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# CALCULATIONS ON FOREST FIRE SPREAD BY FLAME RADIATION

by

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## ABSTRACT

This paper contains some theoretical speculations on the possible heating effect of flame radiation in front of forest fires. Flame variables used are rate of advance, length, angle of tilt and radiant intensity. Taking a simplified case, an expression is derived for the total radiation received by a fuel element before engulfment. This quantity is equated to the energy required to raise the fuel to ignition temperature, and an expression obtained for the ratio of flame length to rate of advance. By using published formulae linking flame length to a fractional power of the fire's energy output per unit length of front, the rate of advance can then be estimated. The final expression links rate of advance, fuel moisture content and flame angle in a way that corresponds roughly to the observed behaviour of surface fires of moderate intensity.

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## INTRODUCTION

In order to advance as a solid front, a forest fire must transfer ahead of it enough heat to ignite the unburned fuel in its path. There are at least three plausible mechanisms for this heat transfer: actual contact by licking tongues of flame, radiation through the fuel layer from the burning fuel particles, and radiation from the flames. The question of the relative importance of flame radiation in propagating fire is not well resolved in the literature. Byram *et al.* (1964) and Countryman (1964) suggest that convective-flame contact is the most important mechanism in the advance of wind-driven fires. Thomas, Simms, and Wraight (1964), on the other hand, showed that radiation through the fuel bed governs the rate of advance of laboratory crib fires, whose thin flames have only a secondary heating effect; the same mechanism controlled the pine-needle fires burned in still air by Anderson and Rothermel (1965).

Observation of forest fires suggests that flame radiation is important in some types. A light wind may, for instance, convert a fire burning gently in dry pine litter with flames about 1 foot high to one with flames perhaps 8 feet high, at the same time increasing the energy output perhaps 20-fold. The rate of advance may be many times what could be accounted for by radiation through the fuel bed, and yet the flames, once fully developed, may tilt no more than 30 degrees or so from the vertical. The flame radiation intensities of some such fires at the Petawawa Forest Experiment Station have been measured with a directional-radiation pyrometer. The range encountered lies between about 0.5 cals/cm$^2$-sec for

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the smaller flames described above to about 1.5 for the larger. Deep flames in large piles of logging slash have been observed to radiate over 3 cals/$cm^2$-sec.

Whenever flame radiation is important in propagating forest fire, the total heat dose received by a particle of fuel as the fire approaches and engulfs it must be significant. In this paper, an expression for this quantity is derived for a simple case and equated to the energy required to bring fuel to the ignition state. The object of this exercise is to develop some unsophisticated expressions that can be tested against experimental surface forest fires on which only fairly simple measurements need be made, in the hope that a reasonable degree of validity can be achieved without a truly rigorous treatment.

## RADIATION DELIVERED BY FLAME

The variables employed are: 1) the rate of advance of the flame, 2) the flame length, 3) the angle between flame front and unburned surface, and 4) the flame's emitted radiation intensity. The following assumptions are made:

1) The flame front extends in a straight line of infinite length.
2) Flame temperature and emissivity are independent of height.
3) The fuel is a smooth, thin layer with negligible thermal diffusivity in the horizontal plane.
4) There are no intervening objects obstructing the radiation, and no absorption by the atmosphere.

Consider Figure 1. BC is a flame advancing toward the left at constant speed V, making an angle A to the surface ahead. The flame's length is L, and its perpendicular height CD. P is a point in the fuel plane at distance x from the base of the flame B, and m is the distance between B and the base of the perpendicular CD.

Suppose that the flame radiates with an intensity E and that, at a given instant, P receives radiation of intensity R. (E and R are in terms of energy per unit area per unit time.) Then R and E are related by the configuration factor F, which, by definition, equals $^R/_E$ and depends on the geometry of the case.

