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THE PROJECTION OF FLAMES FROM BURNING BUILDINGS

by

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SUMMARY

Data on flame projection from the openings of burning buildings obtained by Webster et al and Seigel are compared with the data of Yokoi for the flow of hot gases from openings. Although the bases for these three sets of data all differ to some degree, there is sufficient in common to make it desirable to seek a common interpretation so that each set of data can be augmented by information from the others.

KEY WORDS: Flame, window, size, projection.

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INTRODUCTION

The growing interest in the use of structural steel external to the facades of large buildings has posed the question: how far do flames emerge from openings when there is a fire in the building? It is opportune therefore to re-examine earlier work on this subject, which although directed to the problem of fire spread up the facade of buildings or to the safety of parts of the structure above a fire has relevance here.

Most large scale experiments on this problem have been with narrow windows, that is the width of the windows was of the same order as the height or less. However, as Yokoi[1] has demonstrated by using models, the width/height ratio has an important effect on the flame trajectory; with wide windows the flame does not project far from the facade but clings to the wall above but with narrow windows it tends not to. It is easier for air to enter between the facade and the flames when the flame front is narrow. Clearly then, the "safe" position of external steel work will depend not only on the behaviour of the fire itself within the building but also on the window geometry.

It is the purpose of this paper to compare the results of the work of Yokoi[1], Webster et al[2] and Seigel[3] from a common point of view in order to exploit the extensive data obtained by Yokoi for a wide range of window and facade geometries.

Thomas has already analysed in detail[4] Yokoi's and Webster's data, but the main results of that correlation will be summarised below and supplemented by Seigel's data.

THE WORK OF WEBSTER, YOKOI AND SEIGEL

The main points of similarity and difference between these three sets of data are as follows:-

1. Yokoi reports the temperature distribution within "upward currents", not flames, emerging from the window of a burning enclosure while Webster reports visible flame lengths. Thomas[4] has shown it is possible to match the two sets of data provided a temperature rise is chosen to mark the flame tip. Seigel reports flame temperature and defines the flame tip as the position where this was 540°C.
2. Webster's data were correlated by Thomas by a dimensional analysis essentially the same as that used by Yokoi. This analysis derives from the dominant role of natural convection ie buoyancy, and from considerations of turbulent mixing. Seigel on the other hand treats flames as forced horizontal jets and excludes buoyancy. Yokoi's and Webster's data therefore, may be regarded as directly applicable to fires having the same buoyancy head as the window, ie a fire on one level only, though they can be adapted to other conditions. Some of Seigel's data are in principle applicable to fires on more than one level.
3. Yokoi's data cover by far the widest range of geometrical variation (owing to his use of models) and include the effects of horizontal projections or balconies. They show a fundamental difference between the behaviour of flames from narrow windows and from wide windows below a wall extending above the windows.
4. Webster's data were derived from experiments where there was no wall above the window. Yokoi carried out experiments both for the "wall" and "no wall" condition. Seigel's experiments appear from photographs to have had a wall above the window.
5. Seigel connected an air supply to his fire chamber so that in some of his experiments he could supply combustion air additional to that provided by the windows.

THE WEBSTER-YOKOI CORRELATION

In Webster's data for the "no wall" condition the length of flame l above the floor, is correlated[4] with the rate of burning per unit width of window as follows:

$$\ell = Z_\ell + H = 18.6 \left(\frac{R}{W}\right)^{\frac{2}{3}} \qquad (1)$$

where R is rate of weight loss of fuel - kg/s

W is the window width - m

H is the window height - m

Z_ℓ is the flame length above the top of the window - m

Yokoi's data, for the distance z from the top of the window to the point along trajectory at which the temperature rise of the hot gases is $\Delta\theta_z$, can be correlated using the equivalent radius of the upper half of the window, r_o, with a dimensionless temperature term, $\textcircled{H}$, which includes the rate of heat flow from the window, Q . For the "no wall" condition the correlation is

$$\frac{z}{r_o} = \frac{A}{\textcircled{H}} \quad \text{for } \frac{z}{r_o} \gg 1 \qquad (2.1)$$

where $r_o = \sqrt{\frac{WH}{2\pi}}$

$$\textcircled{H} = \frac{\Delta\theta_z \, r_o^{\frac{5}{3}}}{\left(\frac{Q^2 \, T_o}{C^2 \rho^2 g}\right)^{\frac{1}{3}}}$$

