Fire Research Note

NO. 600

FIRE SPREAD IN WOODEN CRIBS:
PART III THE EFFECT OF WIND

by

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FIRE
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STATION

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SUMMARY

Byram, Clements, Elliott and George have reported experiments on the effect of a wind on the rate of spread of fire through cribs of wood and from their data it is shown here that the rate of spread normal to the deflected flames is the same as in still air. This is interpreted as being the result of the inclination of the fire front in the fuel bed being roughly the same as that of the flames, i.e. the fire is driven by radiation from the solid surfaces in the burning zone. The note also discusses briefly some general topics of the effect of wind on the fire spread.

June, 1965

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE

JOINT FIRE RESEARCH ORGANIZATION

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Introduction

The effect of wind on the spread of fire appears to have been first studied in controlled experiments by Curry and Fons[1]. In their experiments they used beds of pine needles, and similar experiments are being continued today by Anderson and Rothermel[2]. About 1958 Fons began "Project Fire Model" in which the spread of fire through cribs of wood sticks was studied systematically[3]. After his untimely death the work was continued by Byram and he and his collaborators have recently described the effect of wind on the spread through wooden cribs[4]. Some experiments at the Fire Research Station, Boreham Wood, on cribs, have also been reported in summary form[5] by Thomas and Pickard.

If one plots the rate of spread of a fire 'R' against the wind speed 'U' various kinds of curve are obtained. Thus in all the experiments with beds of pine needles, the curve is concave upwards, i.e. $d^2R/_{dU}2$ is positive. On the other hand the experiments with cribs of $\frac{1}{2}$ in sticks described by Thomas and Pickard[5] for winds up to 28 ft/s exhibited the opposite tendency, namely that the rate of spread appeared to be approaching a limiting value at high wind speeds and the curve was convex upwards, i.e. $d^2R/_{dU}2$ was negative (see Fig. 1). The recent data reported by Byram et al[4] for winds up to 13 ft/s show an approximately linear increase in the rate of spread with wind speed. The difference between the curves may be associated with the presence or absence of strips of incombustible material enclosing the sides of the cribs. Enclosing cribs with incombustible sides increased the rate of spread in still air, i.e. the effect of reducing thermal loss is greater than that of reducing the access of air, at least in still air. Such sides increase the effective width of the fire front so that one should expect the relationship between rate of spread and wind speed to be sensitive to the width of the fire front. In a wind, enclosing the sides of the crib may alter the heat transfer to the sides of the crib downwind from flames blown around them.

This report begins with a general discussion of the effect of wind on fire spread in cribs as a result of which it is argued that in deep fuel beds the spread is more likely to be governed by the radiation transferred through the fuel bed than it is in shallow beds.

It is shown that the results recently obtained by Byram et al can be interpreted as fire spread in still air perpendicular to a moving fire front inclined at an angle largely determined by a dimensionless wind speed. A means of examining field data to see if they comply with this view is suggested.

The effects of a wind on a spreading fire

Let us consider a given fuel bed in which the wind speed is increased. So long as the thermal environment of a given fuel element passing through the burning zone is approximately constant, the time for which it remains in a burning zone will be largely independent of the wind speed, and this means that the depth of the burning zone in the direction of fire spread must be expected to increase roughly in proportion to the increase in wind speed. The experiments in still air by Fons and Byram and their collaborators have shown that the residence time is largely a function of the stick thickness and therefore as the stick thickness increases so the depth of the burning zone increases (see also Thomas, Simms and Wraight)[6]. Such an increase in the length of the burning zone means that more heat is lost and more air enters the cribs at the sides so that the width of the crib must be increased if the fire is to be representative of two dimensional spread. As the length of the burning zone increases due to the increase in wind speed the forward part of the burning zone is separated by an increasing distance from the windward side of the fire. The effect of this partly offsets the greater penetrating effect of the higher wind speed so that even if a fire at low wind speeds was not air controlled it might become air controlled as the wind speed became higher. Properties of the fuel bed such as porosity and fuel element size then influence the burning behaviour in a different way and the heating of the unburnt fuel can no longer be treated as if the heat flux were independent of the rate of spread, i.e. the heating of the unburnt fuel and the burning behaviour of the burning zone are not independent and the system becomes more complicated. As the rate of spread increases more fuel is burning and the flames deflected by the wind become longer. The heat transfer to the unburnt fuel will then change from being predominately radiation through the fuel bed to being predominately convection either from above or through the fuel bed.