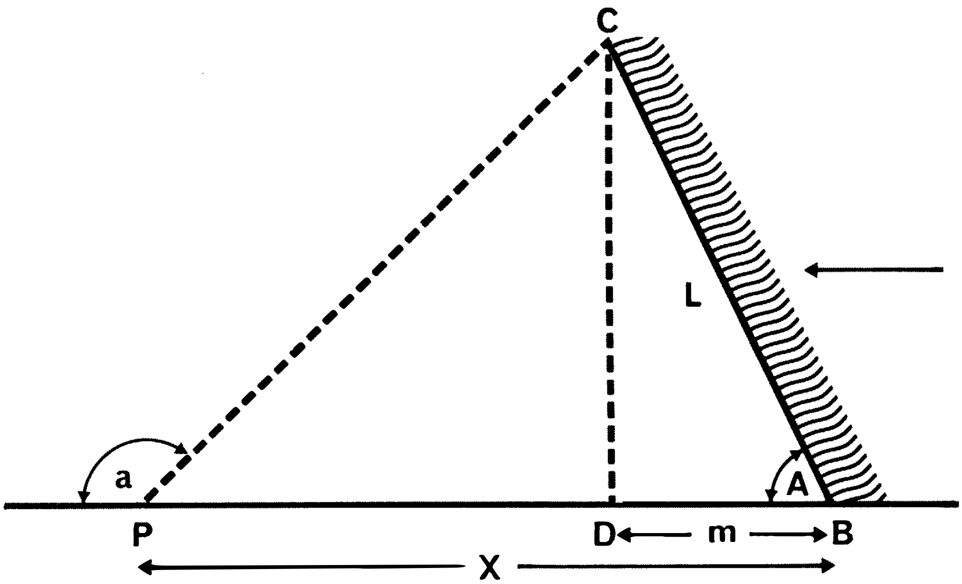


*Figure 1. Diagram of flame advancing over level fuel bed.*

Let Q be the total amount of energy received per unit area at P as the fire approaches and reaches it. Then

$$Q = \int R \, dt$$

$$\text{But } R = FE$$

$$\text{Therefore } Q = E\int F \, dt \quad \text{.............................} \quad (1)$$

This integration is more easily visualized and performed if P is imagined to approach the flame and time t assumed to run from minus infinity to zero at the moment of contact.

In order to integrate expression (1), a statement of F is required in terms of the variable t and also containing A, V and L. McGuire (1953, page 8) gives a formula for F for the case of a receiving element in front of a radiating strip of infinite length. From his general case, the particular formula for Figure 1 (in which the plane of the receiving element intersects one edge of the radiating strip) is:

$$F = \tfrac{1}{2}\,(1 + \cos a) \quad \text{.......................} \quad (2)$$

where a is the outside angle between PC and the fuel surface.

$$\text{Now } \cos a = \frac{-\,PD}{PC} = \frac{-\,PD}{\sqrt{PD^2+CD^2}}$$

But PD = x-m = -Vt-L cos A

and CD = L sin A

$$\text{Therefore } \cos a = \frac{L \cos A + Vt}{\sqrt{V^2t^2 + 2\,LVt \cos A + L^2}} \quad \ldots\ldots\ldots\ldots \quad (3)$$

Substituting (2) and then (3) in (1),

$$Q = \frac{E}{2} \int_{-\infty}^{0} (1 + \cos a)\, dt$$

$$= \frac{E}{2} \int_{-\infty}^{0} \left[ 1 + \frac{L \cos A + Vt}{\sqrt{V^2t^2 + 2LVt \cos A + L^2}} \right] dt. \quad (4)$$

$$= \frac{EL}{2V} (1 + \cos A) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

For vertical flames, this result reduces simply to

$$Q = \frac{EL}{2V} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

In expressions (4) and (5) attention must be paid to sign; thus the numerical value of t is always negative, as is cos A for angles over 90 degrees. Both expressions can be used to illustrate some aspects of flame radiation in front of fires.

