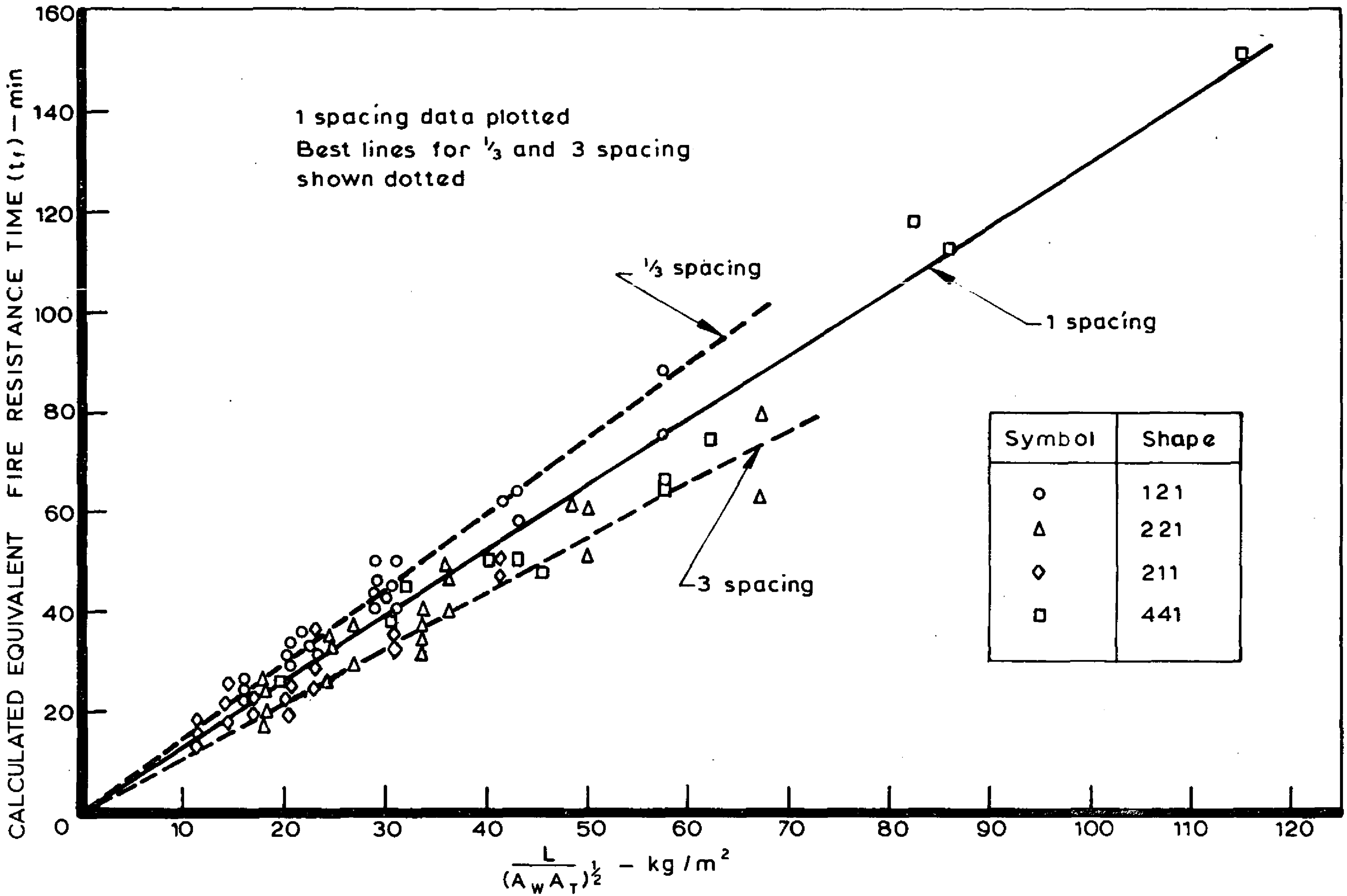


FIG. 7. FIRE RESISTANCE TIME FOR PROTECTED STEEL MEMBERS

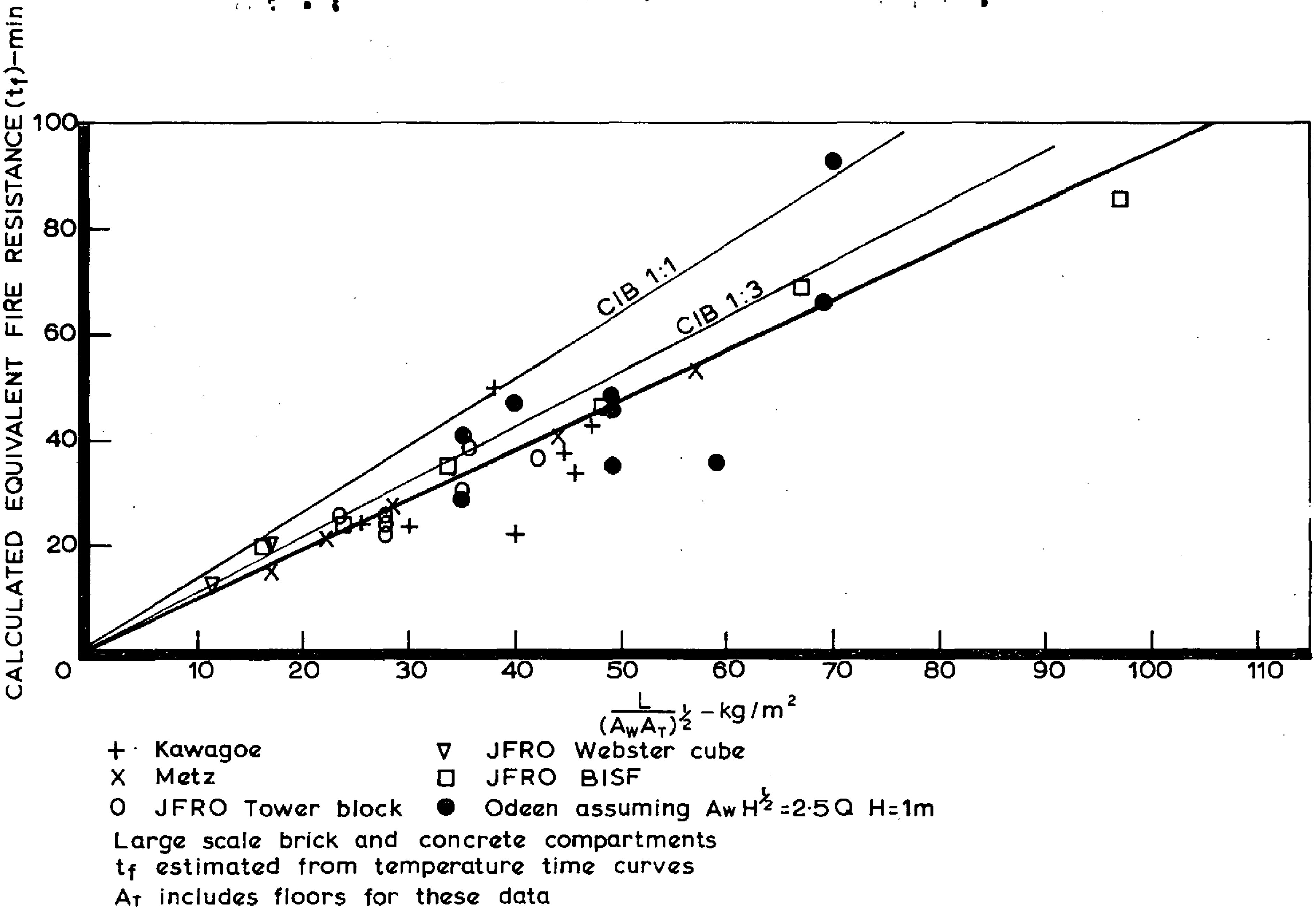


