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FLAMES FROM FIRE FRONTS OF DIFFERENT SHAPES

by

P. H. THOMAS, D. L. SIMMS, and H. G. WRAIGHT

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Fire Research Station.
Boreham Wood.
Herts.
('phone ELStree 1341)

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SUMMARY

The relation between flame height, L, width of burning zone, Dw and rate of burning per unit area, $\dot{m}''$ of wood cribs for a range of experimental conditions is of the form

$$\frac{L}{Dw} = A \left(\frac{\dot{m}''}{\rho\sqrt{g\ Dw}}\right)^{\frac{2}{3}}$$

where g is the acceleration due to gravity

and ρ is a density taken as a constant for a particular fuel.

Although the value of A depends on the shape of the burning zone and the species of wood, it is sufficiently accurate for most purposes to assume its value is 40 when ρ is taken nominally as the density of air and equal to 1.3×10^{-3} g/cm^3.

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INTRODUCTION

The heat transfer from buoyant diffusion flames plays an important role in determining fire hazards, such as the rate of spread of flame over combustible surfaces of all kinds and the separation distances necessary between combustible objects, such as timber stacks or burning buildings. Two of the factors upon which the heat transfer depends are the flame height and thickness; these control the radiation exchange factor and the flame emissivity.

Byram[1] obtained an empirical relation between the height of a flame from a wide fire front and the heat output, viz,

$$L = 0.45\ (H\,\dot{m}')^{0.46} \qquad (1a)$$

where L is the flame height in feet

H is the heat available, taken by Byram as 6500 B.t.u. per lb. of fuel.

and $\dot{m}'$ is the linear rate of burning in lb $ft^{-1} s^{-1}$

In c.g.s. units equation (1a) becomes

$$L = 5.2\ (H\,\dot{m}')^{0.46} \qquad (1.b)$$

Equation (1) is not in dimensionless form. Thomas[2, 3] derived a functional relationship for the same condition using dimensional analysis

$$\frac{L}{D} = f\left(\frac{\dot{m}'}{\rho D\sqrt{gD}}\right) \qquad (2)$$

where g is the acceleration due to gravity

ρ is a density assumed constant for any particular fuel

and D is the length of the burning zone in the direction of spread.

Other dimensionless terms involving properties of the fuel would have to be included in using this functional equation to correlate data for different fuels. Because there is some uncertainty in the choice of a criterion for the boundary of the flame zone, which may differ for flames of different luminosity, a nominal value for ρ has been used. In an early paper[2], ρ was taken as 1.0×10^{-3} g/cm^3. More recently the density of air has been used, 1.3×10^{-3} g/cm^3, and this has been continued in this note. The use of the density of the fuel gases, as for example by Fons[4], presupposes a criterion for the tip of the flame. There is some uncertainty about this, and whilst some assumptions about this have to be made in some discussions of flame height, they can be omitted here.

For convenience it has been assumed that a power law holds between the two dimensionless groups, i.e.

$$\frac{L}{D} = A\left(\frac{\dot{m}'}{\rho D\sqrt{gD}}\right)^{n} \qquad (3)$$

where A and n are constants.

A number of analyses[2-5] for different shapes of burning zone have been carried out resulting in different values of A and n. Thomas[3] has shown that the value of the index n should be $\frac{2}{3}$ for strip sources so long as buoyancy controls the air flow and so long as $L/D \gg 1.0$.

For square or circular burning zones it is appropriate to relate the burning rate to unit area, instead of to unit length of front. Thus flame heights can be correlated by a relation of the form

$$\frac{L}{D} = f\left(\frac{\dot{m}''}{\rho\sqrt{gD}}\right)$$

where $\dot{m}''$ is the burning rate per unit area

For burning zones characterised by two finite dimensions, e.g. length and width, a second independent parameter, describing the ratio of these dimensions must be included

e.g.

$$\frac{L}{D} = f\left[\left(\frac{\dot{m}''}{\rho\sqrt{gD}}\right)\left(\frac{D_c}{D_w}\right)\right]$$

where D_c is one and D_w is the other characteristic length.

In the present paper, a number of more recent results, primarily those of Fons et al[4], are analysed in order to check the validity of equation (3) and to find how the values of n and A vary with the shape of rectangular burning zones and the species of wood.

ANALYSIS OF RESULTS

1. Experiments on Spreading Fires

Fons et al[4] carried out a series of experiments on the spread of fire in wooden cribs constructed mainly from white fir (Abies concolor), with stick thicknesses from 0.7 to 3.2 cm, oven-dry densities from 0.30 to 0.55 g/cm^3, moisture contents from 2.5 to 17.0 per cent and stick spacings from 1: 1 to 1 : 4. Most of the cribs were 24 cm wide and 14 cm high but a few were larger than this. Two cribs were only 7 cm high and these were omitted from the analysis of fire spread because their rates of spread were markedly slower[6] than those of deeper cribs where spread was independent of crib depth. They have therefore been omitted from the present statistical analysis, but are shown separately in Fig. 1.

Some further experiments were done using four other species, magnolia (Magnolia grandiflora) density, 0.45 to 0.55 g/cm^3, basswood (Tilia americana) density, 0.36 to 0.50 g/cm^3, sugar maple (Acer saccharum) density 0.69 to 0.77 g/cm^3 and longleaf pine (Pinus palustris) density, 0.51 to 0.75 g/cm^3, but they were restricted to one stick thickness, 1.2 cm, and with few exceptions, one moisture content, 11 per cent.

Measurements were taken of the rate of spread of fire, R, the length of the burning zone in the direction of spread, D_w, and of the flame height, L, measured from the top of the crib. The burning rate of the crib per unit base area, $\dot{m}''$, was calculated from the values of RW/D_w where W was the weight of the crib per unit base area (the fuel loading).

Some of Fons's data* for cribs of white fir sticks were included in an

* In Fons's notation, W_b is D_c and D is D_w.

earlier analysis[2] where the burning zone was treated as if it were a square of equal area and an equivalent side D, was defined by

$$D = \sqrt{D_c \times D_W}$$

where D_c is defined as the width of the crib and is measured at right angles to D_W.

This gave

$$\frac{L}{D} = 4.4 \left(\frac{10^6 \dot{m}^2}{D^5}\right)^{0.3} \qquad (4)$$

where $\dot{m}$ is the rate of weight loss.

