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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

"SOME EXPERIMENTS ON BUOYANT DIFFUSION FLAMES"

P. H. Thomas, C. T. Webster and M. M. Raftery

SUMMARY

In flames produced by freely burning fuel, buoyancy may play an important role in determining the speed of the gases in the flame zone and hence the flame height.

Measurements have been made of the height of flames from burning cribs of wood on a square horizontal base and a few for two other arrangements. The results are consistent with a dimensionless analysis, leading, for one particular fuel system, to the functional equation $\frac{L}{D} = \mathcal{J}\left(\frac{\dot{Q}^2}{g D^5}\right)$, where L is the flame height, D the linear dimension of the fire or orifice, Q the volumetric flow rate of gaseous fuel at ambient temperature and g the acceleration due to gravity. In turbulent fuel jets $\frac{L}{D}$ is a constant for a given fuel which is shown theoretically to be a limiting case of this relationship.

Fire Research Station,
Boreham Wood,
Herts.

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INTRODUCTION

The thermal radiation from flames plays an important part in the spread of fire, whether the flame be travelling up a hanging fabric, along a ceiling or from a burning building, both in determining the rate of spread of flame along a combustible surface or across a roadway or a firebreak in a forest. In order to assess the magnitude of the effect of radiation it is necessary to know, amongst other factors, the height of the flame for specified conditions of burning, and the paper is concerned with this aspect of the problem. For the purpose of this paper the rate of supply of gaseous fuel will be considered as an independent variable though in fact it is itself partly determined by the radiation from the flames onto the fuel surface, be it solid or liquid.

First considered is a simple situation in which gaseous fuel emerges into an unconfined atmosphere at a volumetric rate Q through an upward facing horizontal orifice of linear dimension D, e.g. the diameter of a circular orifice or the side of a square orifice. The relationship between the flame height L and the independent parameters D and Q are discussed.

The combustion of a fuel emerging from an orifice mixed with no or insufficient oxygen requires the diffusion of oxygen into the stream of gases containing unburnt fuel and combustion products. This diffusion controls the rate of heat release from the reaction over a wide range of conditions - hence the name diffusion flames.

A number of different types of diffusion flame have been studied. Thus Burke and Schumann(1) successfully applied a simplified theoretical model to describe the laminar flames confined in a cylindrical burner. Yagi(2)(3), Hottel and Hawthorne(4), Wohl, Gazley and Kapp(5) have discussed unconfined laminar flames by means of diffusion theory. Yagi(2)(3), Hawthorne, Weddel and Hottel(6) and Wohl, Gasley and Kapp(5) have also studied the length of turbulent fuel jets experimentally and theoretically. A review of work up to 1949 has been made by Hottel(7).

The studies referred to above are, however, not directly relevant to the problem at hand since they deal with flow streams which are essentially of the forced convection type whereas in this problem the flow is essentially free convection. This is because the velocity of the gaseous fuel leaving the solid or liquid surface, i.e. the orifice, may, for a wide range of conditions, be as low as of the order 10 cm/s, which corresponds to a velocity head of several orders less than the buoyancy head available from a flame which may be several metres in height.

Existing diffusion models can be extended, however, to accommodate this effect. A simple model of the kind discussed by Burke and Schumann(1), Yagi(2)(3), Hottel and Hawthorne(4) is first discussed and then extended to allow for buoyancy. Although Hawthorne, Weddell and Hottel(6) did consider the effect of buoyancy in the analysis of a straight-sided conical flow system (Appendix II of their paper) their experiments were confined to the condition where it had a minor role.

APPLICATION OF DIFFUSION THEORY TO UNCONFINED FLAMES INCLUDING BUOYANCY EFFECTS

The general form of the relationships between flame height L, rate of fuel supply and burner size D, etc. for one particular fuel are determined, i.e. the dimensionless parameters which correlate flame height L with Q and D. The paper is not otherwise concerned with quantitative prediction. It is convenient to start from the direct application of diffusion theory for a moving stream of gas, and briefly derive the established results mentioned above. Hottel and Hawthorne, assuming a constant value of the diffusion coefficient D_v for laminar flames, showed that the parameter $D_v t_f/D^2$, where t_f is the time for fuel to reach the flame tip from the burner and D is the diameter of the burner orifice, is a constant for a given fuel system. Therefore, if L is the flame length and v the velocity along the flame axis x,

$$\frac{D^2}{D_v} \propto t_f \propto \int_0^L \frac{dx}{v} \qquad \text{..............(1)}$$

For such a flow system containing viscous, inertia and buoyancy forces a general functional equation involving the Grashof and Reynolds Numbers can be written, i.e.,

$$\frac{v}{V} = f_1\left(\frac{g \cdot B \cdot D^3 \Delta T}{\nu^2}, \frac{V D}{\nu} \cdot \frac{x}{D}\right) \qquad \text{.............(2)}$$

where V is the velocity of the fuel emerging from the orifice; B is the coefficient of expansion of the gases, ΔT the excess temperature in the flame, g the gravitational acceleration and ν a kinematic viscosity. This functional relationship should also contain other terms, e.g. the ratio of the kinematic viscosity of the fuel to that of the air, and the ratio of absolute mean flame temperature to ambient temperature, but all such extra terms are here assumed constant for a given fuel/air system.

By definition the fuel flow rate is given by

$$Q \propto V \; D^2 \qquad \text{.............(3)}$$

It follows from equations (1), (2) and (3) that

$$\frac{Q}{D_v} \propto \frac{V D^2}{D_v} \propto D \, f_2\left(\frac{L}{D}, \frac{V D}{\nu}, \frac{g D^3 B \Delta T}{\nu^2}\right) \qquad \text{.............(4)}$$

where f_2 is a second function. Henceforth different suffixes to f denote different functions.