We shall now show that the absolute height of the fuel bed must be an important factor in separating radiation controlled and convection controlled regimes.

Dimensionless wind speeds

A dimensionless wind speed, convectional in two dimensional problems of forced convection and thermal plumes, has been defined in various forms. In thermal units it is

$$\Omega = \frac{U}{\left(\frac{g\dot{Q}'}{\rho_a c T_o}\right)^{\frac{1}{3}}}$$

and in mass units

$$U^* = \frac{U}{\left(\frac{g\dot{m}'}{\rho_a}\right)^{\frac{1}{3}}}$$

where g is the acceleration due to gravity

ρ_a is the density of air

c is its specific heat

T_o is the absolute temperature of the environment

$\dot{m}'$ is the rate of burning of the fuel per unit width of fire front

and $\dot{Q}'$ is the rate of heat release per unit length of fire front

Physically the former is more meaningful though the measured quantities are usually those appearing in the latter, i.e. wind speed and burning rate. Byram[7] has used Ω in a slightly different form as a criterion determining the contribution of forced convection over large fires and Thomas, Pickard and Wraight[8] have used U^* to correlate data on flame length. If a nominal calorific value of the fuel is used the flame length correlations can readily be expressed in terms of thermal units.

As an example the height of flames from the source of heat in still air has been given by

$$L = \frac{47}{g}\left(\frac{g\dot{m}'}{\rho_a}\right)^{\frac{2}{3}} \qquad \ldots\ldots\ (1)$$

If a nominal calorific value of 8,000 Btu/lb or 4,450 cal/gm is employed and cT_o is taken as 72 cal/gm this relation may be written as

$$L = \frac{3.0}{g}\left(\frac{g\dot{Q}'}{\rho_a c T_0}\right)^{\frac{2}{3}} \qquad \ldots\ldots\ (2)$$

The fact that the numerical coefficient of proportionality is of order unity is a reflection of the fact that the velocity $\left(\frac{g\dot{Q}'}{\rho_a c T_0}\right)^{\frac{1}{3}}$ has greater physical significance than $\left(\frac{g\dot{m}'}{\rho_a}\right)^{\frac{1}{3}}$.

However, a criterion for the transition between a radiation controlled fire spread and a convection controlled fire spread is unlikely to depend solely on Ω or U^*. If we write

$$\dot{m}' = R\rho_b h$$

where h is the height of the fuel bed

and ρ_b is the bulk density of the fuel bed

we obtain from equation (1)

$$\frac{L}{h} = \frac{47}{h^{\frac{1}{3}}}\left(\frac{g\,R\rho_b}{\rho_a}\right)^{\frac{2}{3}} \qquad \ldots\ldots\ (3)$$

So long as the fire is controlled by radiation transfer through the fuel bed $R\rho_b$ is approximately constant, so that the ratio of the flame height to the height of the fuel bed decreases as the fuel bed becomes deeper. The flames produced by a fire in thin layers of dried grass are relatively taller than flames from fires in bushes though absolutely shorter. The dimensionless wind speed is greater for the smaller values of h for any given absolute wind speed and the effects of wind are therefore more likely to produce convective control for the shallower fuel beds. On the other hand crowns are in effect deep fuel beds and if fire spread in bushes is radiation controlled crown fires are also expected to be controlled by radiation through the crowns.

It will be apparent that for a ground fire the depth of the fuel that must be incorporated into the above expressions is not necessarily known a priori since only the top fuel may be burnt. The quantitative determination of the factors governing this have yet to be resolved.