T_o = temperature of atmosphere = 290°K

C = specific heat of gases = 0.24 Kcal/kg

ρ = density of gases = 0.456 kg/m^3 at 500°C

g = acceleration due to gravity = 9.81 m/s^2

and A depends on $\frac{W}{H}$

Thomas showed that these data can be further correlated by putting,

$$A \simeq \left(\frac{H}{2W}\right)^{\frac{1}{3}} = \frac{1}{n^{\frac{1}{3}}} \qquad \text{(2 ii)}$$

which implies that Z depends only on $\frac{Q}{W}$ by analogy with equation 1.

Note that $\frac{r_o}{H} = \sqrt{\frac{W}{H 2\pi}} = \frac{1}{2\sqrt{\pi}} \; n^{\frac{1}{2}}$ (2 iii)

Equation (2) then becomes

$$n^{\frac{1}{3}} \; \frac{Z}{r_o} \simeq \frac{1}{\textcircled{H}} \qquad (3)$$

If we denote the effective calorific value of the fuel by C (Q = C x R) we can write equation (1) for Webster's data as

$$n^{\frac{1}{3}} \frac{\ell}{r_o} = 18{\cdot}6 \; \Delta\theta_e \left(\frac{C^2 \rho^2 g}{\pi \, c^2 T_o}\right)^{\frac{1}{3}} \times \frac{1}{\textcircled{H}} \qquad (4)$$

where $\Delta\theta_e$ is an effective mean temperature rise at the flame tip.

There is a close similarity between equations (3) and (4) and although Yokoi states that his correlation fails if there is significant flaming outside the window, it does appear that his correlation could be used to generalize Webster's data if suitable values of C and $\Delta\theta_e$ can be chosen and if an allowance is made for the difference in origin of l and z. (The origin of the buoyancy head is the base of the fire - not the top of the window - and it was for this reason that Thomas originally chose this form of correlation for Webster's data).

Accordingly, instead of equation (3) the following equation is proposed for correlating Yokoi's data for the "no wall" condition

$$\frac{n^{\frac{1}{3}} \, (Z + H)}{r_o} = \left(\frac{Z + H}{H}\right) \frac{2\sqrt{\pi}}{n^{\frac{1}{6}}} = \frac{B}{\textcircled{H}} \qquad (5)$$

where B is a number which we can identify from equation (4) as

$$B = 18.6 \;\; \Delta\theta_e \left(\frac{C^2 \rho^2 g}{\pi \, c^2 \, T_o}\right)^{\frac{1}{3}}$$

We can use the above values for c, ρ, g and T_o and take 4000 Kcal/kg for C the calorific value of wood volatiles and assume $\Delta\theta_\ell \simeq 540^\circ c$ the same value as was taken by Seigel. This gives B = 2.0 and equation (5) with this value of B is shown in Fig (1).

In Webster's data $n = 2$ and $\frac{n^{1/3}(z+H)}{r_o}$ is approximately $3.2\left(\frac{Z+H}{H}\right)$ which lies between 3.2 and 10.

The agreement is reasonable in the region corresponding to the lower values of $\frac{Z+H}{r_o}$ - typical of flames - but for the region beyond the flames where Ⓗ is less or $\Delta\theta \ll \Delta\theta_\ell$ a value of B $\sim$ 1.3 is more reasonable.

There is in Fig (1) a systematic but small association between B and n but we disregard this in the interests of simplicity.

This correlation of Yokoi's and Webster's data has been derived for the one common situation and, in the absence of other data, we recommend the use of Yokoi's correlations generally.

