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

SOME EXPERIMENTS ON THE BURNING OF FABRICS AND THE HEIGHT OF BUOYANT DIFFUSION FLAMES

by

P. H. Thomas and C. T. Webster

Summary

Some data on the effect of varying the width of fabric on the rate of burning and the flame height are reported.

These flames differ from fuel jets which have been investigated by several workers in that the initial momentum of the fuel entering the flame is small compared with the increase in momentum due to the flame buoyancy.

The results are discussed in terms of an elementary theory for a turbulent flame but more experimental data are required to provide an adequate test of the theory.

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SOME EXPERIMENTS ON THE BURNING OF FABRICS AND THE HEIGHT OF BUOYANT DIFFUSION FLAMES

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Introduction

Experiments on the rate of spread of flame on vertically hanging fabrics have been described by Lawson, Webster and Gregsten [1] and by Webster [2]. All the rates of spread were measured for one width, $1\frac{1}{2}$ in., of fabrics of various weights; the present paper reports some further experiments to investigate the effect on the rate of spread of varying the width of a particular weight of fabric.

The results are of general interest in connexion with the relation between the rate of burning and the flame height, which has also been measured.

Experimental

All the fabric samples used in these experiments were cut from one length of cotton weighing 14.6 mgm. cm^{-2}. Samples 0.63, 1.27, and 2.54 cm wide were cut 2 m. long and samples 5.1 and 10.2 cm wide were cut 3.3 m. long. These lengths were long enough for a steady burning rate to be established [1]. A 36 S.W.G. chromel wire was threaded along the length of the 5.1 and 10.2 cm widths to prevent convection effects causing too great a disturbance.

All the test specimens were conditioned to equilibrium in air at 65°C and 65 per cent relative humidity before use.

The fabric strips were held 15 cm in front of a vertical scale, marked off in 6 in. intervals, and ignited at the lower end, the progress of the flame being recorded photographically.

The quantities measured by means of the photographic record were the maximum steady rate of flame spread up to the fabric and the mean height of the flames for this condition. The height of the visible flame fluctuated as the flame moved upwards. The steady mean value was obtained from several frames on the photographic record and an average taken for the two separate experiments.

In no case was the maximum rate of flame spread a significant fraction of the estimated upward speed of the gases in the flame.

Results

Figures 1 and 2 show respectively the mean steady flame height and the maximum rate of flame spread for the various widths of fabric. Figure 3 shows the relation between the flame height and the product of the width of the fabric and the speed of the flame spread. This product is proportional to the rate of burning in terms of weight loss.

Theory

It is possible to derive some theoretical expressions for comparison with the data obtained in these experiments. We first consider a fuel jet. Hawthorne, Weddel and Hottel [3] have shown that a turbulent diffusion flame in which the fuel velocity at the burner nozzle is very high behaves in a manner which can be described in terms of simple mixing theory, the nozzle velocity determining the gas velocity in the flame and hence the rate of entrainment of air. Hawthorne, Weddel and Hottel showed that the length of a fuel jet is very sensitive to variations in the fuel composition. Thus the length of a carbon monoxide flame is about $^1/6$ that of a propane flame. One would expect a similar effect for fabric flames, and in view of the uncertainty of the composition of the volatiles released from the burning cotton, a complete quantitative comparison between theory and experiment has not been made. Although a more sophisticated theory than the one given below is necessary for a complete analysis, the simplified analysis following is sufficient to derive the form of the relation between flame height and rate of burning for a turbulent flame.

In the flames from a burning fabric the fuel velocity at the base of the flame is very small compared with the velocities higher up the flame which are determined by the buoyancy, so that the rate of entrainment of air into the flame zone is controlled by a velocity which is largely independent of the rate of entry of fuel into the flame. We assume the flame to be tall in comparison with the fabric width and to be in effect conical with a half angle 'α', see Fig. (4) and Plate 1. The velocity 'V' at a height 'x' is taken as $k\sqrt{x}$, where k is a constant. The rate of entrainment of air is $\epsilon . 1/\ell$ where ϵ is an eddy diffusivity and ℓ a characteristic length; ϵ is proportional to ℓ and the local velocity which is $k\sqrt{x}$ so that the total rate of entrainment of air per unit area of air/flame surface δA may be written $\rho_a \, 2\pi . \tan\alpha . x . \delta x \, a \, k\sqrt{x}$ where ρ_a is the density of air and a is the constant of proportionality between the velocity of entrained air and the gas velocity in the flame. By integration $$A = \frac{4}{5} \rho_a \pi a k . \tan\alpha \; H^{5/2}$$