If F, the right-hand side of (4) divided by E, is plotted against t, then the area under the curve represents $^Q/_E$, the radiation exposure as an equivalent time at full radiant intensity E. Families of curves may be drawn to show the effect on $^Q/_E$ of varying either the ratio $^L/_V$ or the flame angle A. It turns out that for cases similar to those encountered in the field, most of the radiation received by a fuel element is delivered during about the final minute before engulfment.

## ENERGY REQUIRED TO PREHEAT FUEL

The fire is assumed here to advance simply by preheating each fuel element to a temperature of 300°C by the time the flames reach it, at which moment the escaping flammable gases are ignited. For this ignition mechanism, used by Thomas *et al.* (1964), energy is required only to raise the fuel and its moisture to the boiling point, to evaporate the water, and to heat the dry fuel to ignition temperature. According to Byram *et al.* (1952), the actual sequence of heating events is not so simple, but the above approximation will serve present purposes.

Then, with temperatures in degrees centigrade and using the symbols in the accompanying list, the energy required to raise unit area of fuel bed to ignition temperature is:

$$q = \frac{M}{100}w\ (100-T_o) + Mwh + cw\ (T_i - T_o)$$

This expression can be simplified by inserting values for several reasonably constant factors.

$$\begin{aligned} \text{Let } T_o &= 20°C \\ T_i &= 300°C \\ h &= 540 \text{ cals/g} \\ c &= 0.35 \text{ cals/g-°C} \end{aligned}$$

Then

$$q = w(6.2M + 98) \quad \dots\dots (7)$$

It is plain that the moisture content M in (7) has a marked effect on the required ignition-energy dose. In fact, q increases by about two-thirds of its dry fuel value for every 10 per cent increment in M. With a radiation heat transfer mechanism, this implies a delaying action that could account for much of the effect of fuel moisture on rate of advance, despite the small fraction of the fire's total energy used to preheat the fuel.

If no energy were lost by re-radiation during the fuel-heating process, the relationship between the energy delivered and the energy required would be simply

$$Q = q/e \quad \dots\dots (8)$$

where e is the fuel absorptivity. However, as soon as the fuel bed is heated above ambient temperature, it begins to radiate to the surroundings. The amount of energy thus lost could be determined from the equation or curve of fuel-temperature rise, but the fuel temperature at any instant depends in turn partly on the cumulative energy lost. This complex problem was treated rigorously by Hottel *et al.* (1965) and will not be further considered here; however, a rough graphical treatment for vertical flames with fuel emissivity taken as unity suggests that the energy lost might be about one-quarter of that delivered, and that this proportion is fairly independent of the ratio $^L/_V$. If this were true enough for practical purposes, the re-radiation loss could be accounted for by adjusting the value of the fuel absorptivity e.

## ESTIMATING RATE OF ADVANCE

Ignoring re-radiation losses, the simple relation in (8) can be used to equate the energy q required to preheat the fuel with the energy Q delivered by the flame. From (5) and (7), an expression for $^L/_V$ is obtained:

$$\frac{L}{V} = \frac{2w}{eE} \frac{(6.2M + 98)}{(1 + \cos A)} \quad \text{.......................} \quad (9)$$

The ratio $^L/_V$ has the simple dimension time--as does $^Q/_E$, the radiation exposure in terms of time at the full radiant intensity of the flame.

To actually express V in terms of the factors on the right-hand side of (9), a relation between L and some fractional power of V is required. At least two versions of such a formula are available, one based on a set of field data (Byram, 1959), and the other (Thomas, 1963) on aerodynamic analysis and laboratory crib-fire experiments. Both relate flame length to the rate of energy output of the fire per unit length of the front, and can be put in the form

$$L = k\ (wV)^n \quad \text{..............................} \quad (10)$$

in which n is a fractional constant and k includes the $n^{th}$ power of the heat of combustion, assumed constant. Expressed in the above form in the centimeter-gram-second (c.g.s.) system, Byram's formula is

$$L = 200\ (wV)^{0.46} \quad \text{........................} \quad (10a)$$

and Thomas' is

$$L = 400\ (wV)^{2/3} \quad \text{........................} \quad (10b)$$

Plainly, these two formulae are quite different quantitatively and deviate more and more at higher values of V.