Fons[4] et al, following Thomas, Pickard and Wraight[5], did not consider the effect of the shape of the burning zone, and treated the results as if they were for strip sources, to give the relation

$$\frac{L}{D_W} = 4.5 \left(\frac{C \dot{m}''}{\rho g \sqrt{g D_W}}\right)^{0.86} \qquad (5)$$

where C is the mass of combustion gas produced from unit mass of solid fuel and ρg is its density at constant pressure = 0.3×10^{-3} g/cm^3.

It may be shown by inserting the numerical values used by Fons for C and ρg that the constant in equation (5) is about 10 per cent greater than the result of the same form given by Thomas, Pickard and Wraight[5]*.

Fons's data are of special interest because a range of values of D_c/D_W were obtained and several species were used.

To discuss the effect on flame length of the ratio D_c/D_W, Fons's results for white fir are considered in three groups, corresponding to different ranges of the ratio** D_c/D_W.

Group	Ratio	No. of results
1	$D_c/D_W \leq 1.5$	12
2	$1.5 < D_c/D_W \leq 2.0$	22
3	$D_c/D_W > 2.0$	20

An initial plot of log (L/D_W) against $(\dot{m}''/\sqrt{D_W})$ suggested that the relationship between these two variables might not be linear over the range of values of $\dot{m}''/\sqrt{D_W}$. A multiple regression analysis of the log of the dimensionless flame height for each of the three groups included a quadratic term in log $(\dot{m}''/\sqrt{D_W})$ and a term to allow for the possible effect of fuel moisture content log M_f, showed that the quadratic term was not significant. This term was then eliminated

* Thomas, Pickard and Wraight[5] measured flame heights from the centre of the crib and the constant has been adjusted accordingly for the comparison.

**In a few of the experiments $D_W > D_c$ and for these, the inverse D_W/D_c has been used and D_c taken as the length of the burning zone in further calculations.

from the analysis and it was found that the effect of moisture content was not significant in the first two groups, but was just significant at the 5 per cent level for the third group. Generally, this level is too low to be considered significant in experiments of this kind, but in order to determine whether this was due to a real variation with the shape of the burning zone or to the arbitrary division of the results into three groups, the third group was sub-divided and a further multiple regression analysis was performed on the seven terms for which $D_c/D_w > 2.3$. The significance of the term for moisture content dropped considerably and plotting out the results showed that a few terms in the group $2.0 < D_c/D_w < 2.3$ were probably responsible for the significance of the term in M_f for the whole of the third group. The moisture content was therefore eliminated from the analysis leaving a power law relation between L/D_w and $\dot{m}''/\rho\sqrt{g D_w}$ for the three groups*. The result of this procedure was:-

$$\text{for } \frac{D_c}{D_w} \leq 1.5; \quad \frac{L}{D_w} = 40 \left(\frac{\dot{m}''}{\rho\sqrt{g D_w}}\right)^{0.68} \tag{6}$$

$$1.5 < \frac{D_c}{D_w} \leq 2.0; \quad \frac{L}{D_w} = 34 \left(\frac{\dot{m}''}{\rho\sqrt{g D_w}}\right)^{0.58} \tag{7}$$

$$\frac{D_c}{D_w} > 2.0; \quad \frac{L}{D_w} = 60 \left(\frac{\dot{m}''}{\rho\sqrt{g D_w}}\right)^{0.76} \tag{8}$$

The absence of any independent effect of moisture is to be expected since M_f is the initial moisture content, most of which has evaporated from any given fuel element by the time the fire reaches it. However, the calculated burning rate, $\dot{m}''$, does depend(6) on M_f.

A further statistical test was then carried out to determine whether the indices and numerical constants of these equations in their logarithmic form were significantly different, i.e. whether the three equations were concurrent or if not concurrent, parallel to one another. This analysis suggested that the lines were parallel, but not concurrent, with a best value for the slope of 0.68; this is not significantly different from the theoretical value(3) of $\frac{2}{3}$ appropriate to tall flames (i.e. $L/D \gg 1.0$). The mean value of **A**, the numerical coefficient in equation (3), for each group was then recalculated giving the following equations:

$$\frac{D_c}{D_w} \leq 1.5; \quad \frac{L}{D_w} = 38 \left(\frac{\dot{m}''}{\rho\sqrt{g D_w}}\right)^{\frac{2}{3}} \tag{9}$$

$$1.5 < \frac{D_c}{D_w} \leq 2.0; \quad \frac{L}{D_w} = 42 \left(\frac{\dot{m}''}{\rho\sqrt{g D_w}}\right)^{\frac{2}{3}} \tag{10}$$

$$\frac{D_c}{D_w} > 2.0; \quad \frac{L}{D_w} = 46 \left(\frac{\dot{m}''}{\rho\sqrt{g D_w}}\right)^{\frac{2}{3}} \tag{11}$$

These equations are shown in fig 1. For the other four species of wood(5) the ratio D_c/D_w lies in the range 1.7 - 3.0 with a mean value of 2.4; these

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* Values of A were also calculated using flame heights measured from the base of the cribs instead of the top. The degree of correlation for each of the three groups showed no significant change and it was therefore decided in this report to take all flame heights from the top of the crib. These results do not however provide any evidence to support one particular position as the best for taking the flame origin in this kind of experiment.

results are shown in fig 2 expressed in the same parameters, and compared with equations (10) and (11); the values of L/D_W for these woods tend to be some 20 per cent lower than those for white fir for the same rate of burning.

2. Other Experimental Results - Non-spreading Fires

2.1. Cribs with a square base

In order to complete the comparison being made here of the effect of the shape of the fire area on the flame height the data for fires on a square base have been replotted with the flame height measured from the top of the crib. The data* obtained by Thomas, Webster and Raftery are shown in fig 3a and the best line of the above form with L varying as $\dot{m}''^{\frac{2}{3}}$ is

$$\frac{L}{D_W} = 43 \left(\frac{\dot{m}''}{\rho\sqrt{g\,D_W}}\right)^{\frac{2}{3}} \qquad \frac{D_c}{D_W} = 1 \qquad (12)$$

Similar experiments by Gross,[7] the results of which he was kind enough to make available prior to publication, were shown to be in agreement with the original correlation of flame length data[2]. He used cribs made from Douglas fir (Pseudotsuga taxifolia), Ash (Fraxinus excelsior), Balsa (Ochroma lagopus) and Mahogany (species unknown); it has been assumed that there is no difference between the species and the results recalculated accordingly (fig 3b)

$$\text{for } \frac{D_c}{D_W} = 1.0; \text{ they give } \frac{L}{D_W} = 47 \left(\frac{\dot{m}''}{\rho\sqrt{g\,D_W}}\right)^{\frac{2}{3}} \qquad (13)$$

The difference between the numerical constants in equations (12) and (13) may be partly, if not wholly, due to the difference between visual and photographic measurements of flame heights[2].