Convection heating of cotton tufts downwind of an alcohol fire

Byram et al[4] illustrate a discussion of the relative importance of convection and radiation from the flames in fire spread by reference to some experiments on the ignition of cotton tufts in the lee of a tray of alcohol burning in winds of 3.7 to 13.3 ft/s. For this situation there is of course no heat transfer through the fuel bed as there is in cribs. Nevertheless it is instructive to discuss these results quantitatively. The burning rate of the alcohol at first decreased slightly (about 10 per cent) from its still air value and then increased to about its initial still air value as the wind speed rose. This is possibly a result of the decrease in radiation due to the bending over of the flames being compensated by the increased convection but for these experiments the variation was small, so that the mean value 37.7 Btu/s will be taken in the following calculations.

Although the tray was a square of side 12.7 in and ignition occurred up to 2 ft from the tray we shall, for simplicity, calculate downwind temperatures as if the heat source were very wide, and neglect the sideways diffusion.

Thomas[9] has correlated Rankine's data[10] for the bent over thermal plume to obtain the temperature rise at a distance x downstream of a line source as

$$\theta = \frac{2.35\,v^2 T_0}{g x} \, \Omega^{0.14} \qquad \ldots\ldots\ldots (4)$$

where $$v = \left(\frac{g\dot{Q}}{\rho c T_0}\right)^{\frac{1}{3}} = \frac{U}{\Omega}$$

In Rankine's data $\theta/T_0 < 0.1$ but this restriction will be disregarded here.

For the value of $\dot{Q}'$ quoted above v is 148 cm/s. The position of the effective equivalent line source is in doubt and the choice of the origin of will be the somewhat arbitrary one of the centre line of the tray. For the five results given by Byram et al for wind speeds in the range 3.7 to 13.3 ft/s, Ω is 0.76 to 2.72 which is mostly in the range to which equation (4) refers. θ calculated from equation (4) decreased as U increases; the mean value was 240 deg C with a standard deviation of 22 deg C. These values would appear to be realistic and show that the cotton tufts were raised to temperatures at which a little extra heating, e.g. by flame radiation, would release sufficient volatiles to be ignited by "darting segments" (sic) of flame. Equation (4) gives estimates of downwind temperatures from wide fires but it does not allow for heat loss and because the heating of the unburnt fuel implies a heat loss from the hot gases further consideration, must be given to the convective processes before equation (4) can be used directly.

However, although convection transfer plays an important and probably the major part in the heating of the cotton tufts to ignition it does not follow that the same is true for spread in cribs which we now show can be interpreted in a different way.

The inclined radiation front

In studies of the propagation of flame through gases it is customary to define a flame speed normal to the flame front and we shall apply this concept to fire spread. Figure 2 shows diagrammatically a section through a fuel bed in which a burning zone is moving steadily at a velocity 'R'; the velocity perpendicular to the radiation front is then R cos ϕ. The points A and B (see Fig. 2) in the unburnt fuel are heated at the same rate so any extra heating by the flames is offset by the lower radiation due to there being no solid surfaces above the fuel bed or by differences in the cooling coefficients at the top and bottom of the bed. It should be noted that any heating of the unburnt fuel bed will change the inclination of the ignition front unless these convection currents are moving perpendicular or parallel to this front. The ignition front will change its inclination until it is parallel to the convection currents, i.e. until there is no convection heating. If this were not so the fire could not spread at a steady rate since points A and B would not be heated equally. If we consider some point away from the upper surface it is reasonable to conjecture that R cos ϕ is, as in still air, a function of the intensity of radiation emitted by the solid surfaces in the burning zone and the stick size. From the theory given by Thomas et al[11] for the ignition of the unburnt fuel allowing for the effects of non-uniform heating of the fuel elements it follows that if the intensity of radiation and cooling coefficient remain the same in the presence of a wind, R cos ϕ should be a constant for any stick size. However, one must expect that the radiation levels do change because of the increased availability of oxygen but it is not certain how much effect this will have because the radiation transfer that spreads a fire originates mainly from the sheltered surfaces on the lee side of the nurning zone which are closest to the unburnt fuel. Any increase in the radiation level will increase R cos ϕ and this increase will be different for different stick sizes.