Equation (4) can be rearranged to give:

$$\frac{L}{D} = f_3\left(\frac{g D^3 B \Delta T}{\nu^2}, \frac{Q}{D_v D}, \frac{D_v}{\nu}\right) \qquad \text{.............(5)}$$

If v/V is effectively constant and thus near to unity, then directly from equation (1):

$$L \propto \frac{Q}{D_v} \qquad \text{.............(6)}$$

the result expressing the linear relationship found by Burke and Schumann(1), Barr(8) and Simmons and Wilson(9), which is generally acceptable for short flames(7).

In turbulent flow without boundaries it is reasonable to neglect the viscous forces, i.e. ν can be eliminated from among the parameters to be considered. Similarly D_v is not a relevant parameter since molecular diffusion is generally much less important than turbulent or eddy diffusion. If the latter diffusion can be described in terms only of V and its variation with position, and a length which is a function of the one characteristic length of the flow system D and position, it follows that the concentration of fuel along the axis of the fuel stream can be functionally described for any given fuel/air system for which the mean temperature and the temperature distribution are assumed to be the same for different values of the parameter $\frac{V^2}{g.B.D.\Delta T}$ by

$$C_x = C_o \, f_4 \left(\frac{x}{D} \quad \frac{V^2}{g.B.D.\Delta T}\right) \qquad \ldots\ldots\ldots\ldots\ldots(7)$$

where C_o is the initial fuel concentration.

The above assumption about the description of turbulence demands that it is generated and determined by the heat source itself and not by the surrounding atmosphere.

Defining the flame tip by the point at which the concentration C_x reaches some value characteristic of the fuel C_L, it follows that for that particular fuel:

$$\frac{L}{D} = f_5 \left(\frac{V^2}{g.B.D.\Delta T} \right) \qquad \ldots\ldots\ldots\ldots\ldots(8)$$

i.e. from equation (3)

$$\frac{L}{D} = f_6 \left(\frac{Q^2}{g.D^5.B.\Delta T} \right) \qquad \ldots\ldots\ldots\ldots\ldots(9)$$

Given the assumptions made above this can be deduced directly from equation (5) eliminating D_v and ν.

Equation (9) is the general result which has been sought.

ALTERNATIVE DERIVATION OF GENERALIZED CORRELATION

Generalization involves the same assumptions about flow and mixing and their primary importance as do the other treatments mentioned above. A somewhat more direct derivation is now given in slightly different terms to elaborate the significance of the above result.

The surface area s of the flame envelope can be represented by $D^2 f_7 \left(\frac{L}{D} \right)$ where f_7 is a shape factor. For a cylindrical flame s is proportional to DL (Fig.1a) and for a long conical flame s is proportional to L^2 (Fig.1b).

Thus for a cylindrical flame of height L and base dimension D

$$f_7\left(\frac{L}{D}\right) \propto \left(\frac{L}{D}\right) \qquad \text{................(10i)}$$

and for a conical flame where $^D/_L \rightarrow 0$

$$f_7\left(\frac{L}{D}\right) \propto \left(\frac{L}{D}\right)^2 \qquad \text{................(10ii)}$$

The rate of air entrainment per unit area can be represented by a velocity

$$v_e \propto \epsilon \cdot \frac{1}{\ell}$$

where ϵ is an eddy diffusivity and ℓ is the characteristic dimension defining the concentration gradient, or a mixing length. Conventionally ϵ in turbulent flow is often expressed as the product of a velocity and a distance, and for a stream of local velocity v is proportional to $v\,\ell$ which leads to

$$v_e \propto v \qquad \text{................(11)}$$

This assumption is essentially the same as that used by Morton, Taylor and Turner(10).

For v in turbulent flow equation (2) with λ eliminated becomes:

$$v_e \propto v \propto V f_8\left(\frac{g.B.D.\ \Delta T}{V^2},\ \frac{X}{D}\right)$$

which expresses all that is implicit in this derivation, namely, that the entrainment velocity is a function of the orifice velocity and the buoyancy, and varies with the distance from the orifice.

If buoyancy is the predominant influence on the distribution of velocity then v tends to become independent of V and in the limit f_8 is proportional to the square root of $\left(\frac{g.B.D.\ \Delta T}{V^2}\right)$

$$\text{i.e.}\quad v_e \propto v \propto \sqrt{g.B.\ \Delta T.D}\ f_9\left(\frac{X}{D}\right) \qquad \text{................(12)}$$

The total air entrained across the flame envelope is thus proportional to the integrated product of v_e and the surface area. This product, for a given fuel/air ratio, must be proportional to Q.

$$D^2 f_7 \left(\frac{L}{D} \right) \times V f_8 \left(\frac{g.B. \Delta T.D}{V^2} \cdot \frac{L}{D} \right) \propto Q \propto V D^2 \quad ....(13)$$

i.e. $$\frac{L}{D} = f_{10} \left(\frac{Q^2}{g.D^5. B.\Delta T} \right)$$

as before in equation (9).

This result is in fact the only one which can be obtained from the assumptions that the flame length L is a function only of D, Q and g.B. ΔT, the independant flow variables, but this method of deriving the result shows that even when the orifice momentum is negligble compared with the buoyancy head the functional relation has the same form.

It will be realized from the above discussion that Q has a dual significance. First, it is a measure of the orifice velocity and secondly, being the flow of fuel, it is a measure of the air requirements of the flame. The variable $Q^2/g.D^5.B.\Delta T$ thus affects the flame height even when orifice momentum is small compared with the gain in momentum from the buoyancy, but under these limiting conditions Q would be replaced by N Q where N is the air/fuel ratio. In view of the neglect of difference between the flame temperatures etc of different fuel systems the use of N Q instead of Q is only a first approximation to a generalized correlation for different fuels.

DISCUSSION OF GENERAL EQUATION

It might be expected that the ratios of the fuel/air molecular weights, the required fuel/air ratio, the ratio of flame temperature to ambient temperature and the fuel and air density ratios, etc. would be involved in determining flame length and it should be noted that this was implied in an equation derived by Hawthorne, Weddel and Hottel(6) when discussing a straight-edged round jet. (Appendix II of their paper).
In fact, for this straight-edged round system they demonstrated the importance of a parameter $\left(\frac{g.D}{V^2 \tan\theta} \right)^{1/5} (1 + \frac{2L}{D} \tan \theta)$ where θ is the angle of expansion of the jet and $\frac{V^2}{g\, D}$ is the group which appears in equation (7).