THE WEBSTER-SEIGEL CORRELATION

Seigel designed his experiments to obtain the maximum burning rate for his wood crib fire load ('normal burning') and when the window size was too small to give the necessary combustion air, he provided up to 135 m^3/min of external air supply. The effect of this forced air supply is to increase the burning rate and the flame length. It would also affect the flame deflection but this has little additional effect on the flame length and it is valid to compare his flame lengths with Webster's data for similar rates of burning (or heat release). Because of certain assumptions which have to be made we have found it more convenient to compare his data with Webster's rather than Yokoi's, but as will be seen, his results are consistent with the above Yokoi/Webster comparison.

Seigel defined his flame tip as the point at which he measured a temperature of 540°C, and his correlation of data is in terms of the total weight of fire load (L) per square root of window area ($\sqrt{A_o}$). To compare these with other data we need to estimate the window width and the rate of burning and to allow for any difference in defining the flame tip.

Seigel quotes his range of window sizes as being from 0.61 m to 1.83 m wide by 1.83 m to 2.44 m high, ie $\sqrt{A_o/W}$ varies from 1.73 to 1.16. Taking an average value we write

$$W = \frac{\sqrt{A_o}}{1.45}$$

We need to know more about the design of the cribs - eg their porosity, to predict the burning time and so have direct measures of R. Here we can only make an estimate.

Seigel used 38 mm wood sticks for fuel and quotes Gross's[5] correlation of burning time with stick size, to give a burning time of nearly 30 min (1800s). This perhaps fortuitously corresponds to the well known $\frac{1}{40}$ in/min for the charring of wood and in the absence of better data it is this we assume for "normal burning".

Thus we have

$$R = \frac{L}{1800} \ \text{kg/s}$$

Substituting in equation (1) we obtain

$$Z_{540} + H = 18.6 \ \frac{\Delta\theta_\ell}{540} \left(\frac{1.45L}{1800\sqrt{A_o}} \right)^{\frac{2}{3}}$$

$$\text{or} \quad Z_{540} + H = 0.16 \ \frac{\Delta\theta_\ell}{540} \left(\frac{L}{\sqrt{A_o}} \right)^{\frac{2}{3}} \qquad (6)$$

where $\Delta\theta_\ell$ is the 'matching' value for Webster's data.

Equation (6) is drawn in Fig 2, for two values of $\Delta\theta_\ell$ assuming an average value for H of 2.14 m. The upper limit of the data for 'normal burning' corresponds to $\Delta\theta_\ell$ about 400°C.

It would appear that Webster's definition of ℓ as the visible flame length corresponds to a mean temperature rise of about 400°C - 450°C. This is lower than might be expected but it must be remembered that a mean temperature at the mean position of a fluctuating flame assessed by eye is likely to be less than that of the actual flame tip. To some extent this is consistent with our previous findings. When comparing Yokoi's and Webster's data a value of, say, $\Delta\theta_\ell \sim 425^\circ$C, would give $B \sim 1.55$ which can be seen from Fig (1) to be about midway between the two lines drawn.

Seigel states that some tests were considered to have limited air supply ('restricted burning') but does not explicitly give the criterion for this. Clearly it would be more satisfactory to obtain a correlation in terms of R rather than L, but the nearest we can approach this is to estimate the value of R in the absence of forced ventilation. For low $\frac{L}{\sqrt{A_o}}$, R will be dictated by the crib design, as explained earlier. For high $\frac{L}{\sqrt{A_o}}$, natural convection would give

$$R \approx 0.09\ WH^{\frac{3}{2}} \qquad (7)$$

This corresponds to the well known expression $5.5\ A_o\sqrt{H}$ kg/min for the burning rate in roughly cubical compartments, but the coefficient 0.09 is not necessarily the same for other shapes of compartment.

