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SOME ASPECTS OF THE GROWTH AND SPREAD OF FIRE IN THE OPEN

by

P. H. THOMAS

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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
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CORRIGENDA

Pages 3 and 4 In equations (1) and (2) and the equation at the bottom of p. 3 and the top of p. 4	$g(\rho_o - \rho_{fe})$ should be $g\rho_{fe}(\rho_o - \rho_{fe})$
Page 6 line 3	(17) should be (7) and $5.3\left(H\dot{m}'_f\right)^{0.45}$ should be $5.2\left(H\dot{m}'_f\right)^{0.46}$

Table (1) should be

Plot No.	Measured flame length cm	$\dot{m}'_f$ g $cm^{-1} s^{-1}$ calculated from equation (7)	$\dot{m}'_f$ g $cm^{-1} s^{-1}$ calculated from equation (3)
III - 3	71	0.068	0.074
I - 2	65	0.057	0.065
II - 2	80	0.092	0.090
III - 2	58	0.046	0.056

Page 8 equation (8)	$\left(\frac{\dot{m}_f'^2}{\rho_o^2 g D}\right)^{0.43}$ should be $\left(\frac{\dot{m}_f'^2}{\rho_o^2 g D^3}\right)^{0.43}$
Page 9 equation (11)	-0.67 should be -0.69
Page 13 bottom of page	$\epsilon = \frac{1}{1+\sigma\lambda}$ should be $\epsilon = \frac{\sigma}{1+\sigma\lambda}$
Page 16	Emmons(23) should be Emmons(24)

F.R. Note No.552.

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SUMMARY

The paper describes some recent work on the growth and spread of fire in the open.

The importance of heat transfer from the flames has led to a study of the factors determining flame size as a result of which the lengths of flames from laboratory fires burning wood have been related to the size and rate of burning of the fuel bed by formulae derived from a simplified dimensional analysis. The effects on the length and orientation of flames of a wind blowing across a long fuel bed are also described. Comparisons made with data from some experimental fires with flames up to an order of magnitude larger are reasonably satisfactory.

The results of preliminary experiments to assess the distance at which separate flames merge together and other published data are shown to be in approximate agreement with a simple theory.

Some studies of fire spread in continuous beds of fuel are being made using long cribs of wood sticks, so far mainly in still air. The results of these experiments covering a range of fuel bed conditions can largely be accounted for by the radiant heat transfer from the burning zone through the fuel bed.

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Introduction

This paper reviews a number of the experimental and theoretical studies that have been made of various aspects of ignition and fire spread in recent years at the Fire Research Station, Boreham Wood. Although it is sometimes possible to make use of actual fires in a quantitive manner to augment or corroborate laboratory findings, the main emphasis in this paper is on laboratory studies, in particular of the size of flames and the conditions under which separate flames merge together.

Ignition

So long as fuel and oxygen are readily available, fires spread when the heat fed back from the fire itself to the fuel exceeds that required to produce inflammable vapours from the solid fuel. The problem of ignition by radiation has been extensively discussed elsewhere[1][2][3], and although there are a number of problems remaining one can say, by and large, that provided the ignition times are not too small, say, less than one-tenth of a second, nor too long, say, greater than ten seconds, it is possible to regard a material as becoming ignited spontaneously when the temperature of its surface when calculated as that of an inert body, exceeds, according to Simms (1960)[1], about 525°C. Once ignition has occurred, the fire feeds back heat to the fuel.

It does not always follow that once ignited a material will continue to burn because heat is conducted into the cold body of the solid behind the surface layers (at a rate which depends on the exposure time) as well as being convected and radiated away from the exposed surface. Very roughly, one might regard the condition for sustained burning as the attainment of a given <u>mean</u> temperature and for transient ignition, the attainment of a given <u>surface</u> temperature. Owing, however, to the complexities of the arrangment of materials, corners, cavities and edges, the minimum conditions for sustaining burning outside the laboratory are not necessarily the same as in a conventional laboratory experiment and it is probably here that there remains one of the largest uncertainties regarding the likelihood of ignition by a given heat dose. When the fire has become large, the transfer of heat from the various parts of the fire to the unburnt fuel will be decisive in determining the rate at which the fire spreads. One of these sources of heating will be radiation from the flame. This is why some estimate must be made of the size of the flame from a fire and how it varies with scale, the fuel supply and the wind. This paper will summarize the results that are now available on flame size, together with some results on flame merging. Some account will also be given of recent work on fire spread in continuous media in still air, where the main mechanism of heat transfer is radiation through the fuel bed.

The size of the flames

A scaling law for flame size has already been derived[4][5] and what follows is a simplified but rather more direct derivation. Consider the system shown in Fig.1 where we have idealised the flame as a region where the density is uniform and lower than that of the surrounding air and where the air entering the upward column comes in from the sides. In general, the velocities with which fuel leaves the surface is so small compared with the velocities produced by the acceleration arising from the buoyancy that it is possible to neglect the initial momentum although the derivation can readily be extended to take it into account.

The mean force acting upwards may, therefore, be described by the expression

$$B = g(\rho_o - \rho_{fl})\, D^3 \, f_1\left(\frac{L}{D}\right)$$

where f_1 is the shape factor for the volume of the flame
D is the diameter of the fire
L is the mean flame height
ρ_o is the density of the surrounding air
ρ_{fl} is the density of the gases in the flame zone
and g is the acceleration due to gravity.

This upward force must equal the rate of change of momentum. The total mass flow is $\dot{m}_a + \dot{m}_f$ where $\dot{m}_a$ is the total air flow and $\dot{m}_f$ the total fuel flow, i.e. burning rate. The mean velocity will be this mass flow divided by an effective cross-sectional area, which may be expressed as

$$\frac{\dot{m}_a + \dot{m}_f}{\rho_{fl}\, D^2} \cdot f_2\left(\frac{L}{D}\right)$$

where f_2 is another shape factor. The rate of change of momentum can then be expressed as

$$F_m = \frac{(\dot{m}_a + \dot{m}_f)^2}{\rho_{fl}\, D^2} \cdot f_2\left(\frac{L}{D}\right)$$

Equating these two expressions gives the ratio of the flame height to the size of the base as a function of a parameter containing the burning rate and the air flow viz.

$$\frac{L}{D} = F\left(\frac{(\dot{m}_a + \dot{m}_f)^2}{g\rho_{fl}(\rho_o - \rho_{fl})\, D^5}\right) \qquad (1)$$

There is still some uncertainty as to what is the appropriate criterion for the end of the flame but provided one can approximately associate the end of the visible zone with a particular ratio of the air flow to the fuel flow for any given fuel, the above expression may be re-written as

$$\frac{L}{D} = F_2\left(\frac{\dot{m}_f^{\,2}}{g\rho_{fl}(\rho_o - \rho_{fl})\, D^5}\right) \qquad (2)$$

If the momentum at the fuel surface is significant the rate of change of momentum is

$$F_m = \frac{(\dot{m}_a + \dot{m}_a)^2}{\rho_{fl}\, D^2} \cdot f_2\left(\frac{L}{D}\right) - \frac{m_f^{\,2}}{\rho_f\, D^2} \cdot f_3$$

where f_3 is a shape factor for the base area ($\frac{\pi}{4}$ for a circular base) and where ρ_f is the density of the fuel as it enters the gaseous phase.

The variable part of equations (1) and (2) is unaltered for any given fuel.

Over a wide range of conditions the densities may be taken as constant for any given fuel so that the variable part of the term on the right-hand side is m_f^2/D^5 and Figs (2) and (3) show some experimental results(5)(6)(7) where flame heights have been correlated in this way. In the absence of detailed information on the densities of the gases in the flame, the density of air has been used in order to reduce the variables to dimensionless units.

For fires of different size it is more convenient to consider the burning rate per unit base area $\dot{m}_f''$ instead of the total burning rate, so that equation (2) would be re-written as

$$\frac{L}{D} = F_3\left(\frac{\dot{m}_f''^{\,2}}{g\rho_{fl}(\rho_o - \rho_{fl})D}\right)$$

Similarly, in terms of $\dot{m}_f'$ the burning rate per unit length of fire front

$$\frac{L}{D} = F_4\left(\frac{\dot{m}_f'^2}{g\beta(\rho_o - \rho_{fl})D^3}\right)$$

The burning rate per unit base area will depend on the arrangment of the fuel, but should not vary markedly with scale provided the general behaviour of the fires are similar, i.e. we would expect it to differ between small laminar fires, ($<$ 30 cm dia.) larger turbulent fires and between certain mass fires in which a rotating convection column causes increased radiation and convective transfer to the fuel bed. However, in the absence of such a fire whirl, the results that have been obtained suggest that the ratio L/D decreases as D becomes larger. The turbulence of the fire may at some point prevent there being a continuous flame envelope so that the instantaneous flame pattern consists essentially of several separate fires with no sharply defined boundaries. If each is regarded as behaving as if their characteristic size was much smaller than the overall size of the fire, the absolute flame size would be smaller than predicted by extrapolating from small laboratory size fires. Such fires will have certain similarities to the convection of heat from large areas of the earth surface. However, the larger the fire area, the more susceptible is the convection column to rotate as a result of the rotation of the earth. The conditions necessary for the presence of a stable fire whirl are at present being studied theoretically and experimentally in the United States. Here we discuss only the results of a laboratory study which probably apply to flames where although small by comparison with fire storms at least include flames from individual buildings.