2.2. Cribs with rectangular base[5]

It has previously been pointed out that the results could be expected to approach a $\frac{2}{3}$ power law as L/D_W increased[3], the larger index found in equation (5) being attributed[3] to the low values of L/D_W in four of the experiments. These results have therefore been excluded from an analysis which assumed a value of $\frac{2}{3}$ for n. This, with L measured from the top of the crib, gives

$$\frac{L}{D_W} = 41 \left(\frac{\dot{m}''}{\rho\sqrt{g\,D_W}}\right)^{\frac{2}{3}} \qquad (14)$$

Equation (14) is compared with the experimental results in fig. 4; the four experimental points where $L/D_W \sim 1.0$, and the regression line obtained earlier[5], are also shown.

2.3. Cribs in enclosures

The results for fires in wooden cribs in enclosures[8] have been extended recently to compartments 2.4 m. (8 ft) cube. These results have also been recalculated assuming that the value of n is $\frac{2}{3}$, measuring the vertical flame height from the top of the crib and using D_W instead of the compartment width D'.

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* The species of wood was previously given as Spruce but is now known to have been Baltic Redwood (Pinus Sylvestris).

This leads to the relation

$$\frac{L}{D_W} = 36 \left(\frac{\dot{m}''}{\rho\sqrt{g\,D_W}}\right)^{\frac{2}{3}} \qquad (15)$$

for the range $1.0 < L/D_W < 4.0$

where $D_W = 0.8\,D'$.

Equation (15) is compared with the experimental results in fig. 5.

The height of a flame from a fire in an enclosure as used in equation (15), is not quite comparable with the height of a flame from cribs in the open. In the open, the flame length can be identified with the flame height, in an enclosure the real flame length is longer than the vertical flame height. Although the difference becomes less important when the flames are long, this is probably one reason why the value of A in equation (15) is less than in equations (9 - 14) although the value of A would be expected to increase with increasing size of D_C/D_W. Another is that the smallest compartment, 0.6 m cube, may be too small to be strictly comparable with full scale. Excluding these data increases the value of A.

2.4. Discussion

The variation of the numerical constant, A, with the shape of the burning zone, D_C/D_W, is shown in fig 6. It is clear from the analysis of Fons's results that there is a significant increase of flame height with the increasing departure from a square burning zone, but, when all the available experimental results are compared, the variation between the experiments carried out in different laboratories and by different groups in the same laboratory is greater than the variation with shape found by Fons. Part of the laboratory variation may be due to the different species used by the different investigators since Fons's own results show that flame heights are higher for cribs of white fir than for the other species. For these reasons it is sufficiently accurate for most practical purposes to take a mean value for A of 40, i.e.

$$\frac{L}{D_W} = 40 \left(\frac{\dot{m}''}{\rho\sqrt{g\,D_W}}\right)^{\frac{2}{3}} \qquad (16)$$

The flames may be treated as emerging from a long strip source, because if $\dot{m}''$ is written as $\dot{m}'/D_W$ in equation (9) to (16)

$$L = B\,(\dot{m}')^{\frac{2}{3}} \qquad (17)$$

where $\dot{m}'$ is the burning rate per unit length of fire front.

The best value of B is 340 in c.g.s. units when L is measured from the top of the crib (equation 17a) and 440 when L is taken from the base of the crib (equation 17b).

Equations (17a) and (17b) are compared in fig. 7 using Byram's value of 6500 B.t.u./lb. (3600 cal/g) for H. For low burning rates (100 mg $cm^{-1}s^{-1}$) equation (1) gives a value about 20 per cent lower than equation (17b) with the flame height measured from the base of the crib and about 7 per cent greater than equation (17a) with the flame height taken from the top. At higher burning rates (c.1000 mg $cm^{-1}s^{-1}$) the agreement is much closer with L taken from the top of the crib (about 30 per cent) than from the base (only to just within a factor 2).

In the course of using these data to estimate air entrainment for a particular application(3) a square fire was considered as a one sided strip fire of a length equal to its perimeter. It is interesting here to consider the relation between the flame heights for the two extreme shapes of the fire area, the strip and the square based fire. For the first for equal flame heights the fuel burning rate of a flame exposed to air on one side only is assumed to be one half of that of a two-sided flame; the flame heights for equal fuel burning rates are accordingly $2^{\frac{2}{3}} : 1$. If the square based fire has a perimeter PD, where P may be less than 4 because the boundaries of the flame zone are not vertical, then from the equation for a two sided strip fire

$$\frac{L}{D} = A \left(\frac{\dot{m}'}{\rho \sqrt{g D^3}} \right)^{\frac{2}{3}}$$

the equation for a square based fire is

$$\frac{L}{D} = 2^{\frac{2}{3}} A \left[\left(\frac{\dot{m}'' D}{P D} \right) \frac{1}{\rho \sqrt{g D}} \right]^{\frac{2}{3}}$$

$$= \left(\frac{2}{P} \right)^{\frac{2}{3}} A \left(\frac{\dot{m}''}{\rho \sqrt{g D}} \right)^{\frac{2}{3}}$$

Since the coefficient A changes only slightly with shape and for practical purposes it may be taken as constant. This is seen to be equivalent to taking a value for P of 2, that is, in the region where the $\frac{2}{3}$ power law applies, viz. $1 < L/D < 10$, a fire on a square base may be treated as producing flames with a mean value for the perimeter of 2 D.

CONCLUSIONS

Over a range of experimental conditions the flame height and depth of burning zone of wood fuels are related to the rate of burning by an equation of the form

$$\frac{L}{D_W} = A \left(\frac{\dot{m}''}{\rho \sqrt{g D_W}} \right)^n$$

The value of the index has been shown not to differ significantly from the theoretical value of $\frac{2}{3}$, if $L \gg D_W$, for which condition the equation reduces to

$$L = B \, (\dot{m}')^{\frac{2}{3}}$$

The values of A and B have been shown to be dependent upon the shape of the burning zone in a series of experiments on one species; there is also a significant difference between species. However, these differences are less than the experimental variation between experiments carried out by different laboratories and different groups within the same laboratory and it is sufficiently accurate to take a mean value for A of 40.