Substituting in (1) we obtain

$$Z_\ell = H\ \left(18.6\ \frac{425}{540}\ (0.09)^{\frac{2}{3}} - 1\right) = 1.9\ H$$

With the average value of 2.14 m for H we obtain

$$Z_\ell \sim 4.1 \text{ m}$$

It is not clear which of Seigel's results can be assumed to have the rate of burning restricted simply by natural convection but where the flames were longer than about 4-5 m these could in theory only be obtained by blowing air into the fire. A 'natural' fire on one level could usually only produce such long flames if there were flammable linings present or if a wind were blowing across the building, as in the Aultsville fires[6]. Values of $\frac{R}{WH^{\frac{3}{2}}}$ of up to about 2.0 have been obtained for some conditions[7] but a more detailed analysis of Seigel's data would be required to explore the relevance of this.

Provided equation (7) for R is valid, the application of equation (1) to give $\frac{\ell}{H}$ = 1.9 is a useful general result. It must be emphasised that although, for a given R, the fire temperature can be calculated from heat balances, there is no theory that can be used to predict R and we must resort to empirical data as in reference (7). In the absence of other information we should use equation (7) for R or a value based on $\frac{1}{40}$ in/min (0.01 mm/s), whichever is the lower. Using this latter value presumes that some estimate can be made of the surface area of the fuel. However, $R/WH^{\frac{3}{2}} = 0.09$ is likely to be the best single value for compartments of common shape. Certainly the ratio of about 2 for Z_ℓ/H is typical of many fires except where there are extensive surfaces of flammable wall linings.

CONCLUSION

We come to the conclusion that whether or not we consider the flame as a driven jet or as a plume which does not lie against the wall, we can use equation (1) with little loss of accuracy in view of the uncertainty in defining the conditions under which 'normal burning' takes place, and in which the flame is a jet or a plume.

Seigel's data apply to narrow windows where the flame does not lie against the wall above the window.

We can presumably use Yokoi's correlations for trajectories for the many geometries he has studied, including wide windows where the flame lies against the wall above the window.

In attempting to calculate the effective value of Q leaving the window in terms of which Yokoi presents his data, we should note that for high $L/\sqrt{A_0}$ with air supplied by natural convection through the window we cannot achieve the normal burning as described by Seigel, though long flames could result when

a) flammable linings are present

b) there is a 'chimney effect' due to fire on floors below the window from which flames issue

c) there is a wind across the fire

In no case can one describe Q or burning rates and consequently flame lengths solely in terms of those implied by $L/\sqrt{A_o}$ since Q depends on rate of burning, not on available fuel. Nor can one evaluate Q necessarily by rates of burning appropriate to cribs in the open - for obvious reasons in case (a), and in (b) and (c) because the air acts as a forced draught over the fuel whereas the burning rates evaluated by Gross and others apply when natural convection is induced by the crib itself.

In view of the arbitrary character of some of the features of these comparisons, eg the effective calorific value of fuel and the burning time in Seigel's experiments, it would probably be fortuitous to obtain better agreement.

Yokoi's data is especially valuable because it gives details of trajectories and, in the absence of data on flames, these would be used as a first approximation taking 540°C as the locus of the flame tip.

This treatment does not enable a complete assessment to be made of the hazard from projecting flames since in the vicinity of most flames there can be considerable heat transfer from radiation and this must be treated separately. However once the position of the flame has been estimated suitable calculations can be made from geometric considerations and a nominal temperature for the flame. This will of course be in excess of 540°C and it would be more appropriate to use direct measurements of flame radiation for example, those in ref (7). Seigel's data on flame temperatures are the only ones available from the work discussed in this report but the heat transfer by radiation is so critically dependent on flame temperature that direct measures of radiation are preferable when suitable values are available.