If N is the overall air/fuel ratio and W the rate of loss in weight of the cotton we have

$$NW = \frac{4}{5} \rho_a \pi . a . k . \tan\alpha . \; H^{5/2} \qquad (1)$$

For the sake of generality we shall write

$$W \propto H^{\frac{5}{2} m}$$

and

$$H \propto W^{\frac{2}{5} m} \qquad (2)$$

where m is a coefficient approximately unity. The reason for the introduction of m is discussed below.

If r is the mean mass rate of burning per unit area
- Q the mean heat flux to the surface
- h the mean heat transfer coefficient
- θ_0 the effective ignition temperature measured above ambient
- c the fabric specific heat
- ρ_f its density
- Δ the thickness
- v the rate of flame spread up the fabric

The length of fabric which is actually burning (see Fig. (4) is

$$L_1 = \frac{\rho_f \Delta v}{2r} \qquad (3)$$

and from a simple heat balance the length of flame preheating the fabric up to an effective ignition temperature θ_0 is

$$L_2 = \rho_f \Delta . v . \frac{c\theta_0}{2(Q - h\theta_0)} \qquad (4)$$

We now obtain from (2) and (4)

$$H = L_1 + L_2 = \frac{\rho_f \Delta v}{2}\left\{\frac{1}{r} + \frac{c\,\theta_0}{Q - h\,\theta_0}\right\} \qquad (5)$$

Writing

$$W \propto \rho_f \Delta v, D \qquad (6)$$

where D is the width of fabric we obtain from (2)

$$H \propto \left\{D \Big/ \left\{\frac{1}{r} + \frac{c\,\theta_0}{Q - h\,\theta_0}\right\}\right\}^{\frac{0.4}{m-0.4}} \qquad (7)$$

From equations (4) (5) and (6)

$$v \propto D^{\frac{0.4}{m-0.4}} \left\{\frac{1}{r} + \frac{c\,\theta_0}{Q - h\,\theta_0}\right\}^{-\frac{m}{m-0.4}} \qquad (8)$$

Discussion

Equation 1 states that the slope in Figure 3 should be 0.40 and the line drawn gives 0.42. The fact that this index is slightly larger than the theoretical value shows m (see equation 2) to be less than 1, viz: 0.95. If m were equal to 1 and the values of r and Q were constant, we should expect:-

$$H \propto D^{0.67} \text{ in Fig. 1}$$
$$v \propto D^{0.67} \text{ in Fig. 2}$$
$$\text{and } H \propto (D.v)^{0.4} \text{ in Fig. 3}$$