Byram et al[4] provide data for the rate of spread under various wind speeds for a number of cribs all having the same stick size $\frac{1}{4}$ inch and spacings between sticks varying from $\frac{1}{2}$ in to $4\frac{1}{2}$ in, a range of 1 to 9 in ρ_b. They covered the sides of their cribs with brown paper treated with diammonium phosphate and also enclosed the downwind end to restrict the air flow into the crib. They also provide values for the deflection of the flames and in the absence of information on the deflection of the radiation front we shall assume that it is equal to the deflection of the flames. This is an assumption which is obviously not always valid but there will be conditions when it is more appropriate than others, and using this data Fig. 3 shows $R\rho_b$ plotted against sec ϕ.

The results show that the use of the mass rate of spread $R\rho_b$ brings together data for a wide range of spacing and $R\rho_b$ is nearly proportional to sec ϕ, i.e. the mass rate of spread normal to the flames is effectively constant. There is some evidence that the correlation fails at the higher wind speeds used by J.F.R.O. but it is not easy to separate such a discrepancy from the error in measuring the cosine of large deflection.

As in still air, the flames are unlikely to contribute much heat compared with the radiation through the fuel bed from the hot surfaces of the fuel elements, (probably because they are too thin to be very emissive) and the result is most probably due to the fire front within the fuel bed being inclined at roughly the same angle as the flames.

If this is so, important factors requiring further study are the deflection of flames, on which some experiments have already been made and the influence on this, if any, of the properties of the fuel bed because this is a step in the upwind boundary layer. Correlations of flame length and height as defined in Fig. (2) have been derived by Thomas, Pickard and Wraight[8] for non-spreading fires. For thin burning zones and $U^* > 1$, these are

$$L = 55 \left(\frac{m'}{g\rho_a}\right)^{\frac{2}{3}} U^{*\,-0.21} \qquad \text{.........} (5)$$

$$H = 38 \left(\frac{m'}{g\rho_a}\right)^{\frac{2}{3}} U^{*\,-0.70} \qquad \text{.........} (6)$$

$$\frac{H}{L} = \cos \phi = 0.7 \quad U^{*\,-0.49} \qquad \text{.........} (7)$$

For low values of $U^* < 1$, $\cos \phi$, of course, tends to unity.

The deflections reported by Byram et al are plotted against ν in Fig. (4) and are seen to follow the same trend with ν as does equation (7) but for the cribs having closely spaced sticks the flames are deflected less than is given by equation (7). The correlations given in equation (5) and (6) were obtained without allowing for variation in stick spacing and will be re-examined to see if there is any detectable effect of the properties of the fuel bed.

Conclusions

It has been shown that for cribs there is a strong correlation between the mass rates of burning R/ρ_b and the flame deflection which is consistent with the spread perpendicular to the inclined front being independent of the wind speed. This means that field data for varying wind speeds could profitably be correlated in these terms.

If data on flame deflections are available these allow two correlations to be made viz: R/ρ_b versus deflection and deflection versus ν or U^*. In the absence of flame deflection data R/ρ_b must be correlated with ν or U^* directly. If uncertainty exists as to ρ_b the ratio of R in a wind to R in still air provides a means of normalising field data for different fuel beds of the same basic type.