The derivation of the one-fifth power is seen from the following argument. For a long conical flame, the flame surface s become proportional to L^2 and independant of D as D/L tends to zero. The value of $\mathcal{V}_e$ tends to become independant of V if flame buoyancy is predominant over orifice momentum, i.e. if $gL \gg V^2$.

In so far as the conical flame can be considered to be a point source, and the influence of the flow conditions at the orifice in determining the pattern of flow becomes relatively smaller as D/L decreases, it might be expected that $\mathcal{V}_e$ would become independant of D as well as V for values of x large compared with D. i.e. from equation (12)

$$\mathcal{V}_e \propto \mathcal{V} \propto \sqrt{x} \quad (x \gg D) \qquad \ldots\ldots\ldots\ldots\ldots(14)$$

and mean values of $\mathcal{V}_e$ are proportional to $\sqrt{L}$. With f_7 proportional to $\left(\frac{L}{D}\right)^2$ and f_8 proportional to $\sqrt{L}$ it follows that $L^{5/2}$ is proportional to Q, i.e. f_6 in equation (9) is the one-fifth power of the variable.

If gravitational effects are absent then $g.B.\Delta T$ cannot affect L and $\frac{L}{D}$ must be constant. This is the well known law for turbulent fuel jets with high momentum [(2)-(7)]. A decrease in buoyancy relative to orifice momentum leads to a decrease in the velocity in the fuel stream and hence less air entrainment, so that L increases. Thus $\frac{L}{D}$ is an increasing function of $\frac{Q^2}{g.D^5.B.\Delta T}$ and $\frac{L}{D}$ should tend to an upper limit which has the value typical of a turbulent jet where buoyancy is of minor importance.

It has been pointed out (equation 10) that $f_7 \propto \left(\frac{L}{D}\right)$ for cylindrical and $\propto \left(\frac{L}{D}\right)^2$ for conical flames. If it were possible for very short flames to be idealized as shown in Fig.(1c) the surface area would be proportional to $D^2\sqrt{1 + \frac{4L^2}{D^2}}$ and so $f_7\left(\frac{L}{D}\right)$ would be almost independant of L for values of $\frac{L}{D} \ll 1$.

Thus if

$$f_7\left(\frac{L}{D}\right) \propto \left(\frac{L}{D}\right)^n \qquad \ldots\ldots\ldots\ldots\ldots(15)$$

the index n might be expected to increase from 0 to 2 with increasing $\frac{L}{D}$.

If from equation ((14) the mean value of $\mathcal{V}_e$ is taken as proportional to $\sqrt{L}$

then from equations (13) and (15)

$$\frac{L}{D} \propto \left(\frac{Q^2}{D^5} \right)^{\frac{1}{2n+1}} \quad \ldots\ldots\ldots\ldots\ldots(16)$$

This equation shows that the $\frac{L}{D}$ versus Q^2/D^5 relationship on a log-log basis is convex upwards. The index of Q^2/D^5 thus varies from some value equal or less than 1 to $1/5$ as $\frac{L}{D}$ increases, until at high values of Q^2/D^5, when orifice momentum becomes significant, it tends to zero and $\frac{L}{D}$ becomes constant. Before discussing the use of this correlation the flow criterion for the existance of a turbulent rather than laminar flame will be briefly discussed.

TRANSITION FROM LAMINAR TO TURBULENT FLAMES

The transition from laminar to turbulent flames has been discussed in terms of a critical Reynolds Number[4]; this is appropriate in determining the condition of the fuel emerging from the orifice and in the flames themselves if buoyancy effects are secondary to those of momentum at the orifice. However, Hottel and Hawthorne were not able to obtain a satisfactory criterion[4], independent of the nature of the fuel. When buoyancy is important the mean velocity of the gases increases rapidly with height and turbulence may be induced at a height which is a small fraction of the total flame height even if the Reynolds Number based on the conditions of the emerging fuel shows this flow to be laminar. It is possible therefore that buoyant diffusion flames may be effectively turbulent when the Reynolds number relevant to the fuel at the burner or orifice is below the conventional value for turbulent flow.

EXPERIMENTAL RESULTS

Cribs on square horizontal base

Results are given in this paper for cribs of wood sticks (spruce) arranged on square horizontal base. (Plate 1). By varying the amount of wood in the crib various mass rates of weight loss ρQ where ρ is the density of the cold fuel gas could be obtained for a given value of D by direct weighing. The height of the visible flame was in each case measured from the base of the crib and was much greater than its height. The burning rate reached a maximum value which remained steady for a period and this rate of burning and the mean height of visible flame corresponding to it were recorded during the experiments. The flames had a short period of fluctuation in height so that the heights recorded photographically were averaged over a period considerably longer than the few seconds taken for a single fluctuation. In this period it is mainly the volatiles from the wood that are burning. Apart from a small amount of carbonaceous residue burning at the crib edge little carbon burnt until the flames subsided and the gross rate of burning fell. The results are plotted in Fig.2. The viscosity μ was assumed to be 10^{-4} C.G.S. units and apart from one result where it was 1250 the Reynolds number at the orifice ($\frac{\rho Q}{D}$) was over 2000 in all cases. Some unpublished data are also available.