Use of the simple expression (10) for relating L and V eliminates any need for considering flame depth at this stage, although Thomas' equation has the condition that length exceed twice the depth. His equation also applies for still air only, but he implies that wind does not strongly affect the true flame length at constant energy output.

Combining expressions (9) and (10), the following result is obtained:

$$(wV)^{(1-n)} = \frac{k\ Ee\ (1 + \cos A)}{2\ (6.2M + 98)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

The value of the fractional power n in (10) is thus seen to be quite critical, since the higher it is the more sensitive V becomes to variation in all the factors on the right-hand side of (11).

Expression (11) gives the rate of advance V in terms of five factors that should be amenable to measurement or estimation. Looking briefly at these factors in turn, weight of fuel consumed w and moisture content M are relatively easy to measure and predict. Flame angle A can be roughly estimated by eye or photography, and prediction is possible with a formula such as Putnam's (1965), which relates wind speed and flame angle for line fires; it can be stated in c.g.s. units as

$$\tan A = 22.4 \left(\frac{L}{W^2}\right)^{1/2},$$

where W is wind speed. This equation indicates that the longer the flame, the less easily it is tilted by wind, a fact suggested also by general observation of forest fires. Spot measurements of the flame's radiant intensity E are easily made, and relations with flame depth or energy output could be used to predict it. (The effective value of L for calculation purposes may need adjustment, since a forest-fire flame seldom presents a solid wall and does not maintain its radiant intensity all the way to the tip.) Finally, in contrast to the smooth plane assumed in the initial theory, natural fuel beds are loose and rough; the particle surfaces may present a variety of angles to the flame, and some radiation may pass through the burning layer to be adsorbed and lost below. These fuel-bed properties, plus re-radiation loss, can perhaps be incorporated up to a point in the fuel absorptivity e, which then becomes an empirical factor needing experimental determination.

In expression (11), V varies with the inverse of w, but is proportional to a power of E or e; basing (11) on (10a) this power is roughly the square, and for (10b) it is the cube. The relationships with angle A