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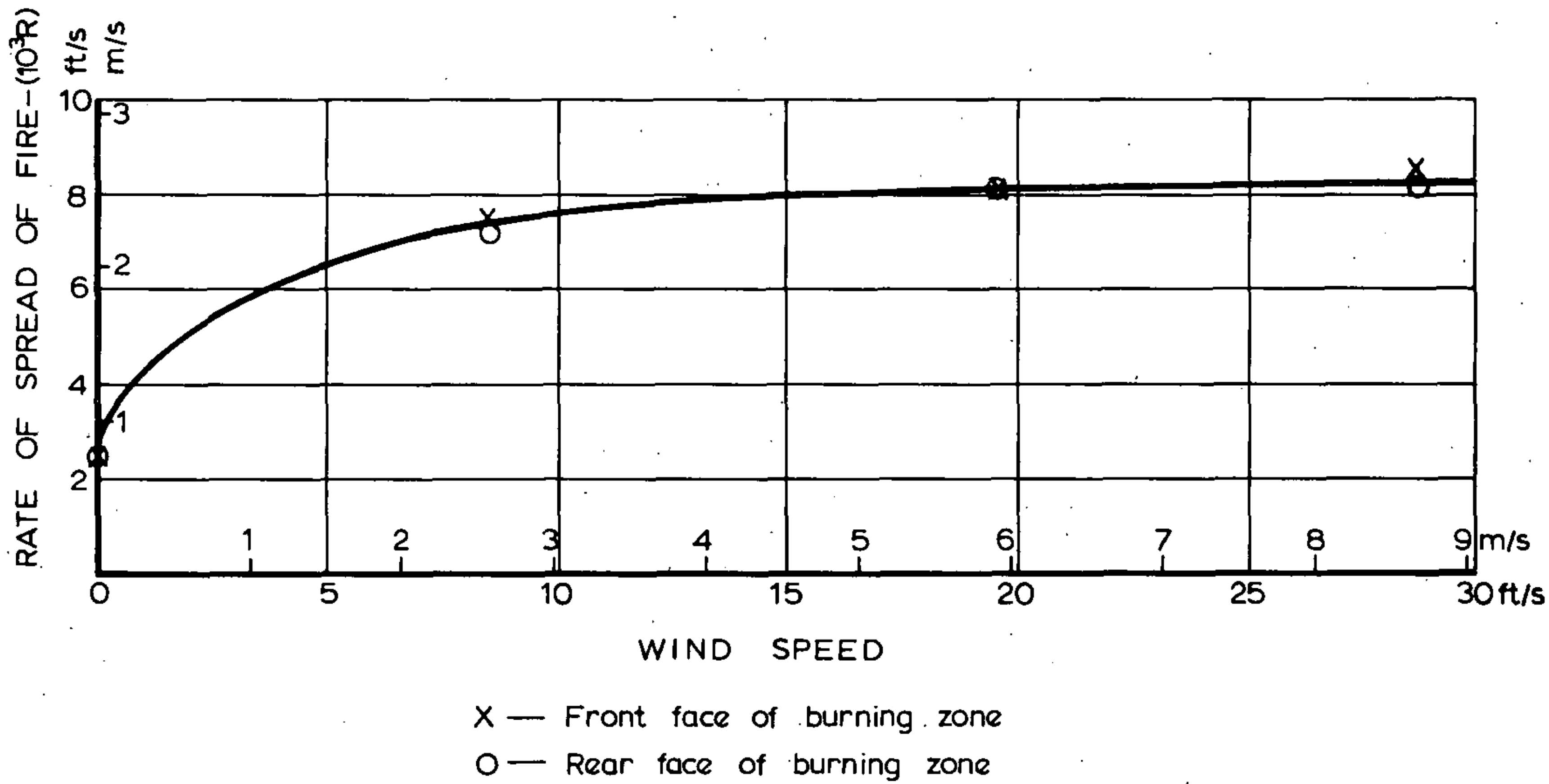