Gross[11], at the National Bureau of Standards, Washington, has burnt sticks of Douglas Fir of square section assembled in the form of cubical cribs. These cribs varied in side from $\frac{5}{8}$ to 36 in. and some had differing numbers of sticks in the horizontal layers, thereby burning at different rates of weight loss for a given cube dimension. The Reynolds numbers based on 10^{-4} C.G.S. units for μ fell in the range 13 to 6,400. Some of the results referred to laminar flames, indeed in one case the flame was less than 2 in. high. All the data where the flames were less than 2 ft (50 cm) high have been excluded and the rest plotted in Fig.2. The results follow the same trend as the results of the Joint Fire Research Organization but are about 20 per cent higher. Since for these cubical cribs the crib height is not small compared with the linear dimension of the base it would be more appropriate to take the base of the flame half way up the crib to obtain a value of L more comparable with the other data. This reduction of $\frac{L}{D}$ by 0.5 is not however sufficient to explain the difference in $\frac{L}{D}$ between the two sets of data.

Use has also been made of some data given by Fons et al[12]. These refer to experiments on the spread of a burning zone along a long wood crib. (White Fir). Data from these experiments have been plotted using an equivalent square base defined by $D = \sqrt{D_c D_W}$, where D_c is the width of the crib and D_W the measured length of the flame zone in the direction of flame spread along the crib. The results where the flame height was not greater than three times the larger of either D_c or D_W have been excluded because they cannot be regarded as approximately radially symmetrical.

These data are also in good agreement with those described above.

Cribs in an enclosure

The second set of experimental results refer to the heights of visible flame observed outside a cubical enclosure when varying amounts of wood (Spruce) were burning within it and one side of the crib was completely open (Plate 2). The mean rate of burning in the period when the burning was approximately constant and the corresponding mean flame height, were measured, the latter visually. The results are plotted in Fig.3. The Reynolds number $\frac{\rho Q}{D}$ with μ equal to 10^{-4} C.G.S. units varied from 2300 to 5400 for the data recorded. It should be emphasized here that these results do not apply to the case where there is a vertical 'wall' above the opening though one would expect such results to be correlated by a relation of the same form.

Flames on strips of hanging fabric

The third set of results refer to the flames from various widths of one type of cotton fabric which was burning while hanging freely. Unlike the previous experimental arrangements the rate of burning could not be varied independently of the linear scale of the fuel arrangement, i.e. Q is a function of D, the width of fabric, and for the smallest width the flame was laminar. Despite the availability of only a few data in this case the results are given and discussed for general interest. No direct measurements were made of the loss in weight. Instead the observed rate of spread of flame up the fabric, when this had reached a constant value was measured and the flame height obtained from ciné records. The results could be plotted in terms of the rate of spread of flame V_s and the width D since V_s is proportional to $\frac{Q}{D}$. However, in order to plot the data in a way comparable with the previous cases the value of the mass of fabric per unit area was used to convert the spread velocity to a rate of weight loss. This neglects the weight of the char residue and may overestimate the value of Q^2/D^5 by a factor of the order 4. The results are given in Fig.4.

The values of the Reynolds number $\frac{\rho Q}{D}$ varied from 400 to 1000 but only the flames from the two smaller widths appeared wholly or partly laminar; for the other widths the Reynolds number was over 800.

DISCUSSION

Cribs on square horizontal base

Fig.2 shows that the results for flames from a square source can be correlated by using the terms in groups suggested by equation (9). The relationship of $\frac{L}{D}$ to Q^2/D^5 is a power law but this is not of fundamental significance and can be used only over a limited, albeit a usefully wide range. The line through the results plotted in Fig.2 is given in C.G.S. units by

$$\frac{L}{D} = 4.4\left(\frac{Q^2}{D^5}\right)^{0.30} \qquad \text{.................(17)}$$

For a given burning rate per unit area i.e. a given value of V this implies that:

$$\frac{L}{D} \propto D^{-0.3} \qquad \text{.................(18)}$$

There are two reservations to the use of a power law:

(1) At large values of Q^2/D^5, $\frac{L}{D}$ should become constant. This constant value is known for certain gases and depends markedly on the air requirement per unit quantity of fuel. For carbon monoxide which has a low air requirement the ratio is about 40 while for propane, which has a high air requirement, it is nearly 300[6]. On a log-log scale these known values are not so much larger than the values found in the experiments for one to extrapolate upwards linearly over a large range. Extrapolation from small to large scale will usually decrease the value of Q^2/D^5 and thus be downward extrapolation.

(2) The second reservation is that, even if buoyancy were the predominant factor and Q only entered the correlation as a measure of the quantity

of fuel and hence air quantity, a power law implies that the flame shape function which expresses the flame envelope surface area is also a power of the ratio $\frac{L}{D}$ (equations (15) and (16)). A straight line extrapolation in either direction based on the above arguments would tend to over-estimate flame length*.

Cribs in an enclosure

The results of the experiments on flames from cubes with one side open also lie on a line of similar form to that for the open fires, (Fig.3) but this correlation is relatively less well established in view of the fewer data available. Since the height of the flame may be expected to be independent of the width of the window it possible (though this is only true in so far as $\frac{L}{D}$ is not large compared with unity) to extend this correlation as a first approximation to the form.

$$\frac{L}{D} \propto \left(\frac{R'^2}{D^3} \right)^m$$

where R' is the mass rate of burning per unit width in a rectilinear enclosure of which the height is equal to the dimension perpendicular to the opening.

For these results where the index m is approximately $\frac{1}{3}$, L is only weakly dependent on D. In this connexion it is perhaps significant that a line source of gas at constant temperature giving a straight-edged plume of constant expansion might be expected to give a two-third power law between height of flame L and R' based on the same arguments that led to a two-fifth power law for a point source. Thus $s.V_e$ is proportional to $L\sqrt{L}$ which is proportional to R' and hence L is proportional to $R'^{2/3}$. In an enclosure there is the added feature of entrainment in the horizontally moving stream under the 'roof', but this might be expected to be small because of the relative difficulty of exchanging cold gas with lighter hot gas flowing over it.

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*In theory increasing L absolutely increases the characteristic velocity $\sqrt{gL}$ so that eventually mixing could cease to be the controlling factor and the kinetics would have to be considered.