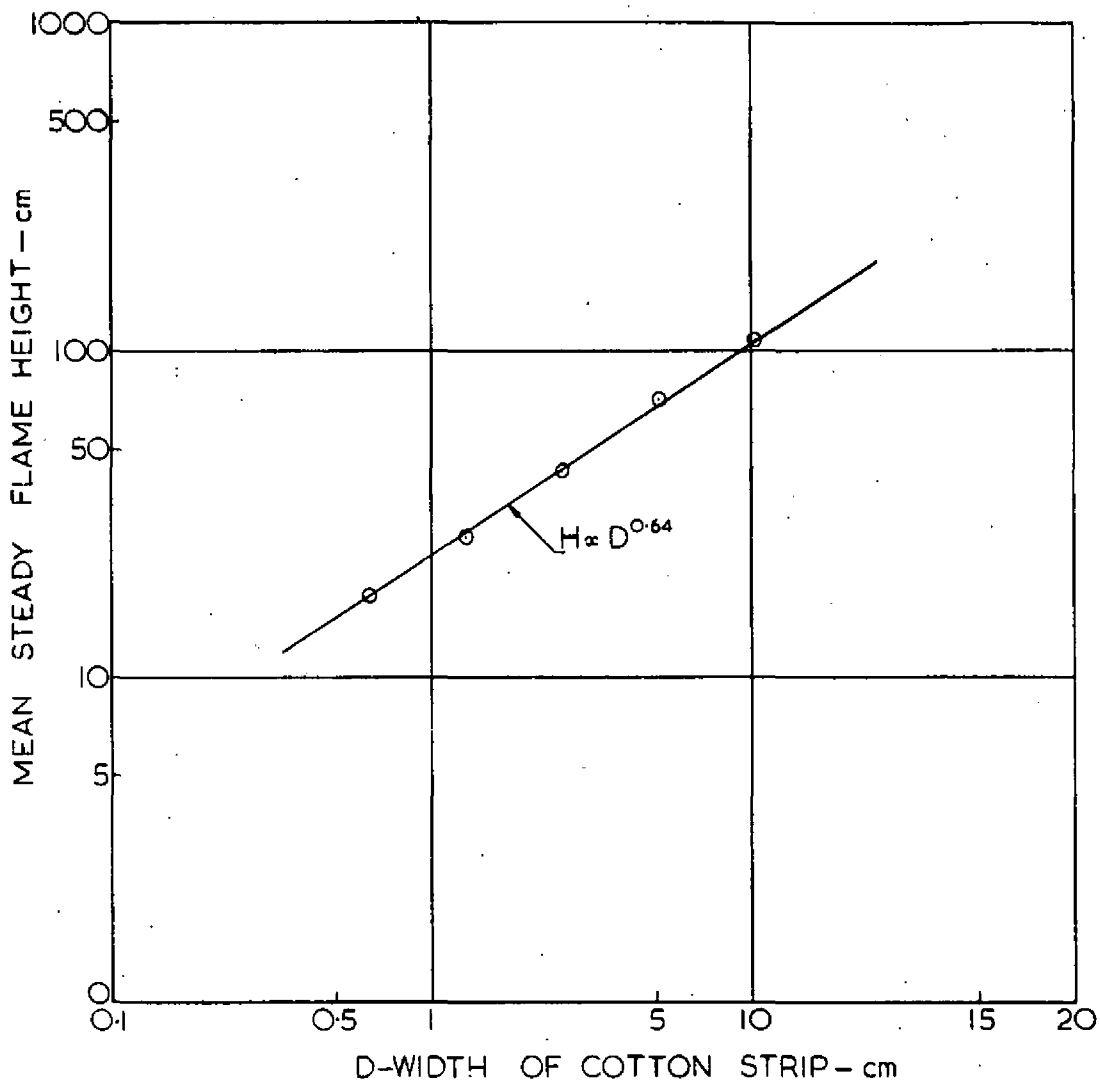
The discrepancies between the data and theory in figures 1 and 3 would hardly be significant, were it not for the fact that the discrepancy between data and theory for the results in figure 2 is large enough to be real.

In terms of the above theory the three observed indices are made mutually consistent by allowing a small change in r and Q with a change in D. It can be shown that taking the observed values of the indices for the data in figures 1 and 3, we can from equations (5), (7) and (8) obtain the value of 0.52 for the index in figure 2. The three relations above, or their equivalents - equations (5), (7) and (8) - are not independent and we shall, therefore, need only to discuss any two of these three. We shall in fact consider those relating flame height to the rate of burning and the fabric width, i.e. the relations expressed in equations (5) and (7). There are two factors which could give rise to the difference between experiment and theory. The first is the presence of a laminar region at the base of the flame. To include the effect of molecular diffusion one may write

$$\epsilon = \epsilon_0 + b V . \ell$$

where b is a constant, V is the mean upward gas velocity and where ϵ_0 is the coefficient of molecular diffusion. The effect of adding molecular diffusion is to reduce the estimated flame length and the effect is most marked with short flames. This would have the effect of increasing the index 0.4 between flame height and rate of burning. The second is that any initial momentum in the fuel entering the base of the flame tends to make the flame more like a fuel jet and this also raises the index of W. Thus for a turbulent fuel jet[3]