ACKNOWLEDGEMENT

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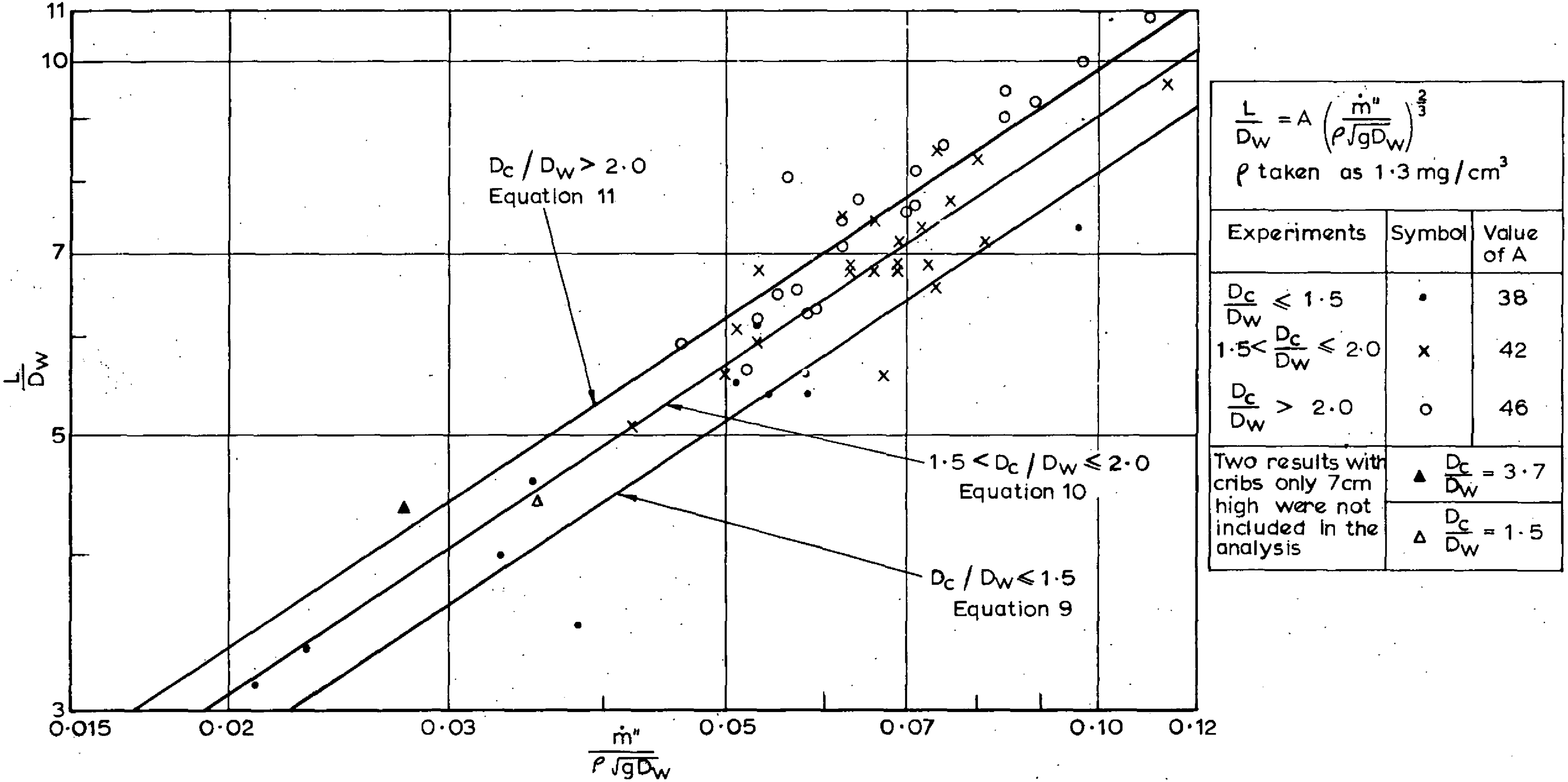
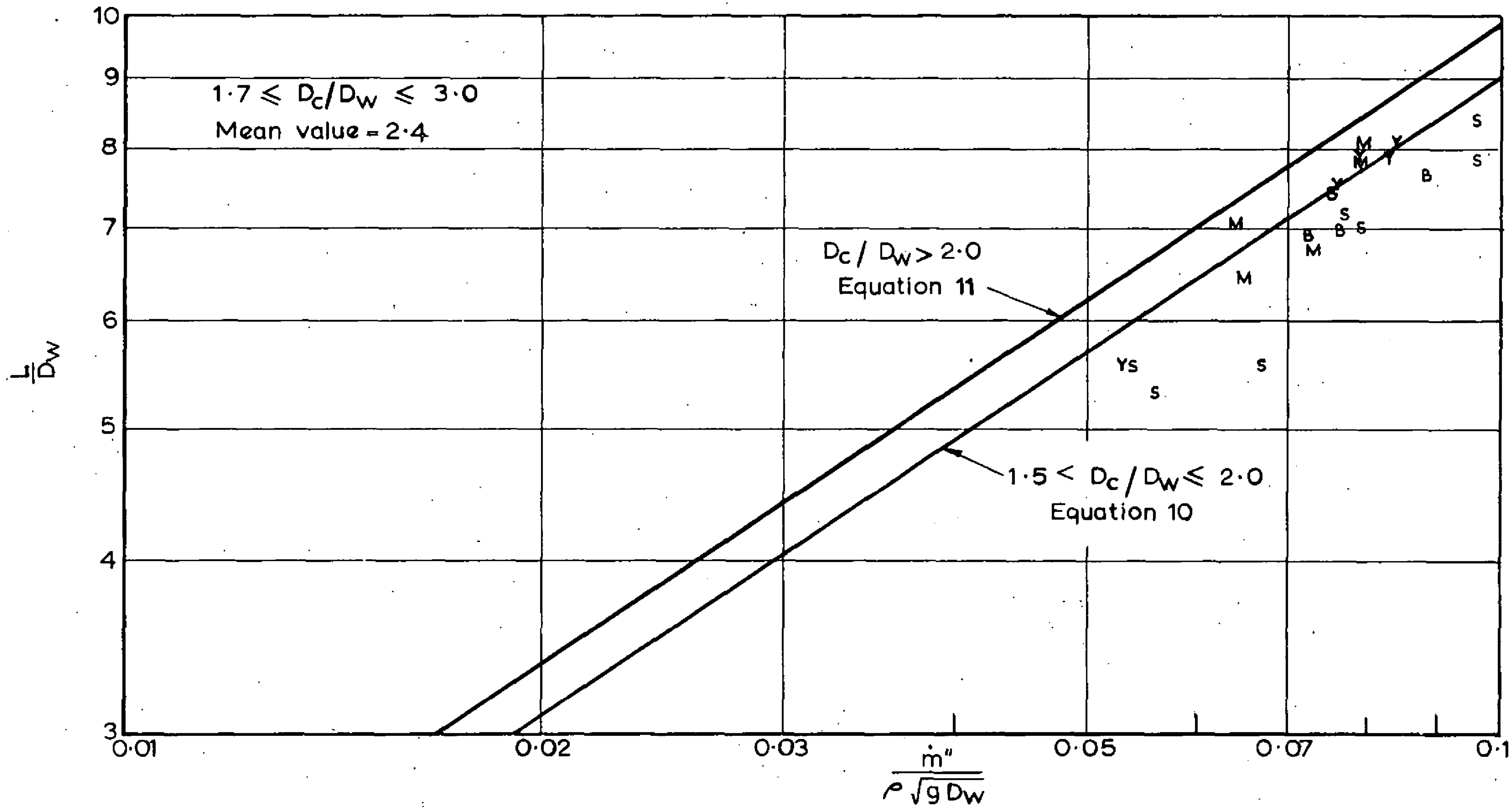