It is sometimes convenient to consider the perimeter of a flame as part of a long front. For $L/D > 2$ the experimental results correlated in Fig.(2) follow the equation

$$L = 400\,\dot{m}_f'^{\frac{2}{3}} \tag{3}$$

where L is in cm and is measured from the base of the fuel bed and $\dot{m}_f'$ is in gm cm^{-1} s^{-1}. (In Fig.(2) the suffix w denotes wood as the fuel).

From this we deduce an expression for flames into which air entered only on one side. As an approximation Yokoi[8] Putman[9] and Thomas[10] have accordingly assumed that for the same height the burning rate in a two sided flame was twice that in a one sided flame and have taken the height of a one sided flame as

$$L = 400\,(2\,\dot{m}_f')^{\frac{2}{3}} = 640\,\dot{m}_f'^{\frac{2}{3}}$$

If a square based fire of size D were considered as a one-sided line fire of length ϕD we would obtain the expression

$$L = 640 \left(\frac{\dot{m}_f'' D}{\phi} \right)^{\frac{2}{3}} \qquad (4)$$

where $\dot{m}_f''$ is in gm cm^{-2} s^{-1} and L and D in cm.

The equation for radially symmetrical or square based fires given by Thomas et al[5] for the data in Fig.(3) where $2 < L/D < 10$ is

$$\frac{L}{D} = 4.4 \left(10^6 \ \frac{\dot{m}_f^2}{D^5} \right)^{0.31} \qquad (5)$$

where $\dot{m}_f$ is the total rate of weight loss in g/s. For the range of the values of L/D in these experiments an equation of the $\frac{2}{3}$ power in $\dot{m}_f$ in which the constant is 420 can be used as an approximation. The results match equation (4) if ϕ is taken as 1.9, about half the value of 4 if the effective flame perimeter was the base perimeter. With ϕ equal to 4 the constant in equation (4) is 253 or 40% less than the value of 420. This suggests that, to a first approximation irregular shaped fires in which $2 < L/D < 10$) can be described by

$$L = 850 \left(\frac{\dot{m}_f}{P} \right)^{\frac{2}{3}} \pm 30\% \qquad (6)$$

where P is the perimeter of the fire base.

The results in Fig.(2) show that for flames rising vertically from long strips the value of L/D at low values of L/D falls below that given by the $\frac{2}{3}$ power law given by equation (3).

Equations of this kind are probably sufficiently accurate to describe approximately the mean height of the flame. Despite the large fluctuations that there are in any real fire, it is the mean size of the flame which will determine the heat transfer by radiation to the unburnt material, since the time constant of heating in a spreading fire is much larger than the period of oscillation of a flame. Few comparisons of large scale fires are possible; some data from large fires and field trails are discussed below.

Comparisons with Field Data

1. An interesting comparison with small scale field data is available from the work described by Van Wagner[11] in some small fires on plots of brush. Van Wagner reports some burning rates calculated from observations of flame

length using an empirical formula given by Byram (12). This formula, translated into c.g.s. units, is

$$L = 5.3 \ (H \ \dot{m}_f')^{0.45} \qquad (17)$$

where H is the heat release in calories per gm of fuel. Byram obtained this equation taking H as 6500 Bt.u/lb i.e. 3600 cal/s and it is presumably based empirically on a collection of field data. From the burning rates tabulated by Van Wagner it is a simple matter to recalculate the flame lengths he measured and to estimate burning rates from equation (3). The comparisons are given in Table 1 where it is seen that the correlation based on the laboratory data is, for this range, in good agreement with the results of empirical correlations of field data.

TABLE 1

Field data by Van Wagner[11]

recalculated i.e. measured L - cm	Plot No.	~~Measured flame length - cm~~	$\dot{m}_f'$ - g cm^{-1} s^{-1} calculated from equation (7)	$\dot{m}_f'$ - g cm^{-1} s^{-1} calculated from equation (3)
66	III-3	~~210~~	0.068	0.067
60	I-2	~~160~~	0.057	0.058
75	II-2	~~110~~	0.092	0.081
54	III-2	~~100~~	0.046	0.051

2. In a recent fire test on a lifeboat[13] the experimental fire covered an area of approximately 17,000 sq.ft and the fuel consisted of 6,000 Imp.gal of kerosene and 30 Imp.gal of petrol. The fire spread over the surface for $2\frac{1}{2}$ min and burnt as a fully developed fire for about 5 min. Once it began to subside, water spray was applied, and the fire was virtually extinguished in a further $2\frac{1}{2}$ min. If it is assumed that the density of the fuel was 0.8, that the maximum rate of burning was equivalent to burning all the fuel in the time $7\frac{1}{2}$ min and that the fire area was approximately square, equation (5) for wood fires on a square base gives $L/D = 0.7$, i.e. the calculated value of L is about 92 ft. Equation (6) gives a lower estimate of about 60 ft. If it is assumed that the flame height is only dependent on the heat release or the air requirements of the fuel, these figures must be increased to allow for the difference between wood volatiles

and kerosene. The ratio of the two values of heat release is approximately $3\frac{1}{2}$, so that the first estimate of flame height is increased by a factor of $3.5^{0.61}$, i.e. from 92 to 200 ft and the second by $3.5^{\frac{2}{3}}$, i.e. from 60 to 128 ft. No measurements were made of flame height but in the report it is said "that the flames reached a height of order of 250 ft" and in view of this being, with little doubt, a maximum figure, while the calculated figure is a mean value for the continuous flame envelope during any fluctuations, the calculations can be regarded as fairly satisfactory.

3. In a large experimental fire at Trensacq, France, in 1955, 803 acres of waste heathland was burnt[14][15]. The vegetation had an average value of 1.7 kg/m^2 and an average height of 1 m, and it is stated in the report "that the necessary time for a fire lighted in the direction of the wind to reach the opposite limit may be evaluated at 35 min." From a plan of the area this figure would seem to correspond to an estimated average speed of about 1.1 m/s, i.e. a value of $\dot{m}_f'$ of 19 g cm^{-1} s^{-1}. Equation (1) gives a calculated flame height of 29 m, which is about $2\frac{1}{2}$ times the observed height of 11-12 m. 29 m is very close to the value calculated on the assumption that the whole area was burning at once. This was inferred by the author from reference (15) but which the detailed report[14] shows was not the case. It is shown below that this discrepancy of $2\frac{1}{2}$ times may well be attributable to the effect of the wind which was reported as being 5-8 m/s.

The effect of wind on flames

A knowledge of the effect of wind on a flame is important not only for fires that occur in the presence of wind, but also for large fires in still air where there is a large air flow induced radially towards the centre of the big fire and behaviour of a fire at its periphery can as a first approximation can be considered as a line front with a wind blowing on it.

The effect of the wind on the flames may involve both the scale and intensity of the turbulence generated by the friction with the ground upwind prior to its interaction with the flame and also that generated by thermal instability as the air flows over the source of heat.

Some experiments have been made at Boreham Wood in a wind produced by a fan drawing air over some wood cribs[16] weighed continuously while being burnt. The arrangement was as shown diagrammatically in Fig.(4). Various wind speeds and widths of burning zone were employed and different designs of crib were used to give different burning rates for any given length of crib D in the direction of the wind.

Neglecting the resistance to flow of the fuel bed leads to overestimating the fraction of the air which actually enters the crib through the openings between the sticks. For all the experiments the average fraction was less than about 12 per cent and the results can be used to give an approximate measure of the effect of wind on flames generally. The results have been correlated in terms of the same dimensionless groups as have been found appropriate for still air with the addition of a group which is essentially a Froude number i.e. U^2/gD constructed from the independent variables U and D, though physically, of course, the parameter g is associated with a vertical dimension i.e. the flame height as deflected and the difference in density. The difference in density has been omitted for the same reasons as in still air and the vertical dimension is a dependent variable. The scale of the turbulence l upstream of the fires would be constant for all fires, independent of the fire and its intensity would be related to U. If these upstream conditions were important, a ratio l/D would be relevant. i.e. the parameter D should appear on its own in the correlation. However, the data obtained so far in this range of experimental conditions can be reasonably correlated in terms of the above dimensionless groups without a dimensional factor D and accordingly the results have been expressed by

$$\frac{L}{D} = 70 \left(\frac{\dot{m}_f'^2}{\rho_o^2 \, gD}\right)^{0.43} \left(\frac{U^2}{gD}\right)^{-0.11} \tag{8}$$

$$H = 56 \left(\frac{\dot{m}_f'}{\rho_o \, U}\right) \left(\frac{U^2}{gD}\right)^{0.13} \tag{9}$$

relations which are shown in Fig.(5) and (6).

The equations may be rearranged in terms of

$$S^* = \frac{gS}{\left(g \frac{\dot{m}_f'}{\rho_o}\right)^{\frac{2}{3}}} \quad \text{and} \quad U^* = \frac{U}{\left(g \frac{\dot{m}_f'}{\rho_o}\right)^{\frac{1}{3}}}$$

where S stands for any of the dimensions L, D or H.

The term $\left(g \frac{\dot{m}_f'}{\rho_o}\right)^{\frac{1}{3}}$ is closely related to the rising velocity characteristic of line plumes $\left(\frac{g \dot{Q}'}{\rho_o cT}\right)^{\frac{1}{3}}$ where $\dot{Q}'$ is the rate of heat release per unit length of front, c is the specific heat of the gases and T the absolute temperature of the surroundings. In the absence of data for different fuels and adequate data for the effective heat release and the proportion lost by radiation and a properly defined criterion to determine the end of the visible flame, no attempt is being made here to translate the above data from mass burning rates to heat release rates. Byram[12] has already pointed out the significance of $U/\left(\frac{g\dot{Q}'}{\rho_o cT}\right)^{1/3}$ in defining the extent of the effect of wind on the flames from line fires.