FIG. 1. FIRE SPREAD IN CRIBS WITH COVERED SIDES

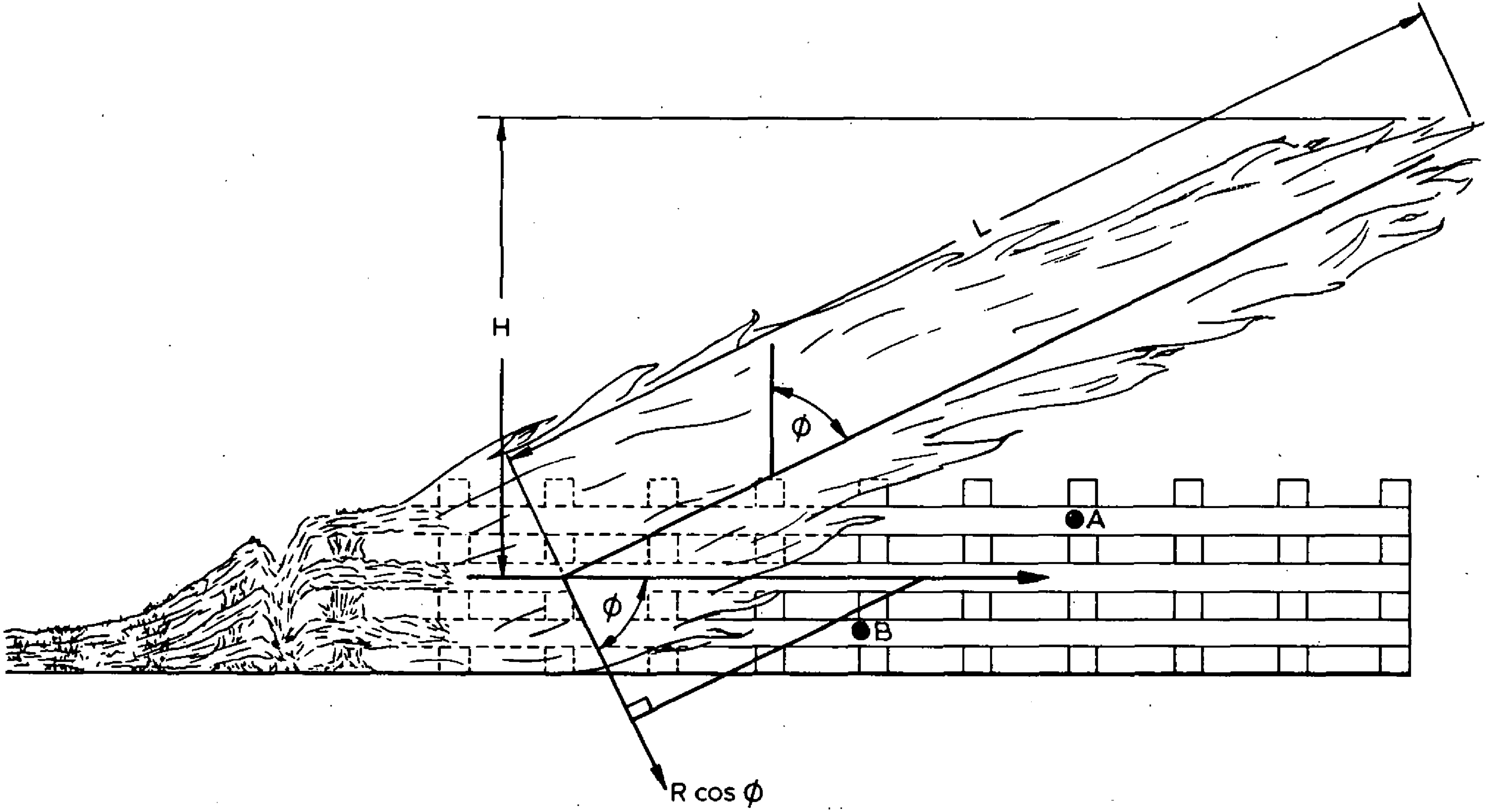

FIG. 2. PROPAGATION OF FIRE IN CRIBS