Results for cribs of white fir (Fons et al)

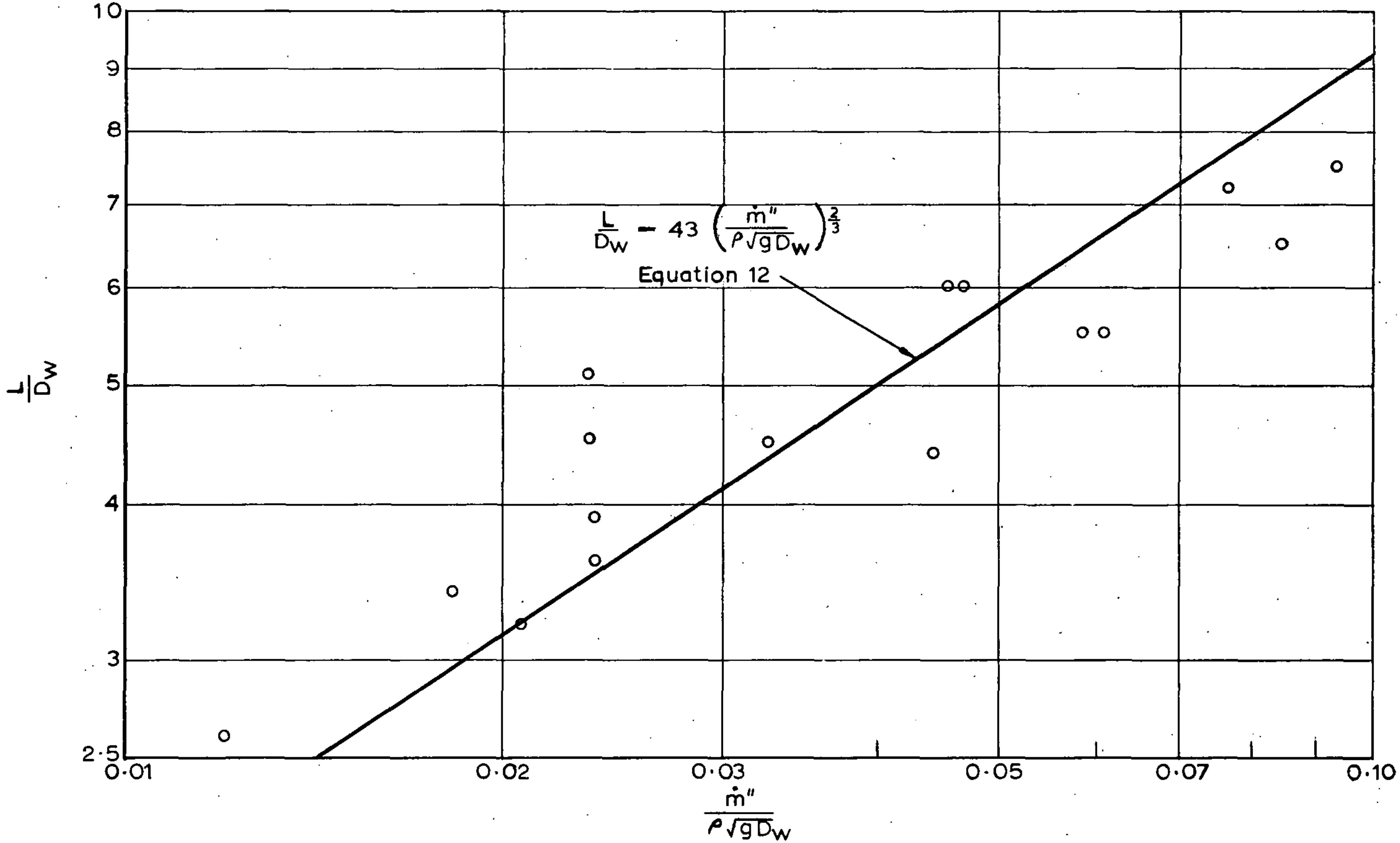
FIG.1. FLAME LENGTH AND BURNING RATE



M – Magnolia
B – Basswood
S – Sugar maple
Y – Longleaf pine

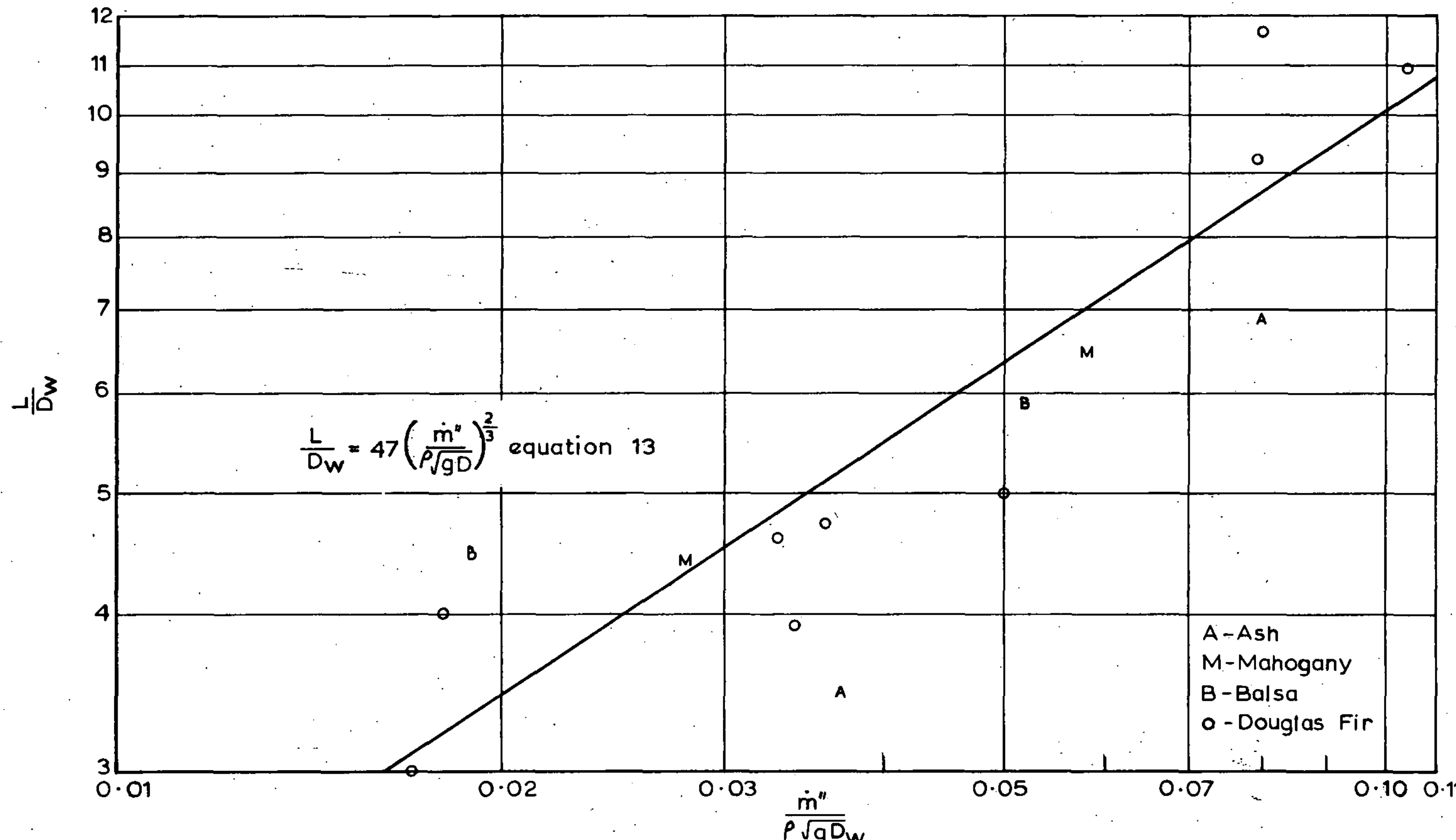