If the burning zone length D is important only as a measure of the fuel flow and the above results are interpreted as pertaining to a line rather than a strip front, L and H should be expressable in terms of U* without D*. The data of equations (8) and (9) have therefore been re-arranged as

$$L^* = 70 \quad U^{*-0.21} \quad D^{*-0.19} \tag{10}$$

and
$$H^* = 38 \quad U^{*-0.67} \tag{11}$$

and it may be noted that in these experiments, the term D cannot strictly be omitted from the equations for flame length, but in equation (11) for H this term is not statistically significant and has been dropped so that H is in a form which is applicable to lines and strips in the range covered by these experiments ($5 < D^* < 25$). Equation (10) is an empirical power law and cannot be extrapolated to zero U or zero D. For still air and small D

$$L^* = H^* = 47$$

The still air equation for H* can be used up to U* equal to about 1 and the wind equation for $U^* > 1$. For L* the demarkation may be made higher $U^* \sim 3$. As defined in Fig.(4) H is the maximum height reached by the flame. If instead a height H' is calculated from the deflection and the flame length L the resulting correlation of the experimental data, gives a simple result

$$H' U/\dot{m}_f' = 42 \times 10^3 \quad cm^3/g \tag{12}$$

Inserting 1.3×10^{-3} g cm^{-3} for the density of air, this ratio becomes the ratio of air in a layer of depth H' to the fuel emitted. This ratio is 55* an order of magnitude larger than the stoichiometric requirement, and provides a suitable point at which to discuss the mixing of air with flammable gases in a flame.

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*The combined effect of the air flow into the crib and the definition of H' from the centre of the crib is probably less than 10 per cent.

The effect of the wind on the flames in the Trensacq fire may be estimated assuming the advancing fire can be regarded as a fire front. Inserting $\dot{m}'_f = 19 \text{ g cm}^{-1} \text{ s}^{-1}$, $\rho_0 = 1.3 \times 10^{-3} \text{ g cm}^{-3}$, $g = 981 \text{ cm/s}^2$ and U a mean value of 650 cm/s for the range 5-8 cm/s we have $H = 1150$ cm from equation (9), which agrees closely with the reported values of 11-12 m. It is not of course certain to what extent the fire can be regarded as a line fire but the correlations for H are even less sensitive to this restriction than are those for L.

Entrainment of air into flames

Following the work of Taylor(17) Taylor, Morton and Turner(18) it has become customary to discuss the flow in jets and plumes and other free turbulent systems in terms of an entrainment constant expressing the ratio of a velocity of flow in terms of an entrainment constant expressing the ratio of a velocity of flow V_e induced towards the flame and entrained into it, to the local velocity of the main turbulent stream, suitably defined, W. There is some uncertainty as to the effect of large temperature differences between the stream and its surroundings on this ratio, but it is reasonable to assume that since the process of mixing is governed by inertia forces the proportionality should be between the momenta of the two streams, i.e.

$$\rho_0 V_e^2 = E^2 \rho_{fl} W^2 \qquad (13i)$$

where E is the entrainment constant.

As yet there is no data available for the vertical velocity of the gases in a flame, though there is some information about the speed at which the visible flame tip rises during an oscillation, and making use of this to provide an estimate of the average vertical velocity $\overline{W}$ one can employ the above expression for entrainment and the value found experimentally for E in low temperature plumes (viz. E = 0.16) to estimate the entrainment into flames. In the case of flame on a wide long front, no assumption need to be made regarding the flame boundary and the following equations have been used (9)

$$\overline{Ve} = 0.16\overline{W} \qquad (13ii)$$

$$\overline{W} = \tfrac{2}{3} W_{tip} \qquad (13iii)$$

$$W_{tip} = 0.51 \left(\frac{gL\,\theta_{fl}}{T_{fl}}\right)^{\frac{1}{2}} \qquad (13iv)$$

where W_{tip} is the mean vertical velocity of the flame tip at a height L. The bar denotes an average value over the flame height and θ_{fl} is the temperature rise in the flame zone of absolute temperature T_{fl}. From these equations

$$\overline{V_e} \doteq 0.054 \left(\frac{g\,L\,\theta_{fl}}{T_o}\right)^{\frac{1}{2}} \tag{14}$$

In a radially symmetrical flame it is necessary to define a boundary across which entrainment occurs because the flow outside the flame is not constant at differing radial distances. Taking the boundary as a cylindrical zone of diameter equal to the base of the fire gives values for the air fuel ratio of the order 60-80. This is only a little larger than was found from equation (12); 60-80 is the range found using H given by equation (11) instead of H', (See Fig.(6)). This ratio corresponds to a mean flame tip temperature of about 300-400°C. Most of the air drawn towards these fires in fact rises up with combustion products around the flame without ever taking part in the combustion process.

The concept of entrainment is a flexible one and this is an advantage which outweighs some of its weaknesses, but information is still required on the vertical velocities within the flame zone and a proper criterion for the end of the flame is needed before a theory of flames from free burning fires can be said to be established.

Merging of flames

When two flames lean towards each other the radiation falling on unburnt fuel between them is more than twice the sum from one fire acting alone, so that the rate of spread of the fire through this fuel is increased. In order to discuss fluid flow problems of merging, it is necessary to have as simple a description for a single fire and in what follows, use will be made of the simplified theory of entrainment to estimate the separation at which two flames from nearby fires merge together. Consider two rectangular burners of length D and width W separated by distance S as in Fig.(7A). Air that normally is entrained on the side nearer the adjacent fire has to enter the region between the two fires along the channel between them. Since the process of entrainment is caused by eddies produced by the turbulent, rising motion of the burning gases, it is assumed that the flow into the flame is unaltered by the small change in pressure, or by the leaning of the flame from the vertical. Hence, if V_e is the entrainment velocity, the velocity of the gases into the central channel when the flames just merge leaving an approximately triangular section, is $2\ V_e\ W/S$ and the pressure drop across the flame is

$$\Delta p = \frac{\rho_o V_e^2}{2g} \left(\frac{4W^2}{S^2} - 1 \right) \tag{15}$$

so that the horizontal thrust is

$$T = \frac{\rho_o WL V_e^2}{2g} \left(\frac{4W^2}{S^2} - 1 \right) \tag{16}$$

The vertical force acting on the flame is the buoyancy.

$$B = (\rho_o - \rho_{fl})\ V = \rho_o \left(\frac{\theta_{fl}}{T_{fl}} \right) V \tag{17}$$

where V is the effective flame volume and the deflection from the vertical is therefore given by their ratio, i.e.

$$\frac{T}{B} = \frac{S}{2L} = \frac{W\ L\ V_e^2}{2g} \left(\frac{4W^2}{S^2} - 1 \right) \frac{T_{fl}}{V.\theta_{fl}} \tag{18}$$

V_e is calculated from equation (14) and the volume V is taken as D.W.L. so that

$$\frac{L}{D} = 9.3 \sqrt{\frac{S^3}{W^2 D\ (1 - S^2/4W^2)}} \tag{19}$$

When $S \ll W$ as is usually the case when L/D is, say, of order 1-10 the equation for the critical separation distance S_c is given by

$$S_c = 0.23\ \left(DW^2\right)^{\frac{1}{3}} \left(\frac{L}{D}\right)^{\frac{2}{3}} \tag{20}$$

L is an indirect measure of the burning rate.

Some experimental data obtained by my colleagues Baldwin and Wraight[19] using burners 1 ft x 1 ft or 1 ft x 2 ft in size and burning town gas are shown in Fig.(8). Some of the deviation of the experimental points from the line for small flames is probably associated with the presence of a large laminar flow region. Also burning did not take place over the whole base area with low gas flows.

Putman and Speich[20] have also presented data on the ratio of the height from a group of flames to the height of a single flame for a range of values S/L. They used burners of small diameter (0.371 in) and the value of L/D was sufficiently large for the value of D not to influence the behaviour. S/L would then be constant instead of increasing as L/D decreased.

Their result has been plotted allowing for a correction for the thrust of the fuel flow leaving the burner.

Putman & Speich also performed experiments with two sets of seven burners, each set behaving as one fire. The ratio of the flame height for the pair of sets to the flame height from one set is given in terms of the dimensionless separation and it varies from 1.0 for complete separation to 1.41 for fully merged flames. For presenting the data in this report a value of 1.2 has been taken for the onset of merging. The theory can be adapted to four burners placed at the corners of the square and experimental results for this sytem are also shown in Fig.(8). From photographs of a recent large-scale fire involving two nearby stacks of timber over 150 ft in length it is clear that the flames were merged together. An estimate has been made of the rate of burning and a point plotted in Fig.(8). Although this does not give a large scale value for the critical condition, the point is on the correct side of the critical line and not too far from it. No other large scale fires have yet been compared with this theory which is being developed for application to more complex arrangements of several sources.

Fire spread in experimental fuel beds

It is comparatively recently that attempts have been made to study the spread of fire at a basic level and in one of these fire spreads through a continuous bed of fuel which, for these experiments, is a crib of wood. Large numbers of such experiments have been conducted by Fons and his colleagues in "Project Fire Model" in the United States[7]. They burnt cribs constructed of layers of wood sticks parallel to each other, spaced horizontally by a fixed distance, each alternate layer having the sticks running at right angles to the layer beneath. We define the following parameters which can be used for other types of fuel bed.

σ = (S/V_b) the surface S per unit of fuel bed-volume V_b ?