Flames on strips of hanging fabric

The results for the burning fabrics are shown in Fig.4 but because ρQ varies with D, they do not in any way prove that the form of the independent variable is Q^2/D^5 though, given this form from the experiments on cribs in the open, the correlation is as shown in Fig.4. As has been stated above, the smallest of these flames had a significant portion of laminar flame. The fabric data lie on a continuation of the correlation curve for the open wood cribs (Fig.5), despite the difference in the fuel, the definition of D and the presence of a laminar region. This is no doubt largely fortuitous.

Comparison with data on burning fuel tanks

Blinov and Khudiakov(13) have published data for flame heights from burning fuel tanks but the number of these where the Reynolds number exceeds 2000 and which are accordingly stated to be fully turbulent(13)(14) is very small (less than 5) and only three refer to one type of fuel. For the two largest fuel tanks, the ratios of $\frac{L}{D}$ were the same (1.7) and the authors stated that these results were in the region where such a constancy was to be expected in the light of work on turbulent fuel jets. This argument has been referred to in two reviews(14)(15) of the paper by Blinov and Khudiakov. While it is true that the constancy of $\frac{L}{D}$ cannot be accounted for by the arguments of the present paper since for a given V, $\frac{L}{D}$ is proportional to $D^{-0.3}$ (equation (18)) it is to be noted that the liquid burning rate in these tests was of the order 5 mm/min giving a gaseous velocity of the order 20 cm/s. Since the two flame heights were of the order 350 and 4000 cm respectively giving corresponding values of $\sqrt{g\ L}$ of 600 and 2000 cm/s and $\frac{L}{D}$ was much smaller than the values typical of turbulent fuel jets, it seems incorrect to use an argument which depends for its validity on the assumption that the velocity at the orifice determines the velocities and mixing conditions at higher levels in the flame. It would seem desirable for further experiments to be carried out as the conclusion about the constancy of $\frac{L}{D}$ in these experiments depends only on the result of one of two burning tests.

CONCLUSION

An approximate dimensional analysis leads to a simple dimensional relationship between flame height, burning rate and orifice size for buoyant diffusion flames. Data are presented which conform to this correlation over the experimental range. The well known law for turbulent fuel jets has therefore been generalized to allow for buoyancy effects and this enables a principle of similarity to be defined for flames from fires of freely burning fuel.

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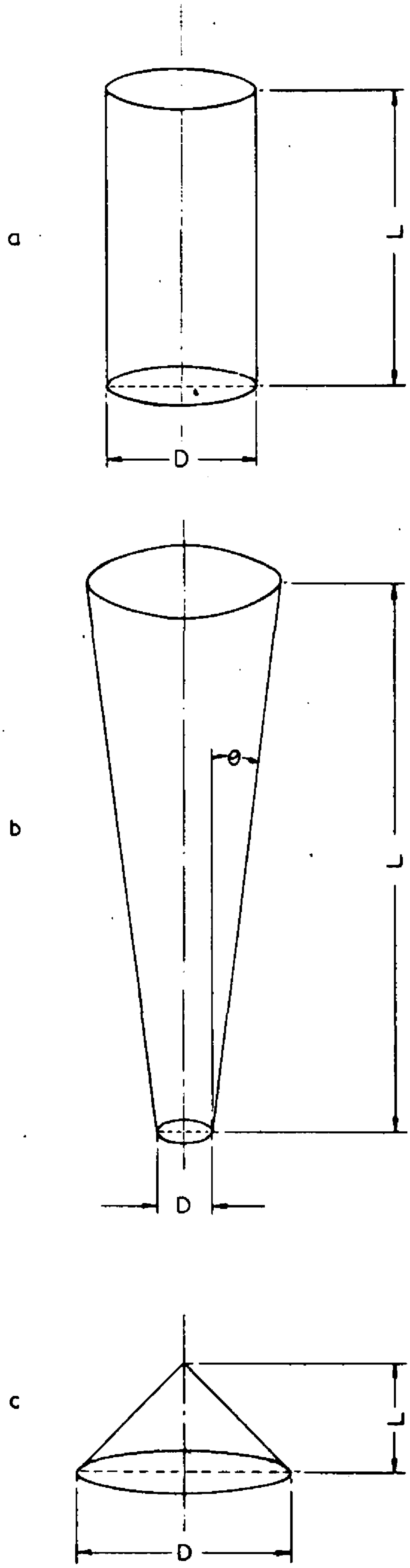