FIG. 8. CORRELATION OF LARGE SCALE FIRE TESTS BASED ON PROTECTED STEEL MEMBERS

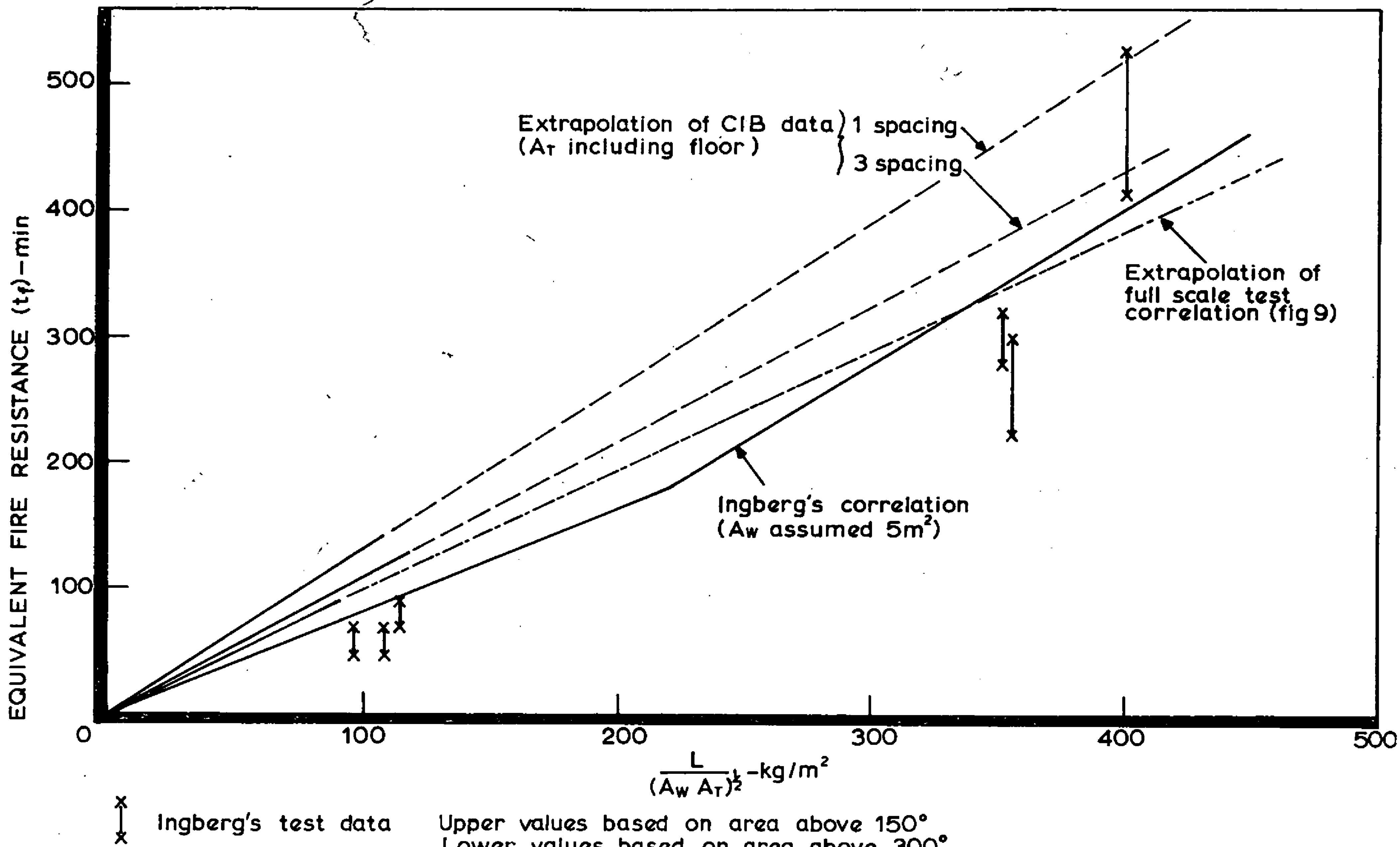