λ = volume of voids/surface of solid

From these definitions it follows that the porosity (the volume of voids per unit of volume) is given by

$$\epsilon = \frac{1}{1 + \sigma\lambda}$$

4σ = $\frac{\text{surface fuel}}{\text{vol. fuel}}$

λ = $\frac{\text{vol voids}}{\text{surface}}$

$\epsilon = \frac{\sigma\lambda}{1+\sigma\lambda}$

and for a crib of sticks of side a separated by a distance s we have

$$\sigma = {}^{4}/_{a}$$

$$\lambda = {}^{s}/_{4}$$

For the cribs used by Fons et al σ varied from about 6 cm^{-1} to 1.2 cm^{-1} and λ was 0.8 cm.

It has been found[21] that the rate of spread R can be estimated from a theory of which the following is a simplified version. The heat balance of the fuel ahead of the fire is given by

$$R \rho' C \theta = Q_n \qquad (21)$$

where Q_n is the net forward flux allowing for cooling losses

C is the effective specific heat of the moist wood.

θ is the temperature rise causing ignition in the presence of flame, taken as 300°C (Simms (1963))[1]

ρ' is the mass of wood heated to ignition per unit volume of fuel bed.

For thin fuels

$$\rho' = \rho_b = \frac{\rho_s}{1 + \sigma\lambda} \qquad (22)$$

where the suffix b denotes bulk and s denotes solid

i.e.

$$R = \frac{Q_n (1 + \sigma\lambda)}{\rho_s \; C \; \theta} \qquad (23)$$

For thick fuels

$$\rho' = \frac{\sigma \rho_s \Delta}{1 + \sigma\lambda} \qquad (24)$$

where Δ is the mean depth of heating taken as $1/\sigma$ for uniform heating in thin fuels but for thick fuels as of order

$$\Delta \sim \sqrt{kt} \qquad (25)$$

where k is the thermal diffusivity and
where t is the effective heating time of the element which may be written as

$$t \sim \frac{l}{R} \tag{26}$$

where l is the effective mean length heated ahead of the advancing fire which for radiation transfer through the fuel bed may be taken as the mean free path of the radiation. For cribs this is not a simple function, but assuming provisionally that the crib can be treated as a collection of particles we have

$$l \sim \frac{4(1 + \sigma\lambda)}{\sigma} \tag{27}$$

Equation (23) above gives the rate of spread for thin fuels while equations (21) (24) - (27) give for thick fuels .

$$R = \left(\frac{Q_n}{2\theta}\right)^2 \frac{1 + \sigma\lambda}{\sigma(\rho_s c)^2 k}$$

A more detailed theory allowing for cooling within the fuel bed gives the same result with

$$Q_n = Q - 2.67\, H\theta$$

where Q is the gross heat transfer and H the cooling coefficient. Moreover, a more complete treatment can be used to calculate the theoretical value of R over the range of stick sizes between thick and thin fuels. The calculations express $R\,\rho_b\,C\,\theta/H$ as a function of ${}^{Ha}/_{k}$ and ${}^{Q}/_{H\theta}$ or any combination of these. In some fires the value of Q will itself be related to the rate of burning and to the properties of the fuel bed, particularly in cases where its porosity is low so that the burning is controlled by the diffusion of air through the unburnt fuel and the remaining ash, as in a smouldering system. However, for fires where this dependence is weak, i.e. where the burning zone can be considered to be relatively independent of the design of the fuel bed, we can treat Q as a constant. The experimental results are shown in Fig.(9) normalised statistically to a moisture content of 10%. The best value of Q found by fitting a theoretical line through the data obtained by Fons and some other data obtained at the Fire Research Station, Boreham Wood, gives a value for Q in the range 1.5-2 cal cm^{-2} s^{-1} according to the choice of H. This value for the gross heat transfer is typical of radiation from a burning zone at about 800°C. The value of $R\rho_b$ corresponding to the lower limit of the data, i.e. for thin fuels is about 6.5 mg cm^{-2} s^{-1}, Curry and Fons[22] previously obtained values for the rate of spread in a variety of fuels over the range.

$$6 < \sigma < 100 \text{ cm}^{-1}$$
$$0.1 < \lambda < 0.9 \text{ cm}$$

and except for the most tightly packed beds $\lambda < 0.3$ cm and the thinnest fuel wood shavings or excelsior, $\sigma \sim 100$ cm^{-1}, a similar value is obtained for $R\rho_b$ [23] (see Fig.(10)). There is a systematic increase in the value of $R\rho_b$ as λ decreases until a maximum is reached after which $R\rho_b$ decreases rapidly with decreasing porosity, but the effect of λ is not large if $\lambda > 0.3$ cm and is possibly attributable to changes in the cooling coefficient within the fuel bed. Subsidiary calculations show that the thicknesses of flame extending above the fuel bed were not large enough for the flames to be very emissive and that the heat transferred to the fuel bed by the radiation from the flame could be neglected compared with the radiation through the fuel bed itself. It is notable that this theory also is in agreement with the observation that the rate of spread was virtually independant of the height of the fuel bed, i.e. R depends on ρ_b not on the total amount of the fuel per unit area. For very low values of ρ_b, R should reach an upper limit beyond which no spread will be possible at lower values of ρ_b. This effect which is associated with the emissivity of the burning zone has been discussed by Emmons[23] who has also described certain theoretical features of the conditions for the start of spread and what happens immediately afterwards.

It is interesting to note that the Trensacq fire spread against the wind at about 1.7 cm/s which for fuel about 1 m high gives a value of 3 mg cm^{-2} s^{-1} which is half the value calculated for wooden cribs which were mostly only 15 cm high, but in view of the difference in the burning of any one piece of fuel in a wind and the greater cooling loss, effects which counteract each other, it is not possible to pursue the comparison further at this stage. However, the spread with the wind at 190 mg/$cm^{-2}s^{-1}$ which represents a heat transfer of about 2000 cal cm^{-1} s^{-1} shows that the spread rate and the heat transfer rate are between one and two order of magnitude faster than can be attributed to radiation from the burning zone. If flames radiate as a black body at say 3 cal cm^{-2} s^{-1} on a wide front then a fraction of between $\frac{1}{2}$ and 1 of this radiated heat is transferred to the fuel. For flames 11 m high the heat radiated on to unit width of the fuel bed is approximately 1700 cal cm^{-1} s^{-1} which is approximately the same as that required to maintain spread at the rate observed. The uncertainty in the heat exchange factor, in the effective intensity, and in the contribution of convected heat obviously require further consideration but clearly although flame radiation may be unimportant in fire spread in still air or against the wind it may be of considerable importance for fire spread in a wind. However, if $R \rho_L$ is assumed constant in still air it follows that the mean burning rate $\dot{m}'_f$ is proportional to the fuel bed height and from equation (3) it follows that the height of the flames relative to the height of the fuel decreases. Their absolute height increases and their emissivity becomes high if the duration of flaming of the fuel elements increases with increasing thickness of fuel. The implications of these changes are at present being studied. Although laboratory results on cribs in still air have been related to beds of fine fuels simulating real conditions no similar comparison has been made for very thick fuels. There are some similarities between such a crib and fire spreading on a wide front in an urban area but the comparison is obviously not a straightforward one.

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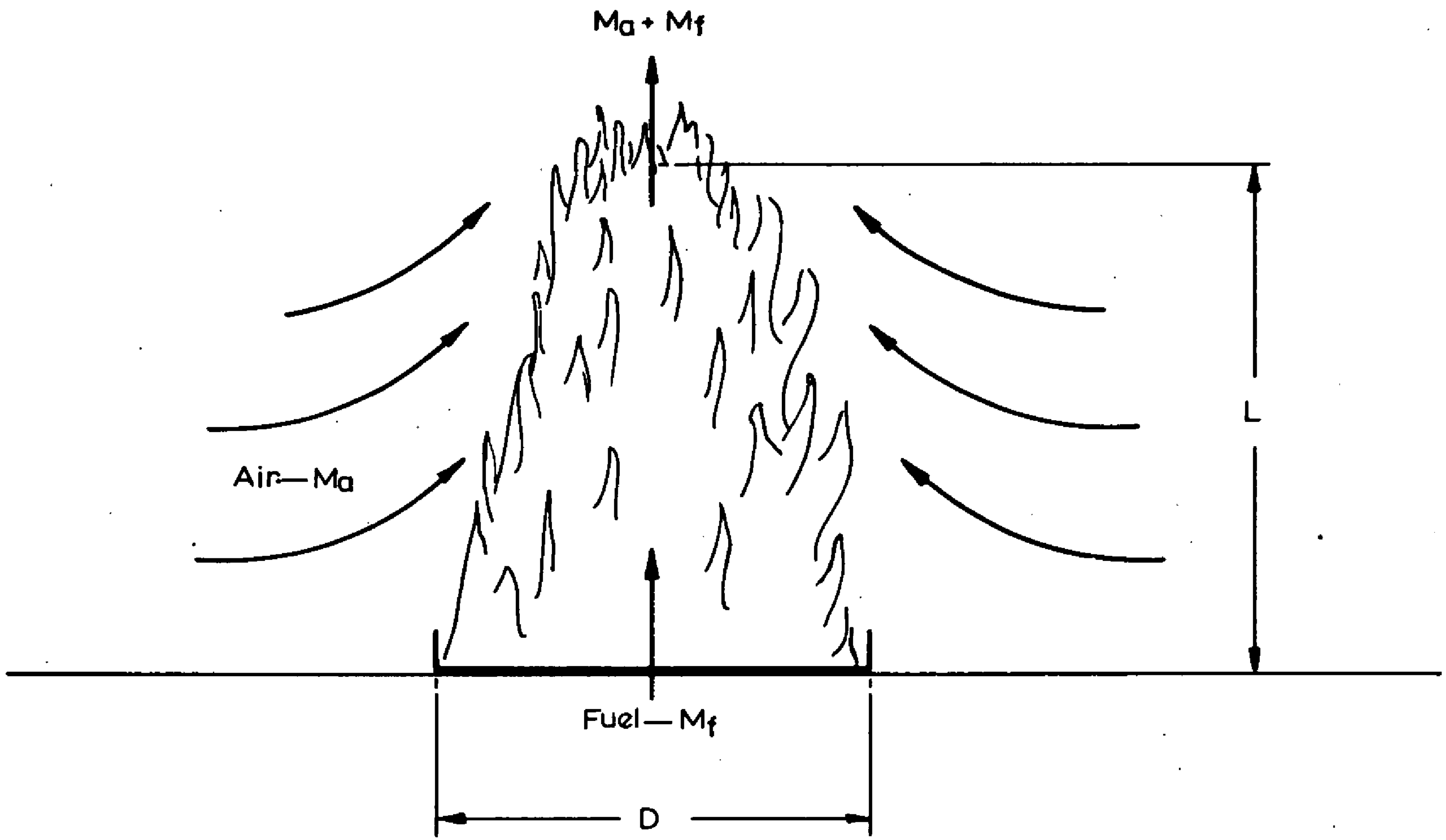