FIG. 1. DIAGRAMMATIC REPRESENTATION OF FLAMES

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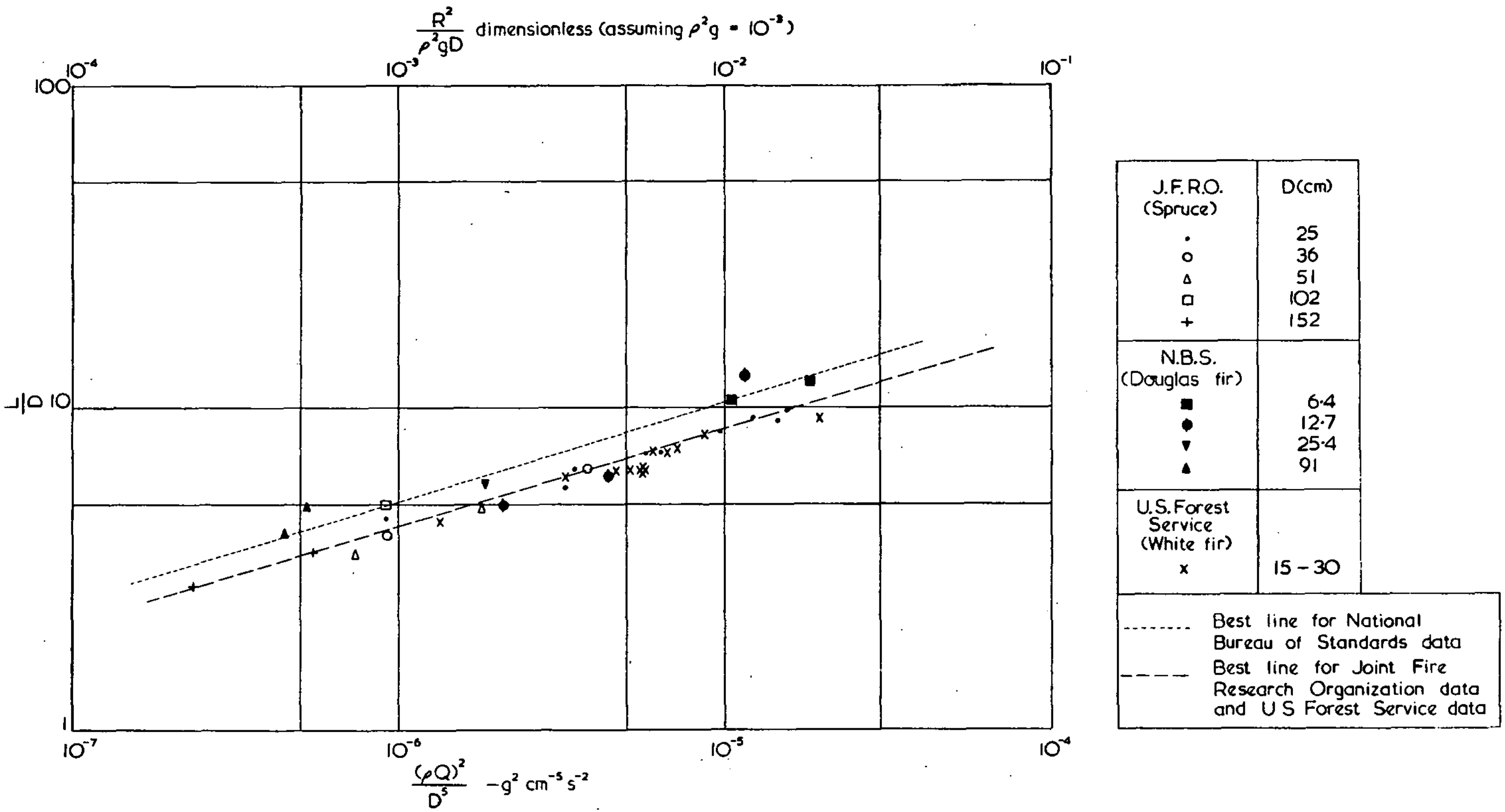


FIG. 2. CORRELATION OF FLAME HEIGHT DATA
Still air — approximately radially symmetrical