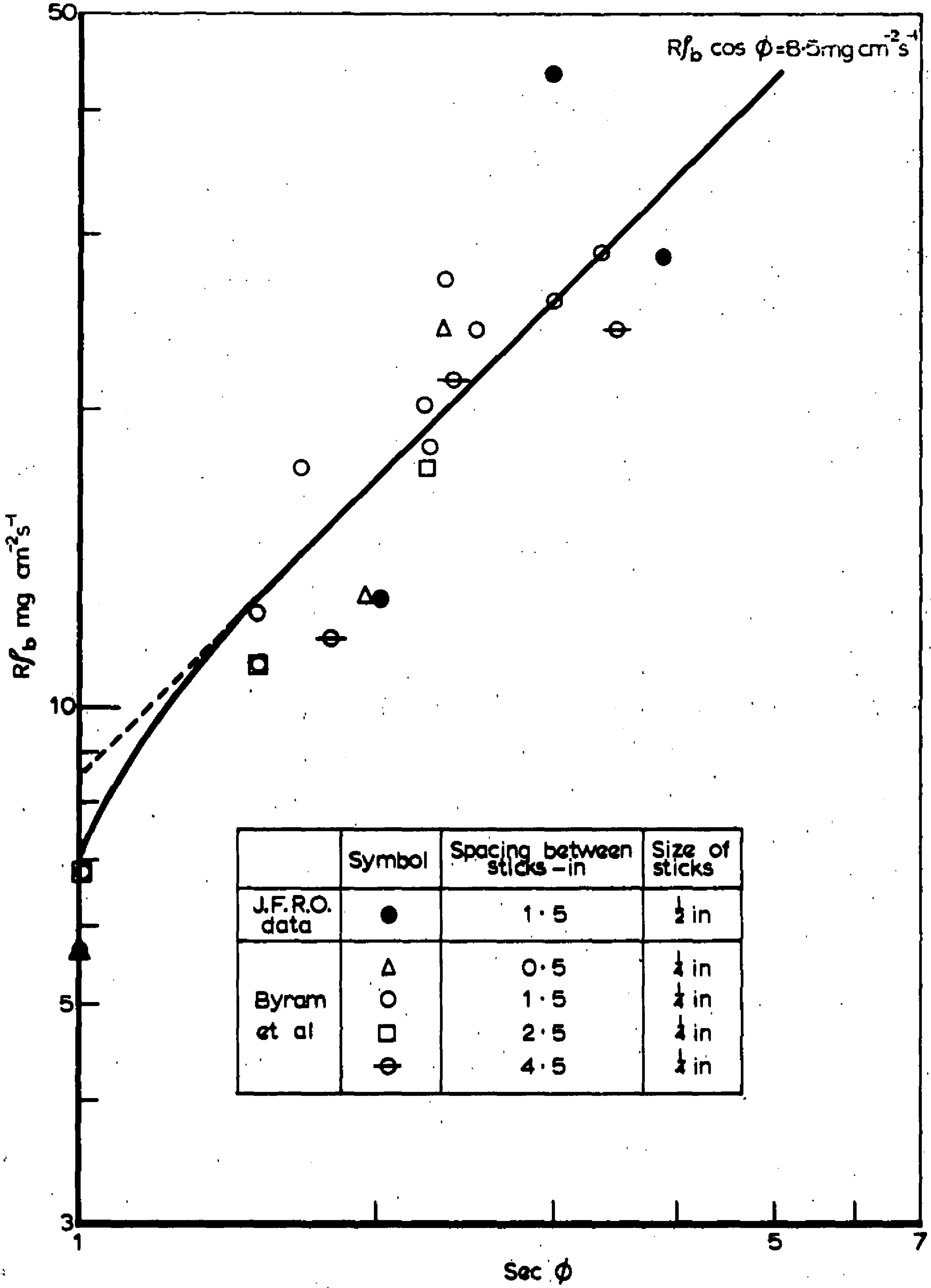

FIG. 3. EFFECT OF INCLINATION OF FIRE FRONT

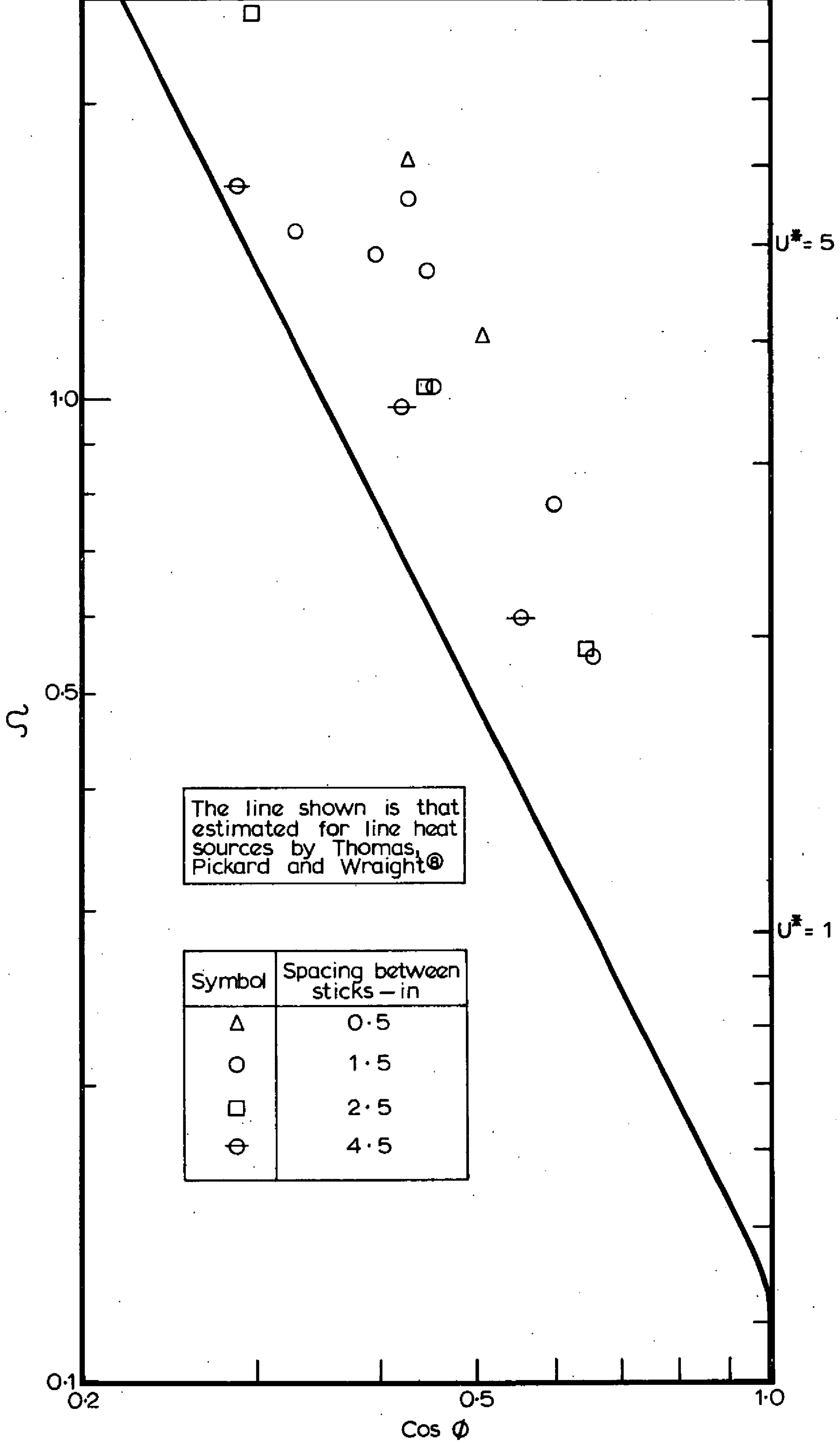

FIG. 4. DEFLECTIONS MEASURED BY BYRAM ET AL

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