FIG. 1. DIAGRAMMATIC SKETCH OF FLAME FROM A SINGLE FIRE

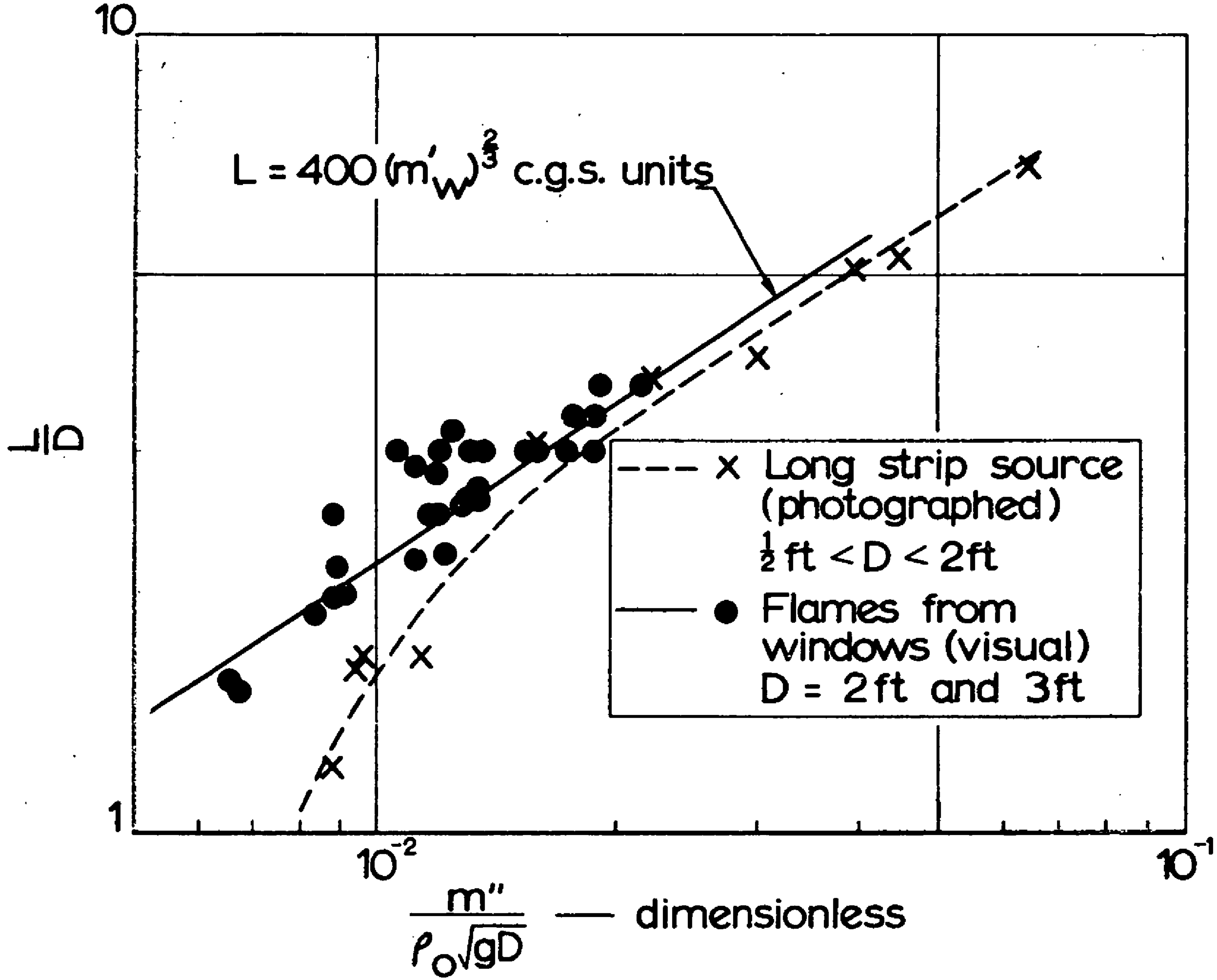


FIG. 2 FLAMES FROM LONG STRIPS AND WINDOWS

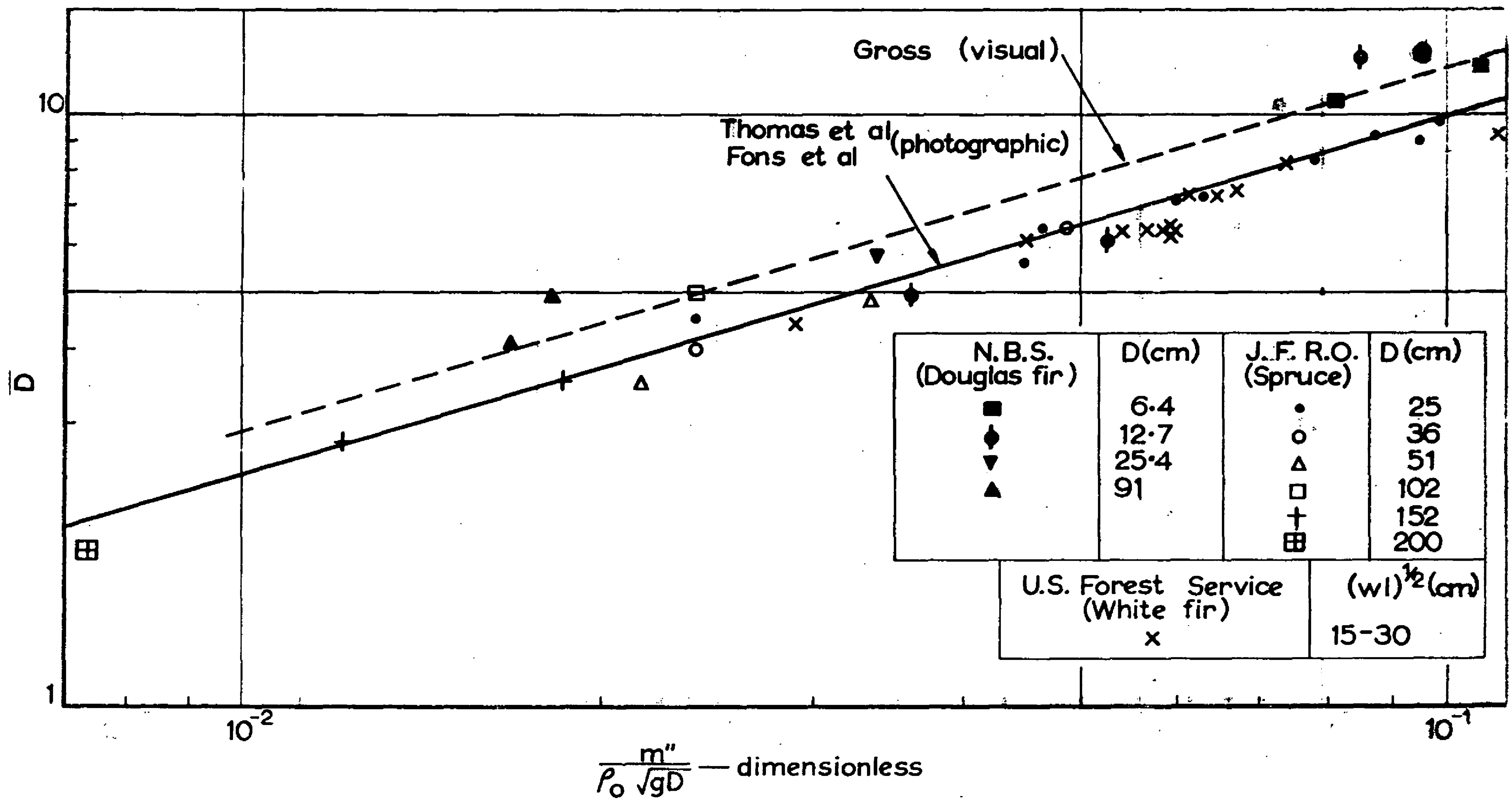
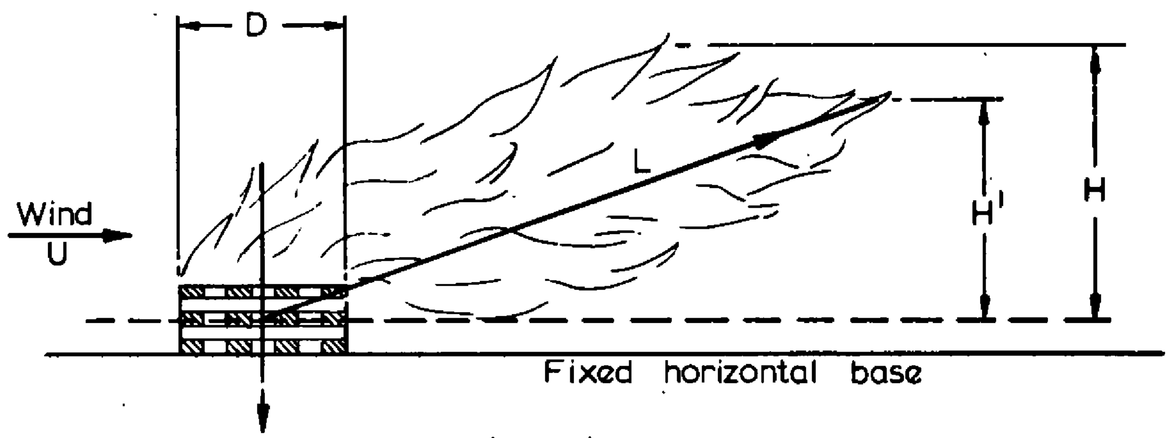