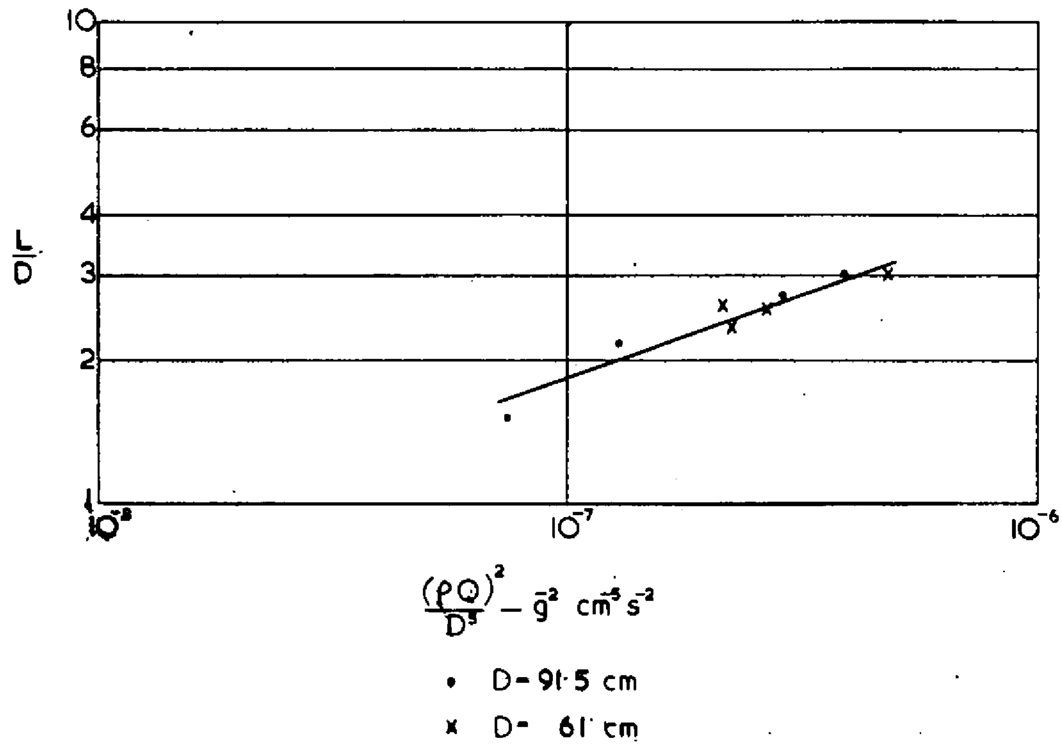


FIG. 3. FLAME HEIGHT FOR FLAMES FROM WOOD CRIBS IN CUBICAL ENCLOSURES WITH ONE SIDE OPEN

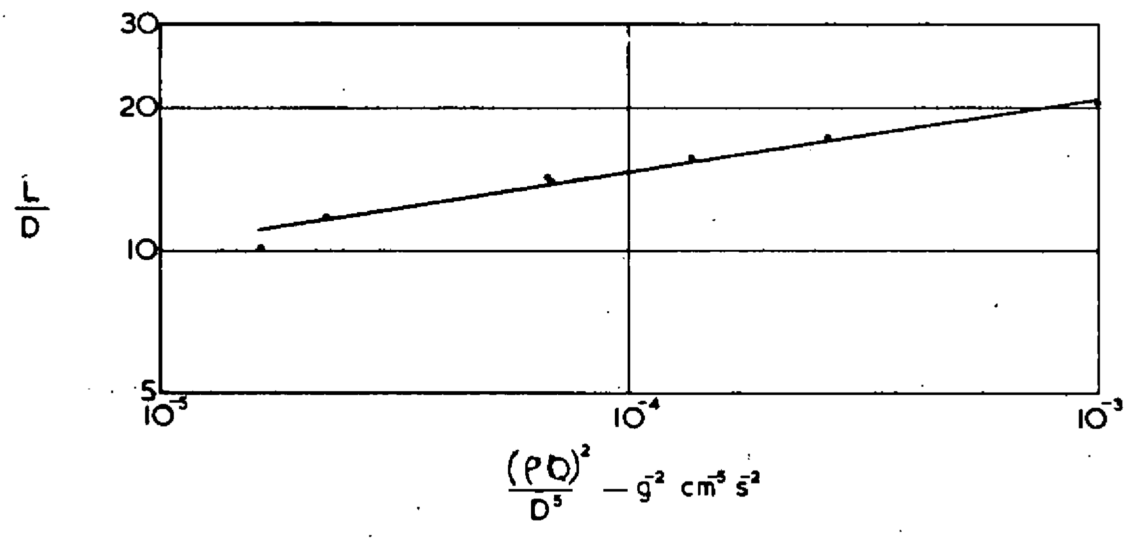


FIG. 4. FLAME HEIGHTS FOR STRIPS OF FABRIC BURNING UPWARDS

F.R. 449

1/3994

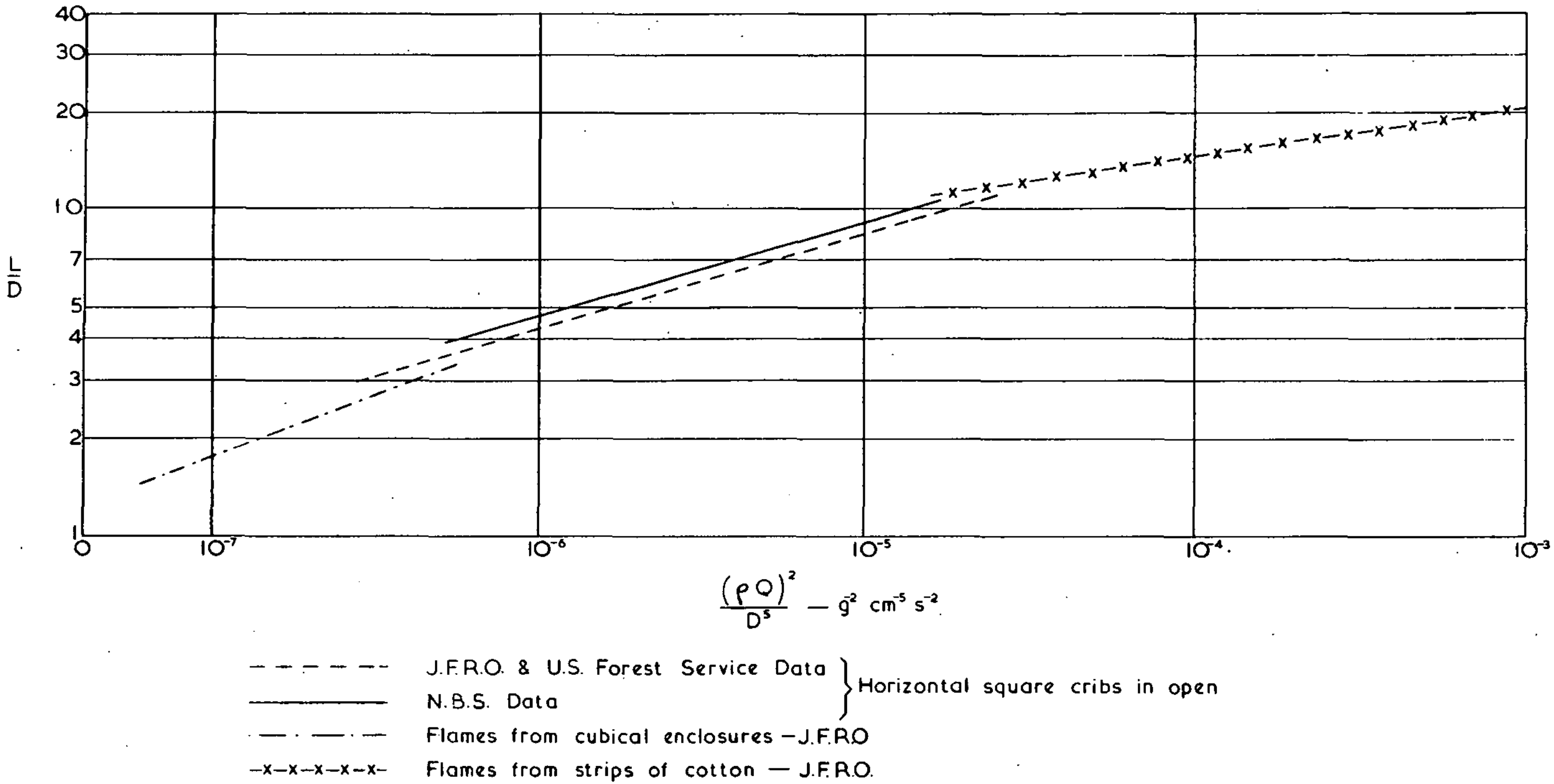
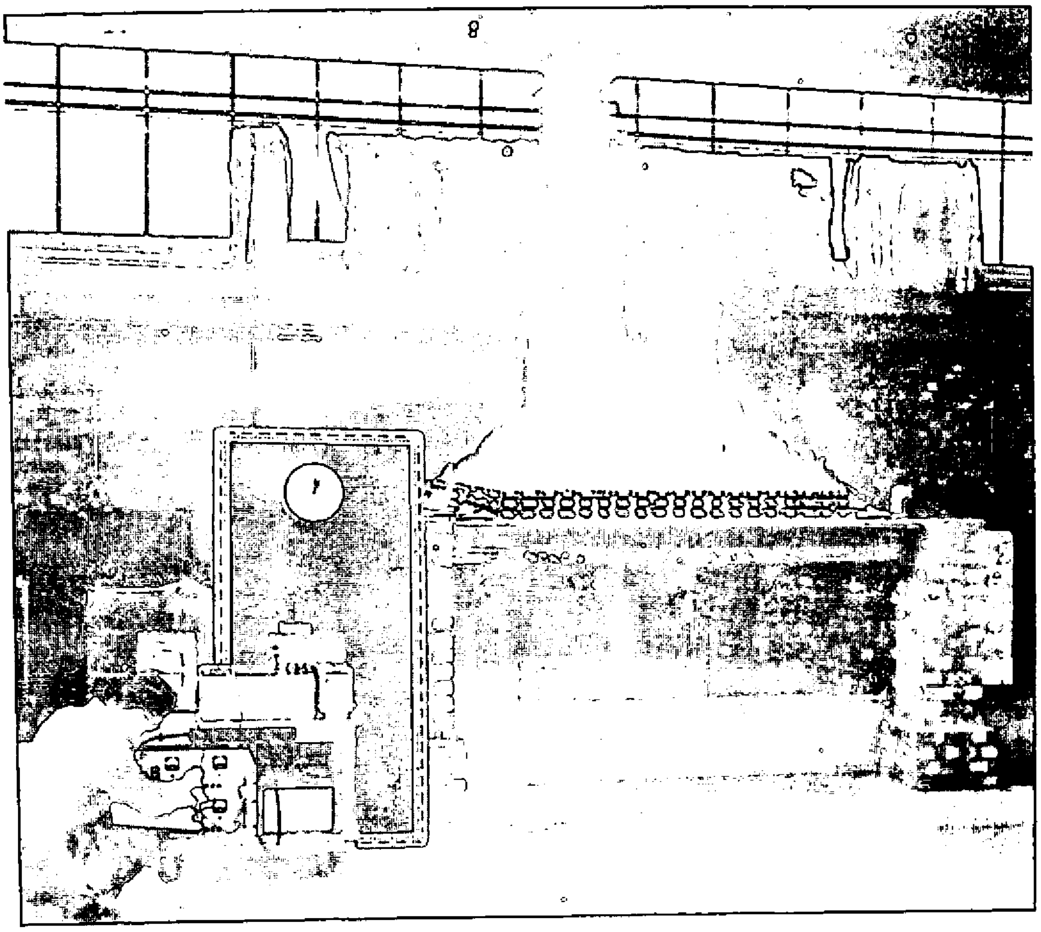