$$H \propto D \qquad (9)$$



Weight of cotton 14·6 mg cm^{-2}

FIG. 1. FLAME HEIGHT AND WIDTH OF COTTON STRIP

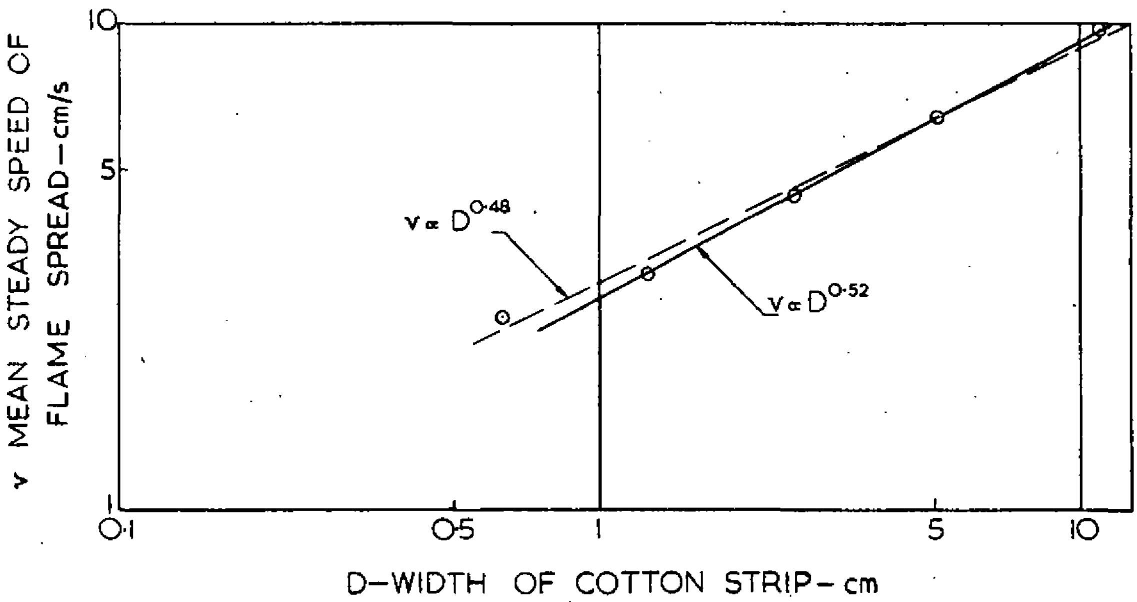


FIG. 2. SPEED OF FLAME SPREAD

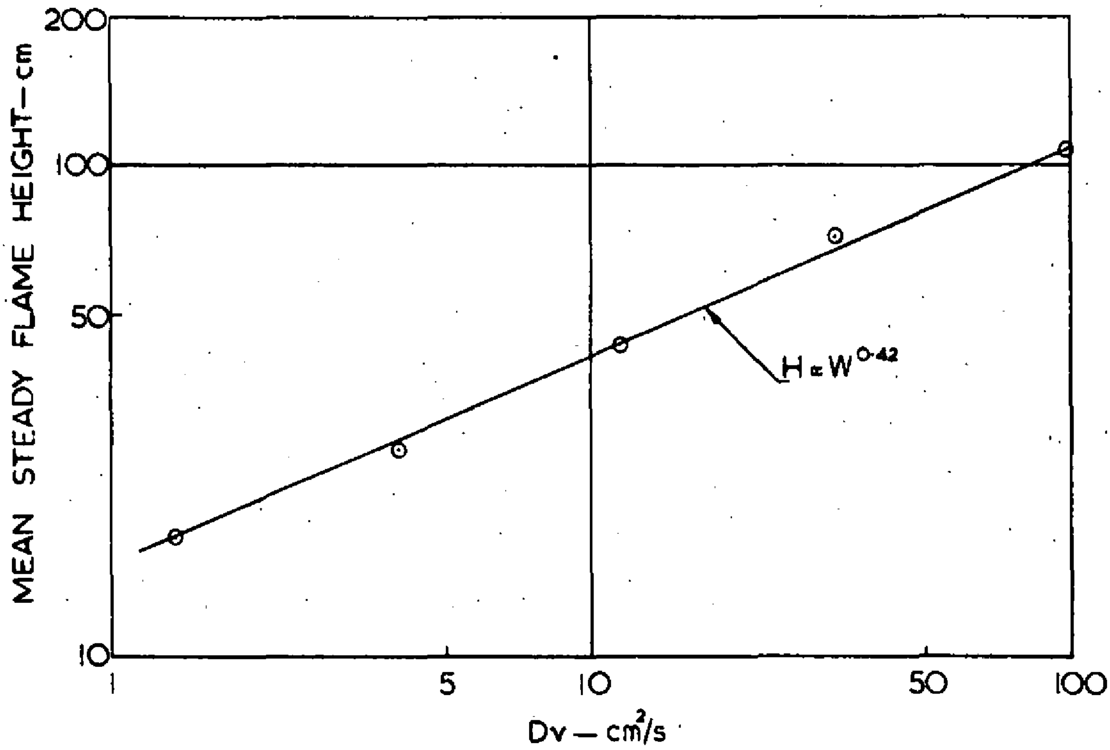


FIG. 3. FLAME HEIGHT AND BURNING RATE
(The gross burning rate W is proportional to DV)