FIG. 3. CORRELATION OF FLAME HEIGHT DATA
Still air – approximately radially symmetrical



Cribs 3ft wide, $6'' < D < 24''$

Cribs used 4 layers of $1'' \times 1''$ sticks spaced $3''$ apart

12 layers of $\frac{1}{2}'' \times \frac{1}{2}''$ sticks spaced $1\frac{1}{2}''$ apart

or 24 layers of $\frac{1}{4}'' \times \frac{1}{4}''$ sticks spaced $1\frac{1}{4}''$ apart

Alternate layers of wood at right angles

FIG. 4 DIAGRAMMATIC EXPERIMENTAL ARRANGEMENT FOR EFFECT OF WIND ON FLAMES

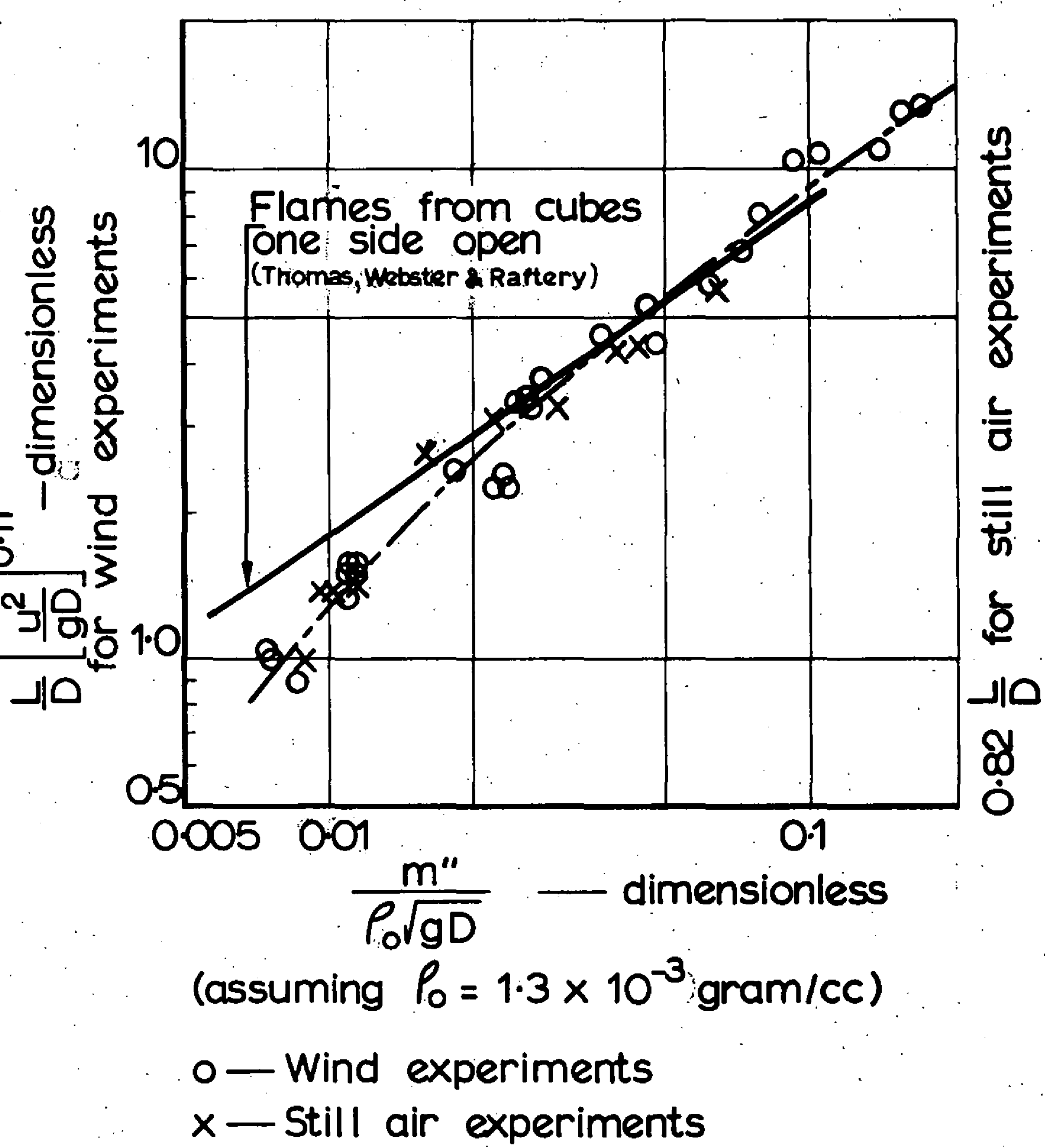


FIG. 5 EFFECT OF WIND SPEED AND BURNING RATE ON FLAME LENGTH

1/5537 Publication

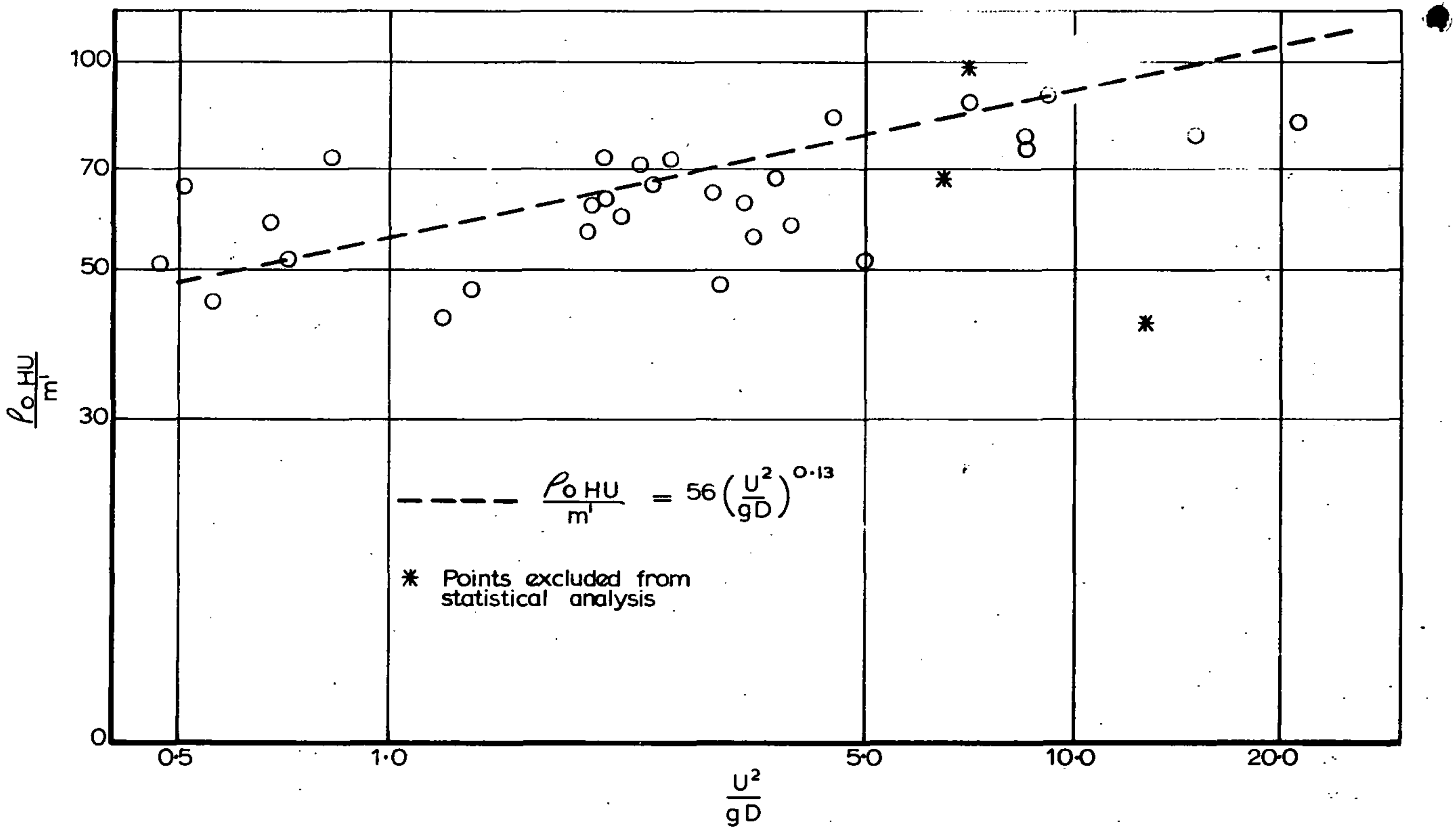


FIG. 6. THE HEIGHT REACHED BY FLAME IN A WIND

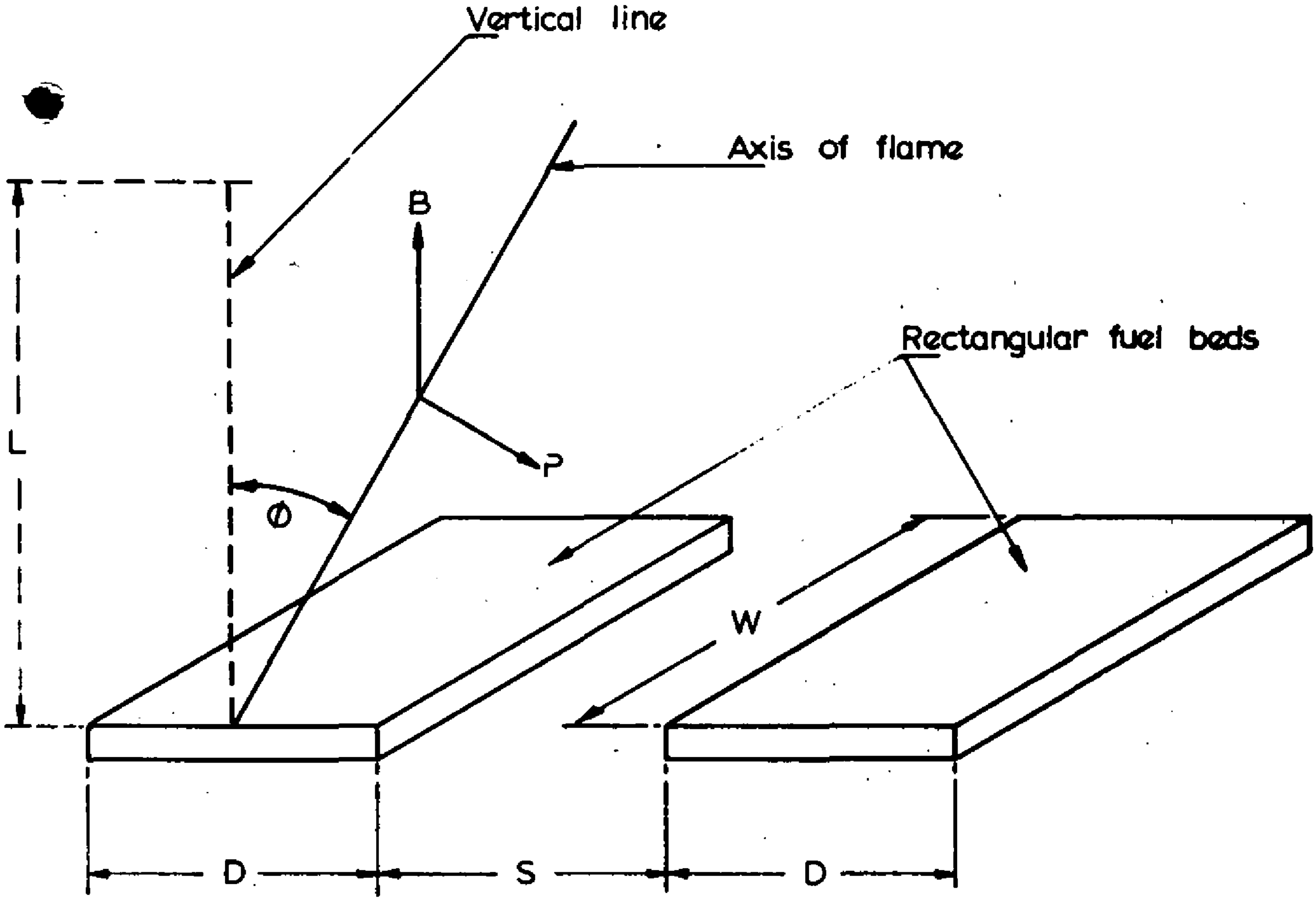


FIG. 7 a. ARRANGEMENT OF THE TWO RECTANGULAR FUEL BEDS SHOWING THE FORCES ACTING ON AN INCLINED FLAME

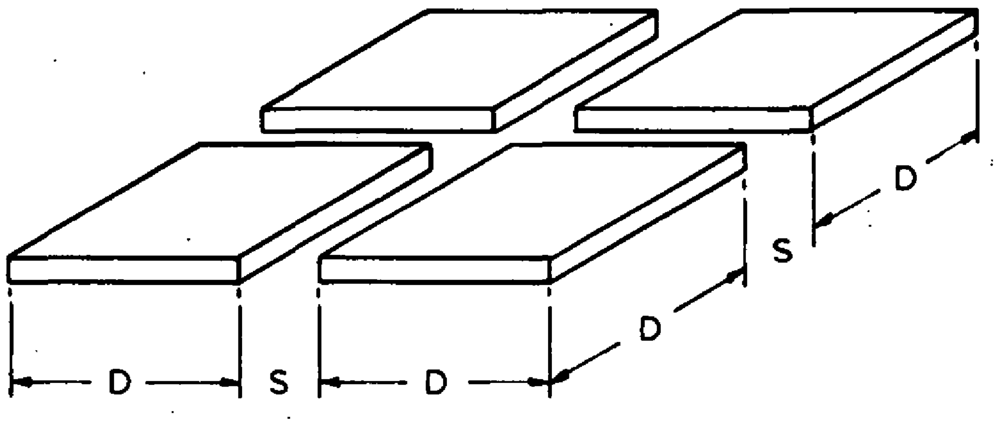
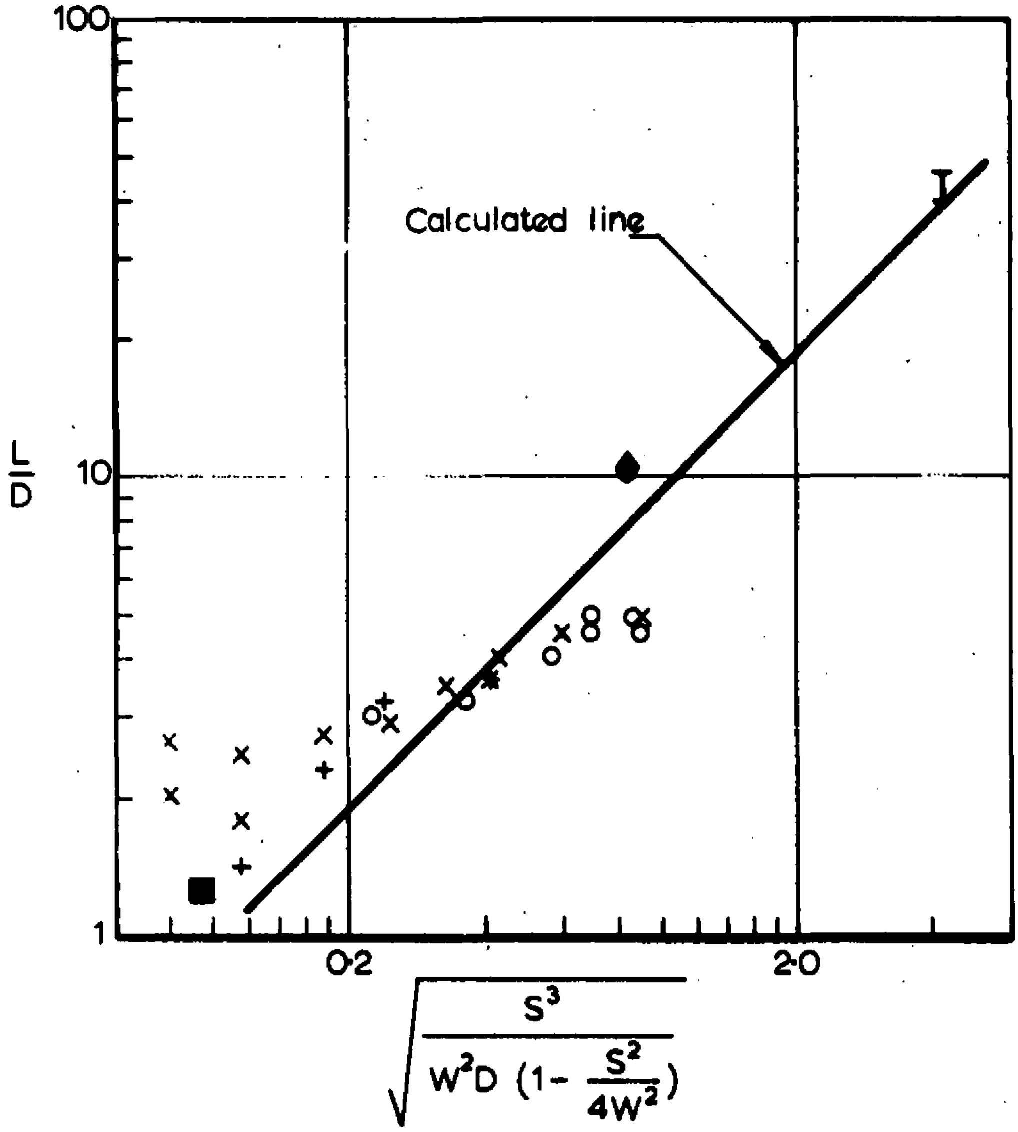