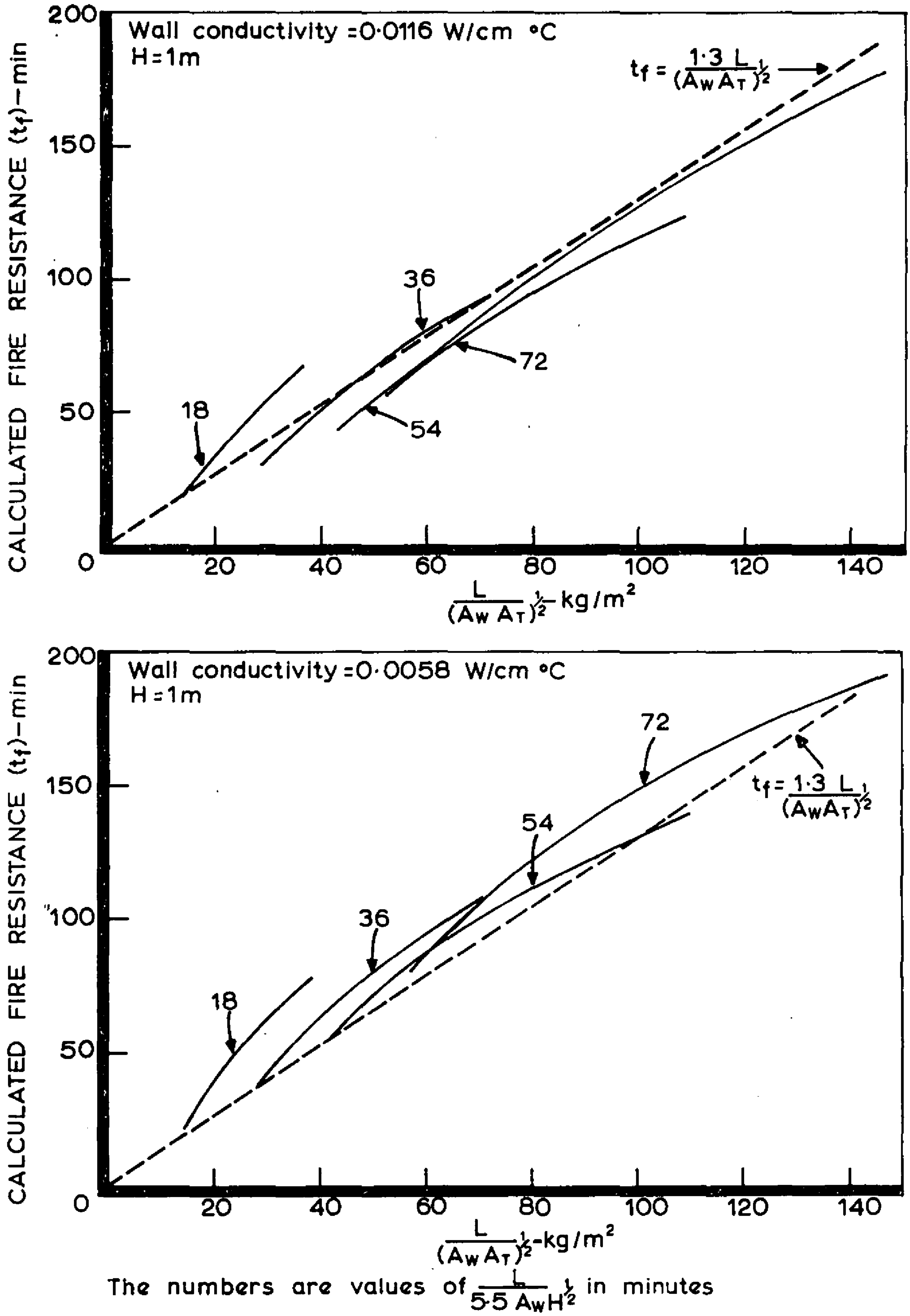


FIG. 9. INGBERG'S RECOMMENDATIONS AND THE CORRELATION OF CIB DATA



The numbers are values of $\frac{L}{5 \cdot 5\ A_W H^{\frac{1}{2}}}$ in minutes

FIG. 10. CALCULATIONS OF t_f USING METHOD OF KAWAGOE AND SEKINE (1964)