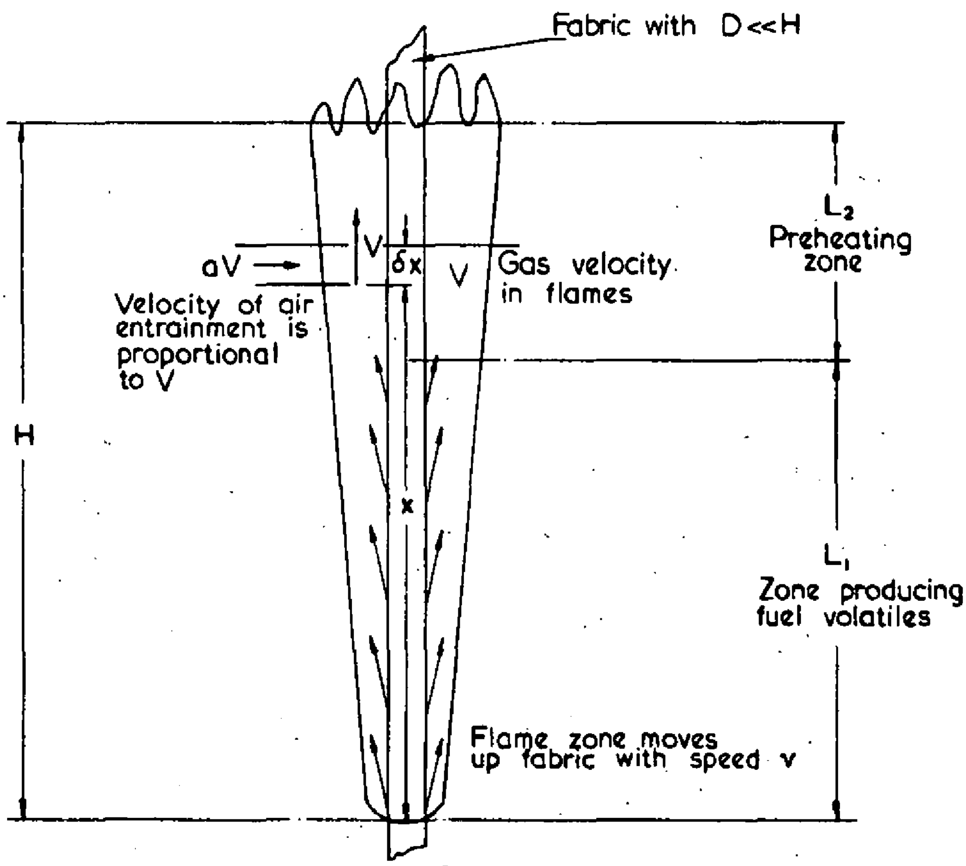


FIG. 4. DIAGRAM OF THEORETICAL MODEL