FIG. 7 b. ARRANGEMENT OF THE FOUR SQUARE FUEL BEDS



Data source	Symbol	Fuel bed	W/D
JFRO (Town gas)	o	1′ x 1′ (2 burners)	1
	x	1′ x 2′ (2 burners)	2
	+	1′ x 1′ (4 burners)	equivalent to 2
Putman and Speich	I	2 burners 0·371″ dia	1
	♦	2 sets of 7 burners each 0·371″ dia	1
Southall timber yard	■	2 timber stacks each 150′ x 40′	3·75

FIG. 8 MERGING OF FLAMES FROM SEPARATED FIRES

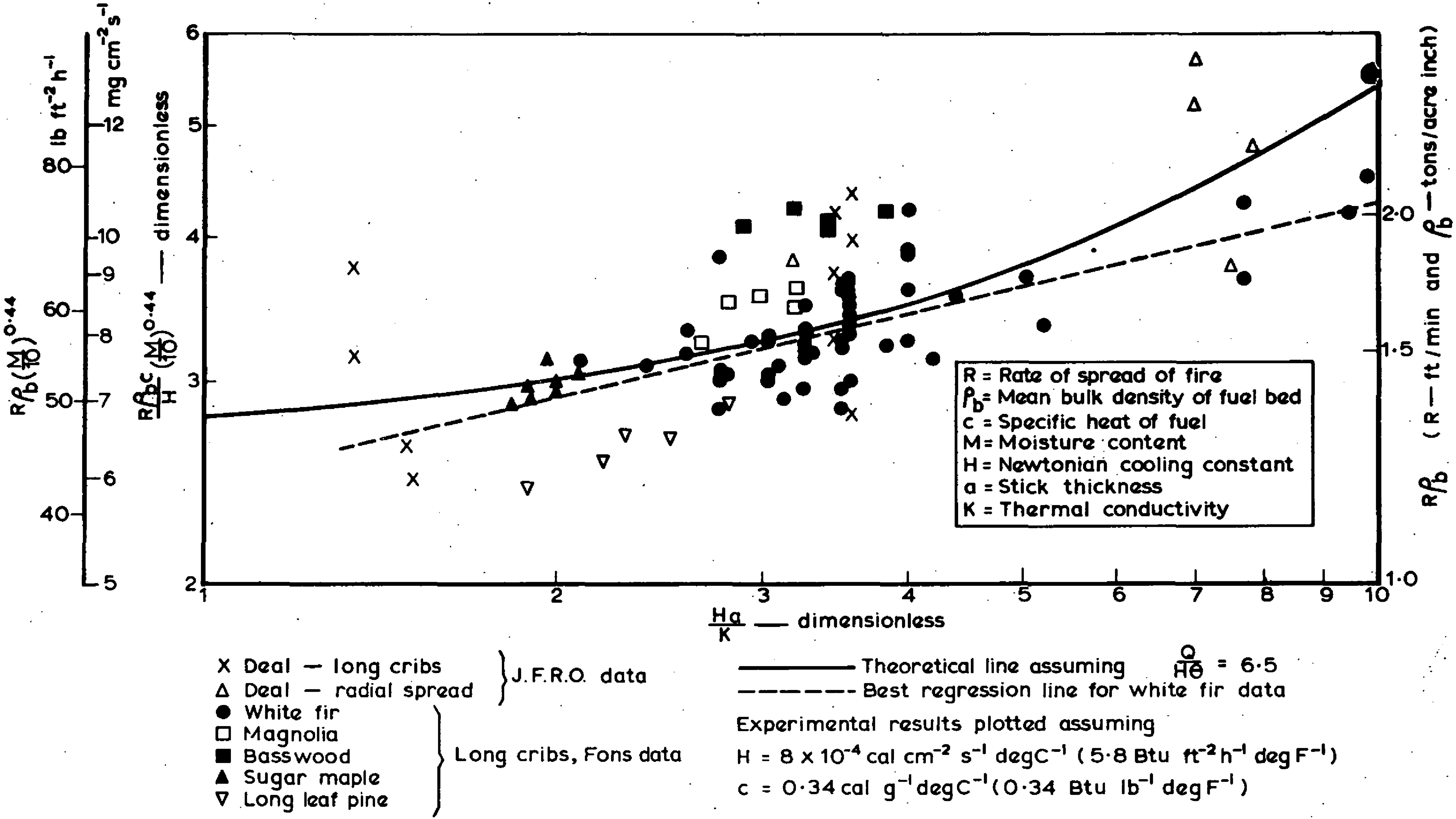
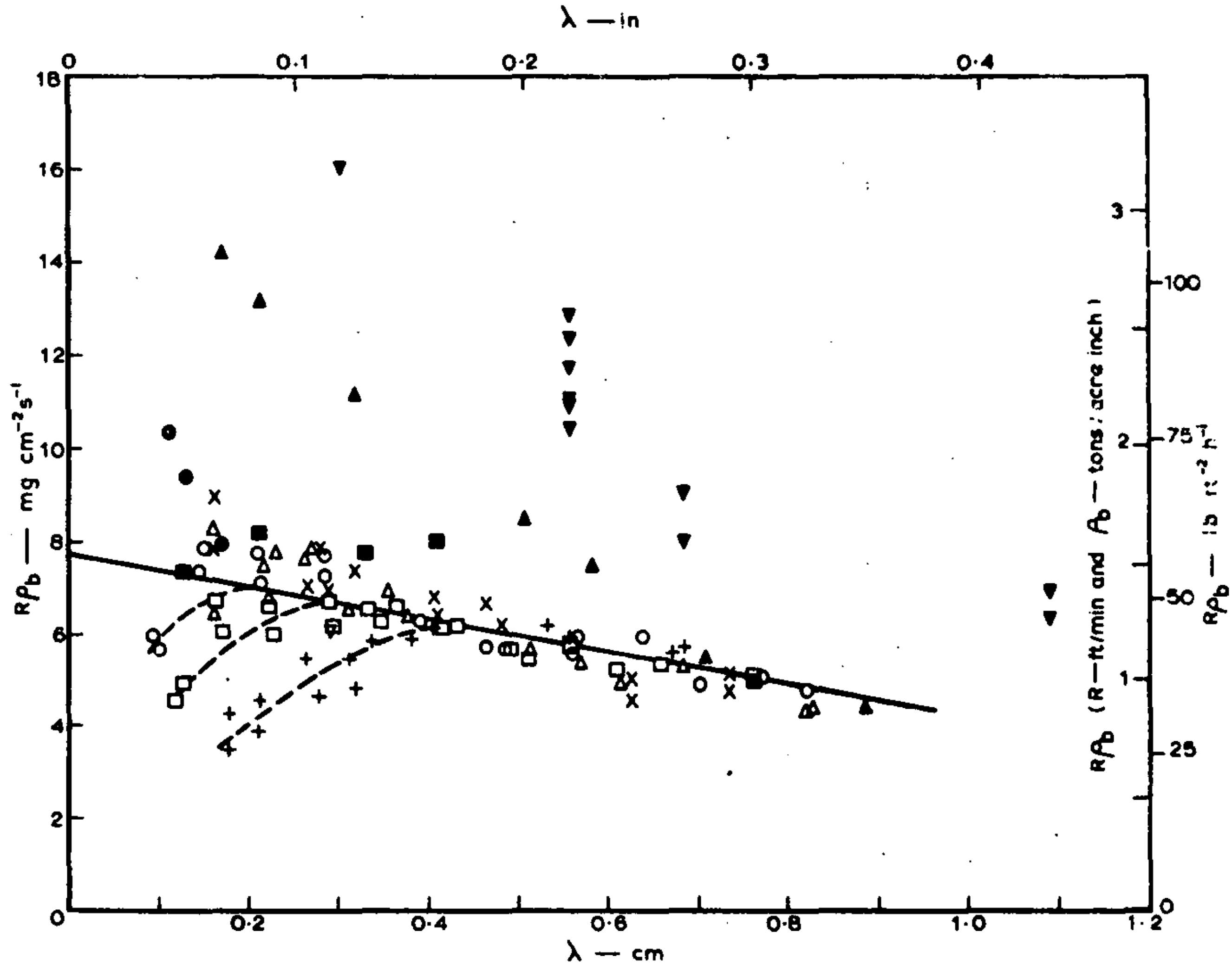


FIG. 9 RATE OF FIRE SPREAD IN CRIBS OF 0·7 – 3·2 cm (0·3 — 1·3 in) WOOD



R = Rate of spread of fire

ρ_b = Bulk density of fuel bed

$$\lambda = \frac{\text{Volume of voids in fuel bed}}{\text{Surface area of solids in fuel bed}}$$

Full line correlates all data except wood shavings and tightly packed beds

Symbol	Volume to surface ratio of fuel (cm)	Volume to surface ratio of fuel (in)	Type of fuel	Species	
+	0·160	0·063	Square section sticks	— Ponderosa pine	Curry and Fons data
□	0·066	0·026	Square section sticks	— Ponderosa pine	
○	0·041	0·016	Square section sticks	— Ponderosa pine	
△	0·028	0·011	Square section sticks	— Ponderosa pine	
×	0·023	0·009	Square section sticks	— Ponderosa pine	
■	0·020	0·008	Pine needles	— Ponderosa pine	
●	0·018	0·007	Pine needles	— Lodgepole pine	
▽	0·015	0·006	Pine needles	— Sugar pine	
▲	0·010	0·004	Wood shavings	— Poplar excelsior	
▼	0·011	0·004	Wood shavings	— ——	J.F.R.O. data

FIG. 10 SPREAD OF FLAME IN KINDLING