Results for cribs of different species (Fons et al)

FIG.2. FLAME LENGTH AND BURNING RATE



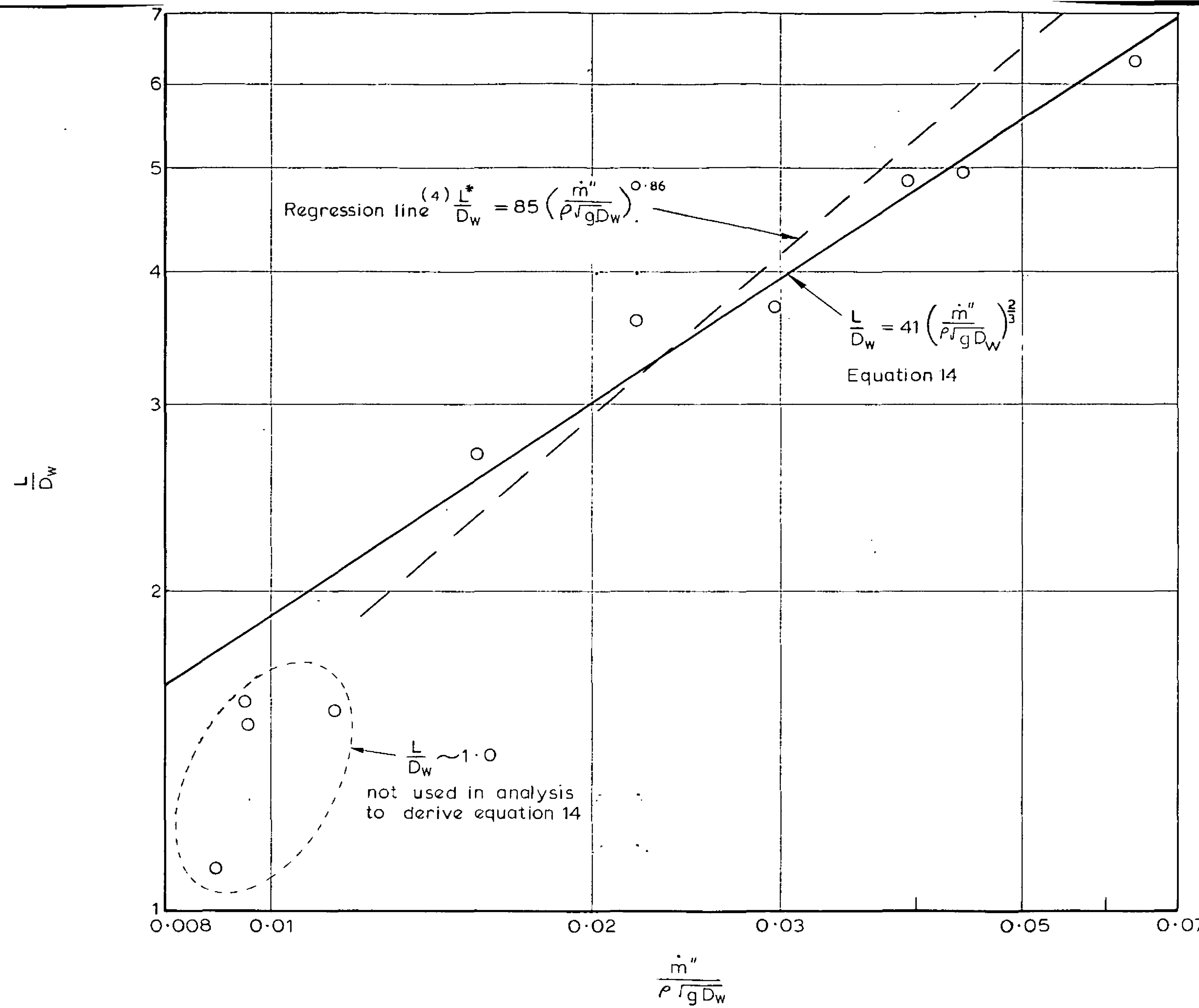
Thomas, Webster and Raftery's results — Square based cribs $D_c / D_W = 1 \cdot 0$