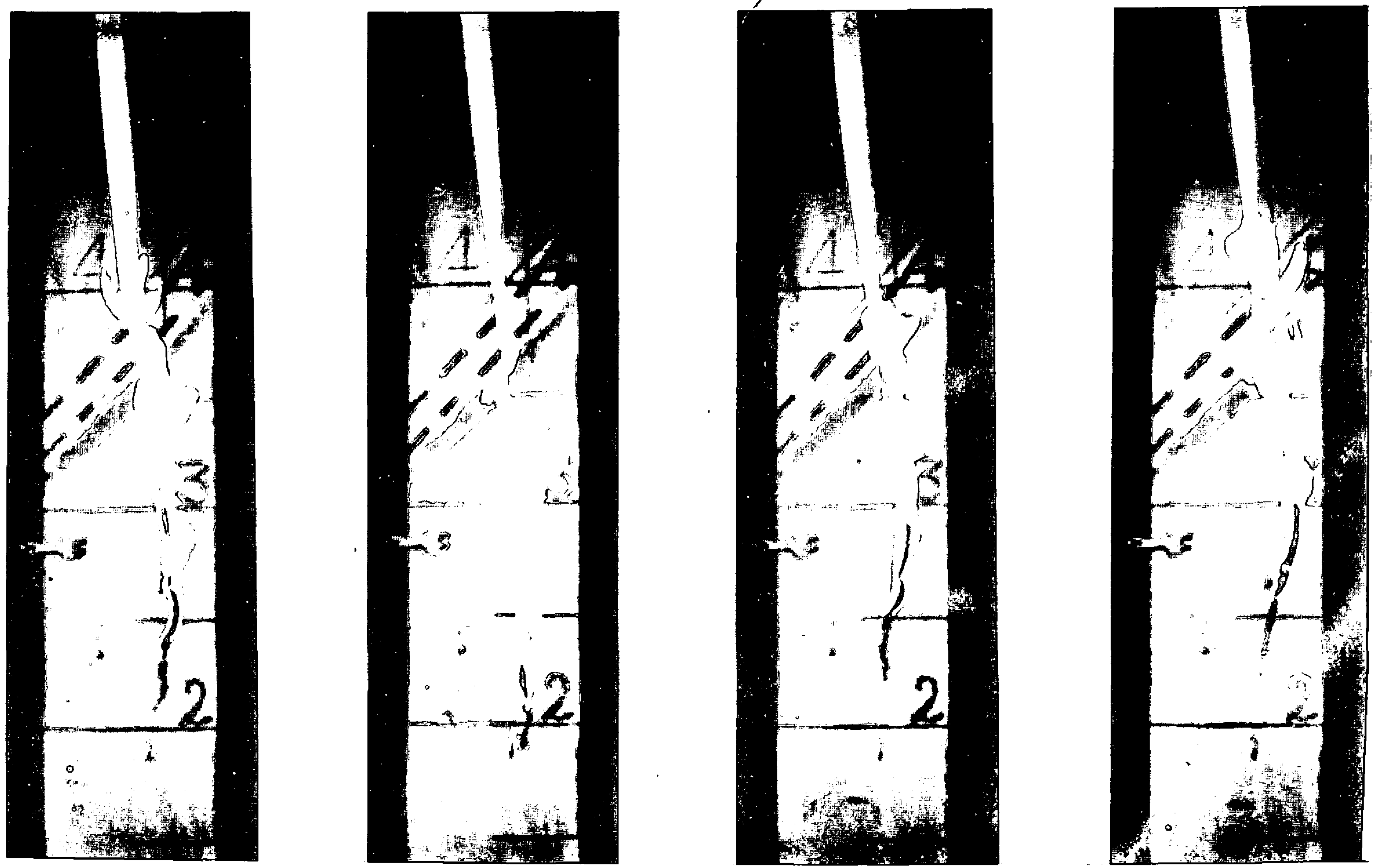


PLATE 1. TYPICAL FLAMES ON 2 IN. STRIP — VERTICAL SCALE IN FT.