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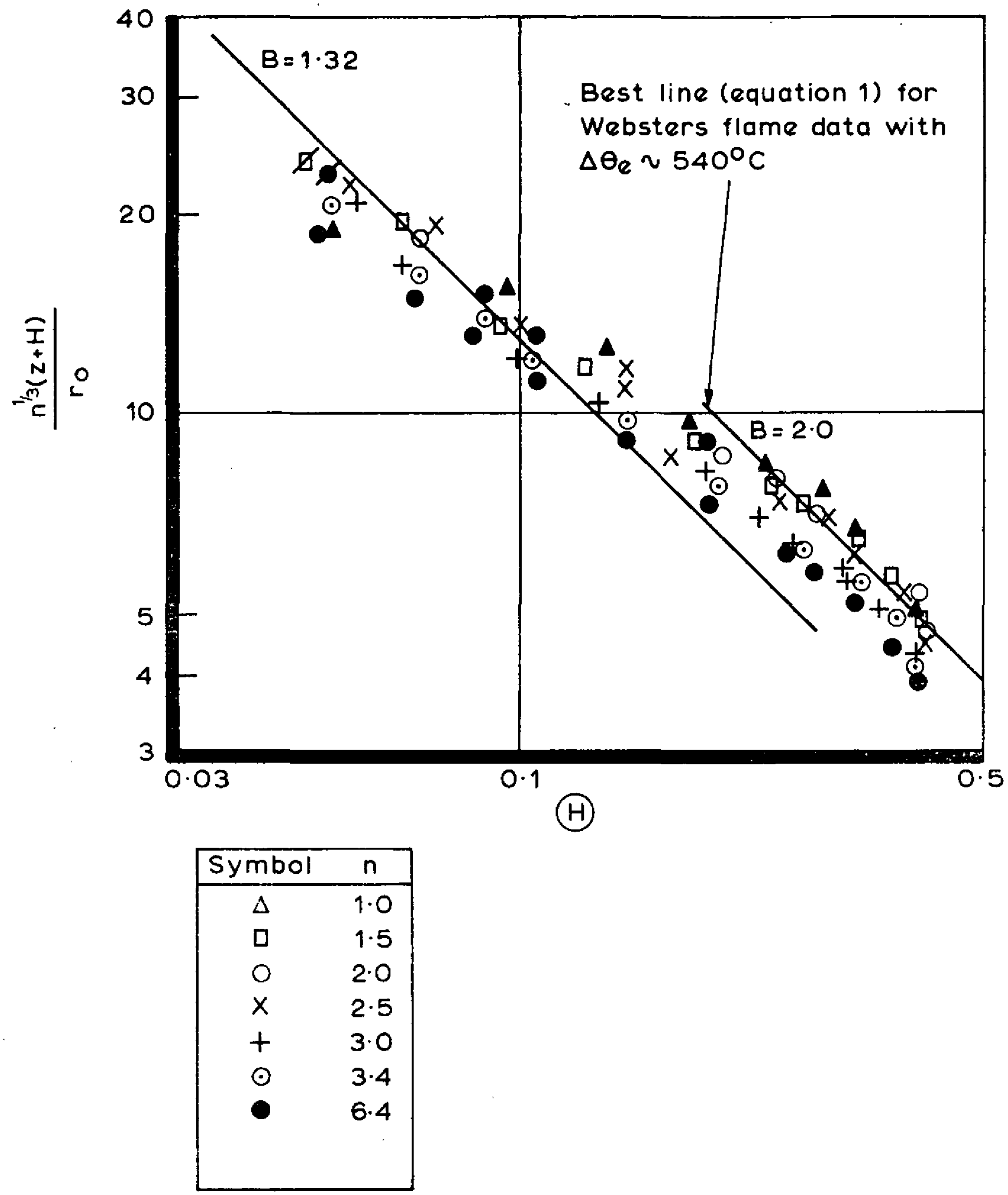
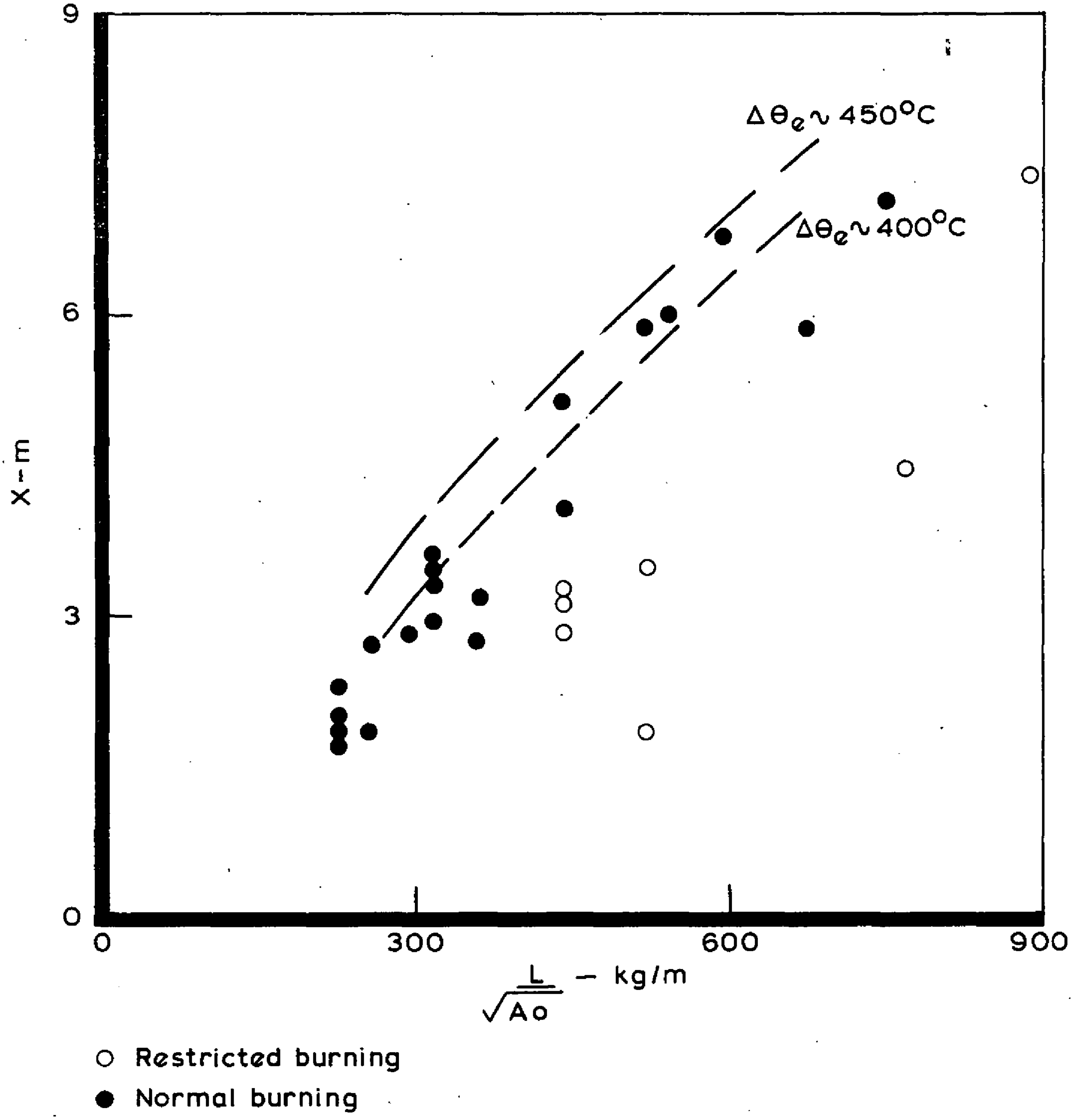


The line is equation 5

FIG. 1. YOKOI'S DATA PLOTTED AS $n^{1/3}\ \frac{(z+H)}{r_O}$



The line is equation 6 assuming H is 2·14m and corresponds to a correlation of Yokoi's and Webster's data with a matching temperature rise for the flame tip

FIG. 2. SEIGEL'S DATA