FIG.3a. FLAME LENGTH AND BURNING RATE



Gross' results – Cubical cribs $D_C / D_W = 1 \cdot 0$

FIG.3b. FLAME LENGTH AND BURNING RATE



Thomas, Pickard and Wraight's results $1.5 \leq D_c / D_w \leq 6.0$ ——— Rectangular based cribs

L^* — Flame length from centre of crib

FIG.4. FLAME LENGTH AND BURNING RATE

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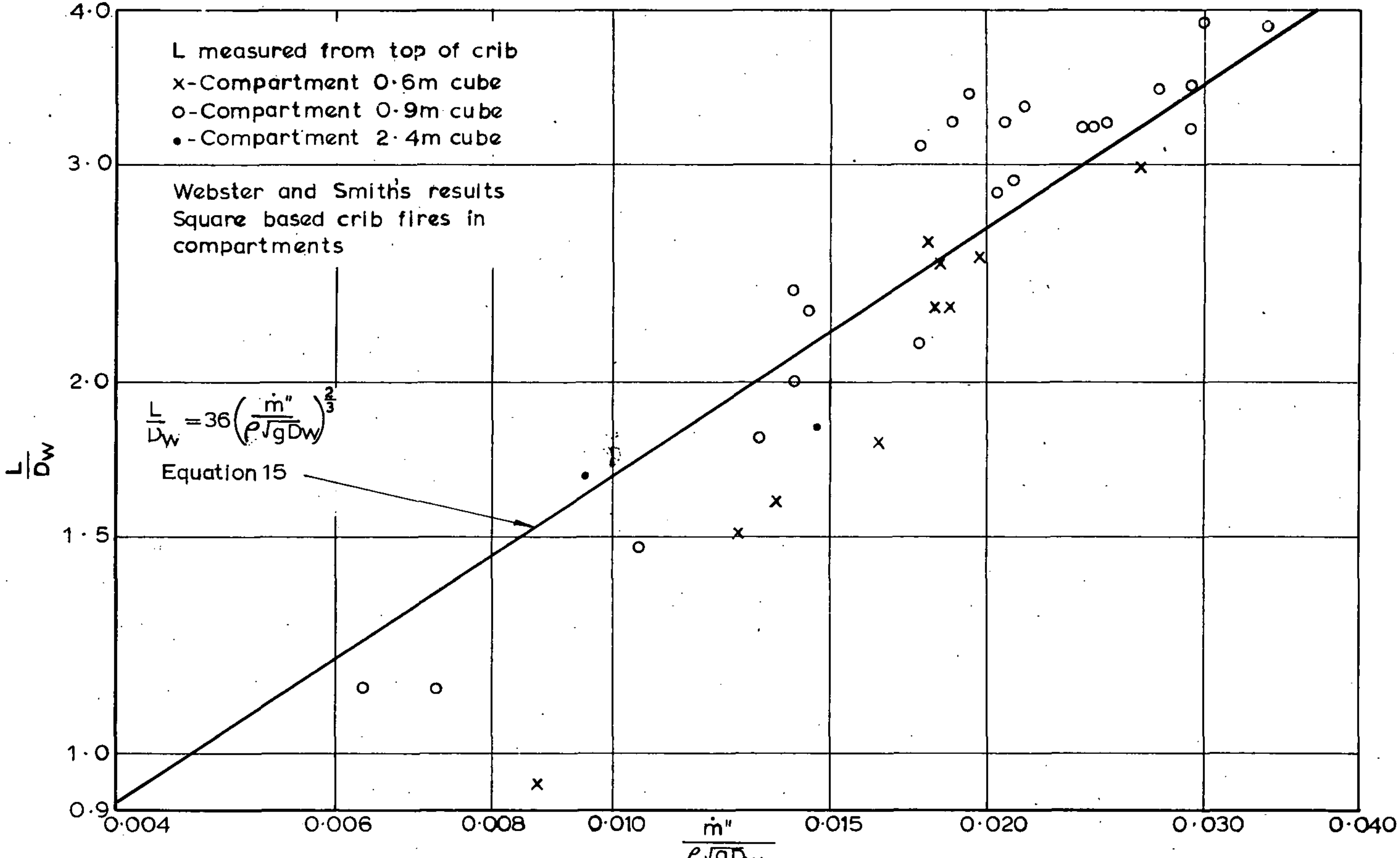
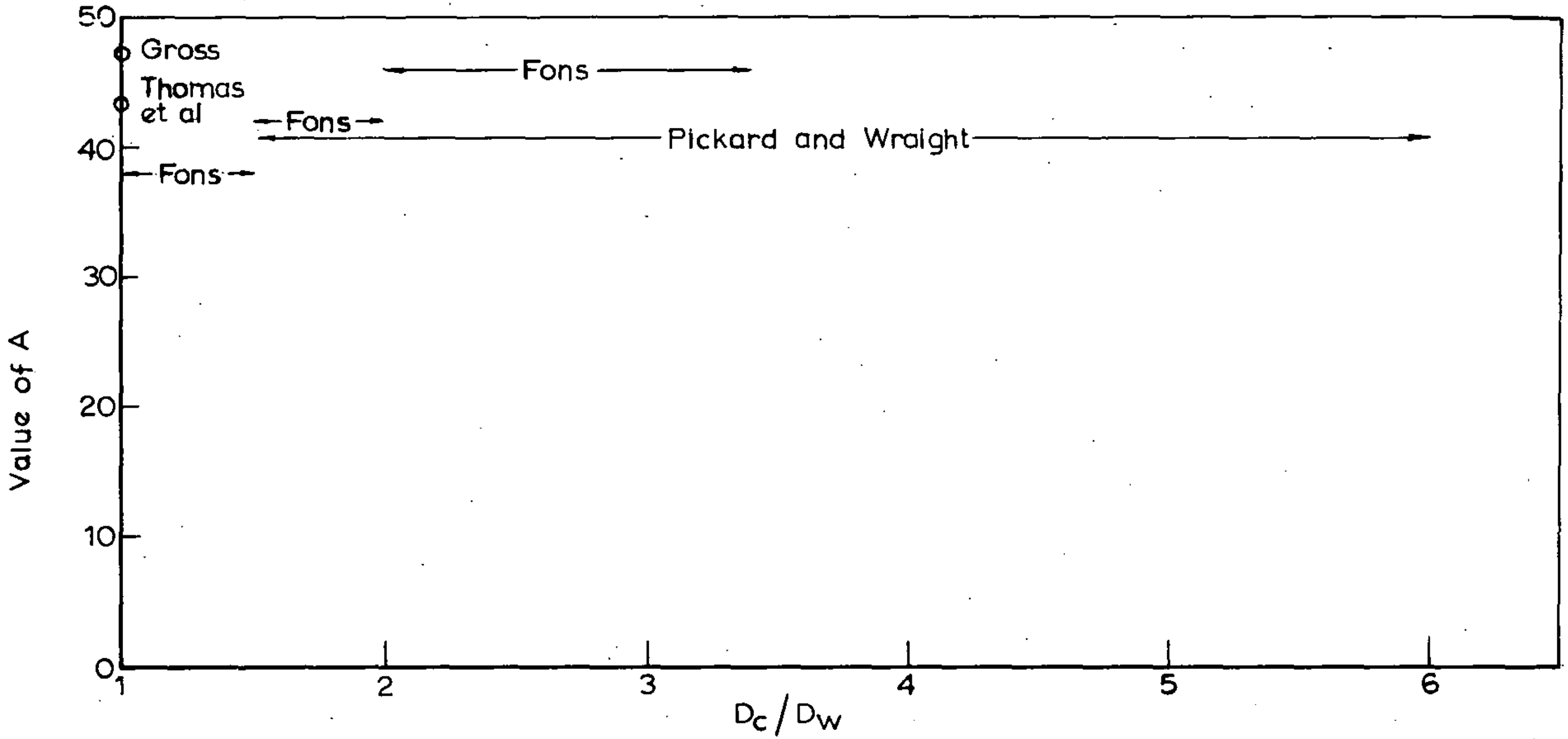