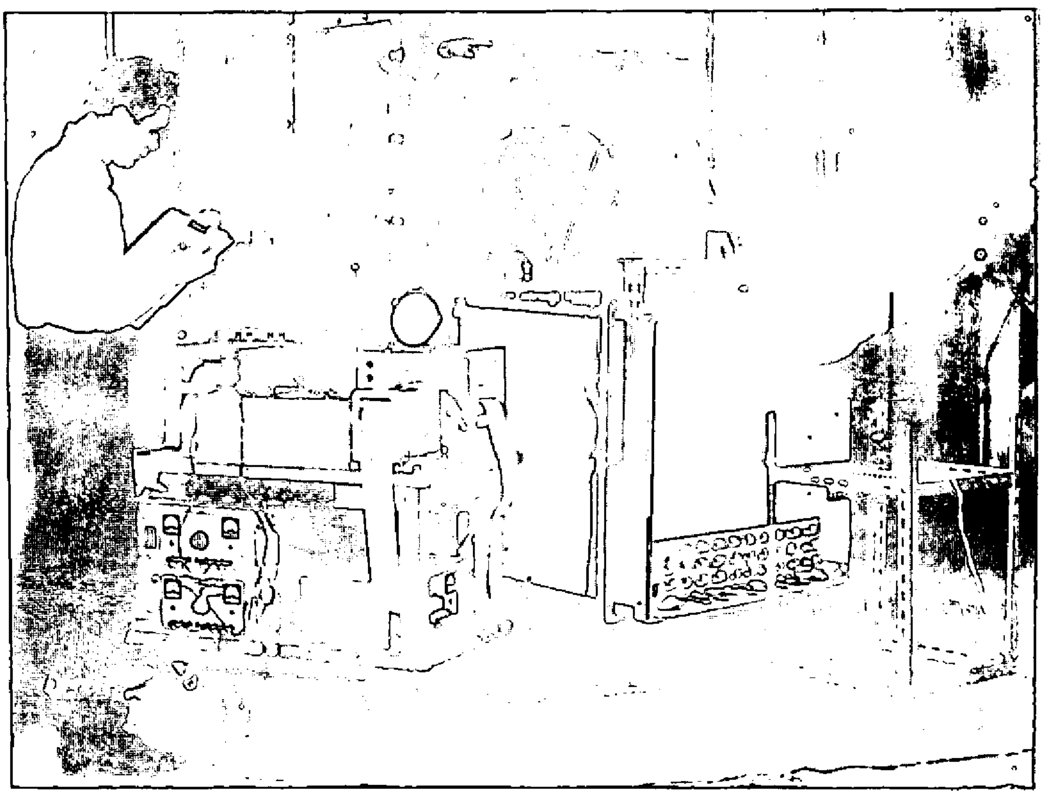


FIG. 5. BEST LINES FOR FIGS 2, 3 & 4



FLAMES FROM CRIB ON SQUARE BASE OF 101 CM
(EXPOSURE TIME 1/10 SEC.)
PLATE 1.



GENERAL VIEW OF EXPERIMENTAL ARRANGEMENT
FOR STUDYING FIRES FROM CRIBS BURNING IN
CUBICAL ENCLOSURES (MEASURED SCALE NOT SHOWN)
(EXPOSURE TIME 1/10 SEC.)
PLATE 11.