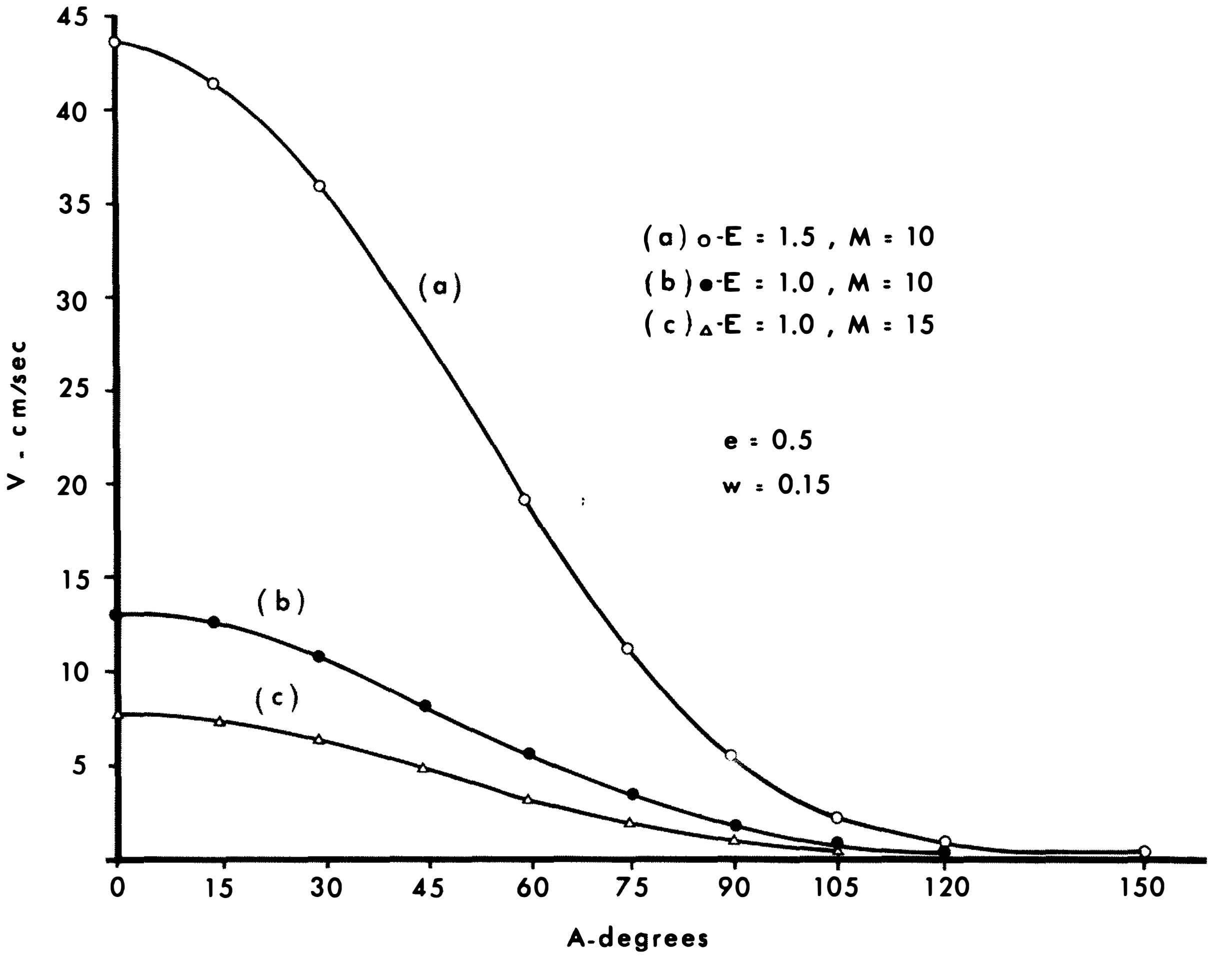


*Figure 2. The relation between rate of advance V and flame angle A for three combinations of radiation intensity E and moisture content M, calculated by expression (11a).*

and moisture content M are more complex, and samples are shown in Figures 2 and 3. For illustration purposes the following form based on (10b) is used:

$$(wV)^{1/3} = \frac{200 \text{ Ee } (1 + \cos A)}{(6.2M + 98)} \quad \ldots\ldots\ldots\ldots\ldots\ldots(11a)$$

In Figure 2, V was plotted against angle A for three combinations of E and M. In Figure 3, V was plotted against M for three combinations of E and A. In all cases, w was held at 0.15 $g/cm^2$ and e at 0.5. Plainly V is in very delicate balance and slight changes in the constants in expression (10) or in any of the factors in (11) are greatly magnified in the resulting values of V. (The plotted values of V are, of course, hypothetical.) The relation