FIG.5. FLAME LENGTH AND BURNING RATE.



$$A = \frac{L / D_W}{\left(\frac{\dot{m}''}{\rho\sqrt{g D_W}}\right)^{\frac{2}{3}}}$$

FIG.6. VARIATION OF FLAME LENGTH WITH SHAPE OF BURNING ZONE

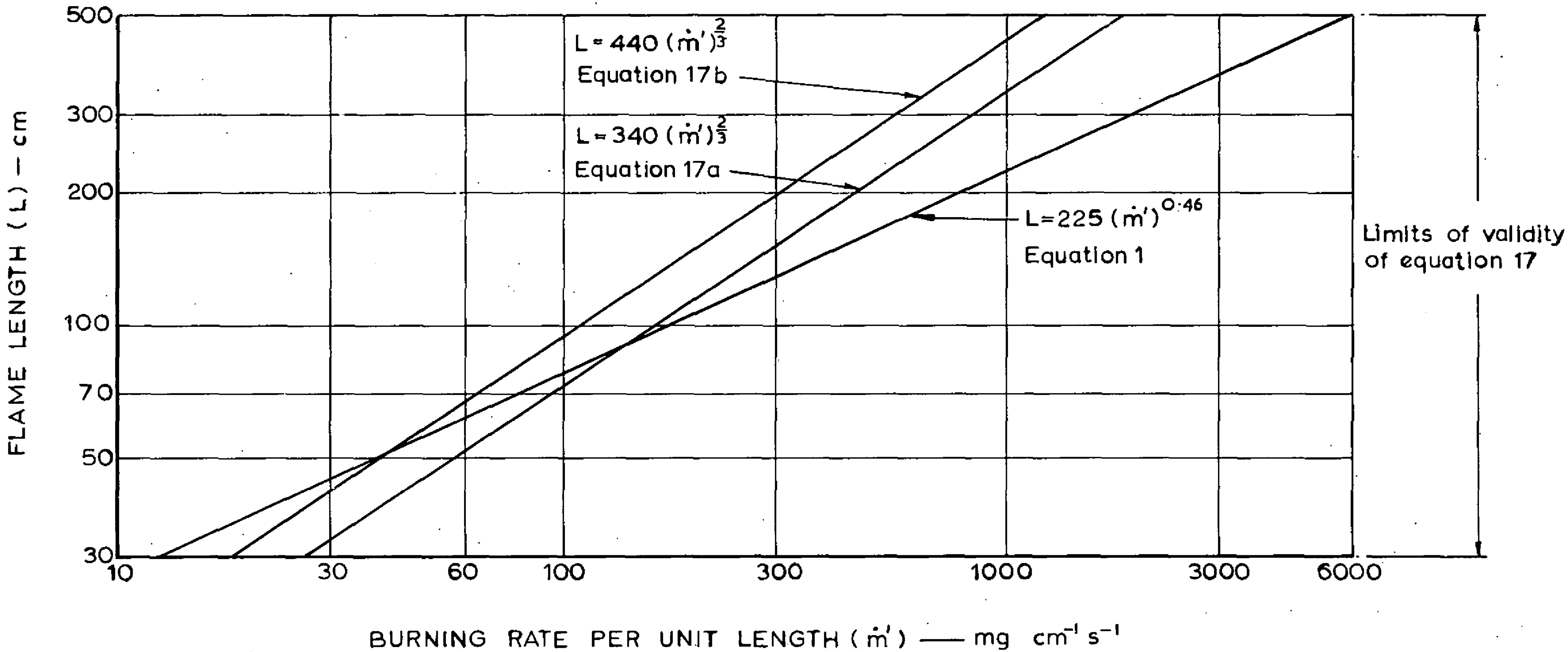


FIG.7. COMPARISON OF FORMULAE FOR FLAME LENGTH