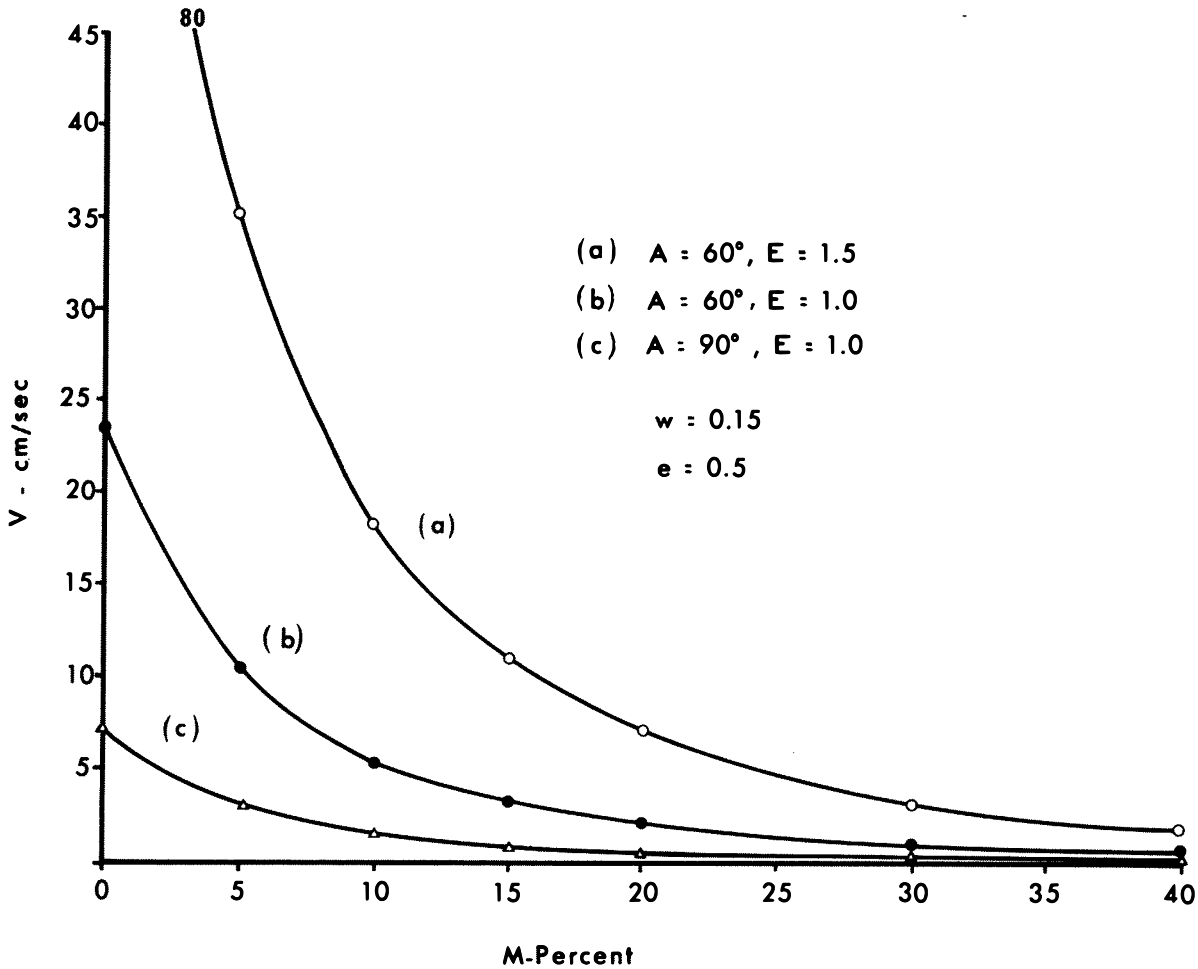


*Figure 3. The relation between rate of advance V and fuel moisture content M for three combinations of radiation intensity E and flame angle A, calculated by expression (11a).*

between V and A or M cannot, however, be expressed by one simple curve; rather, as V increases because of a reduction in A or M, the flame depth will increase and E will rise. Any reduction in A or M is thus compounded and amplified, causing V to rise faster than shown by any curve based on one variable alone.

## OBSERVATION AND EXPERIMENT

Unfortunately no complete sets of field measurements are available for testing expressions (9), (10) or (11), but data on rate of advance, fuel consumption and burning conditions have been obtained for about 35 surface fires, both experimental and wild, in or near the Petawawa Forest Experiment Station. The rates of advance range from about 0.5 cm/sec for fires backing gently into the wind to about 20 cm/sec at extreme hazard; a simple reversal of wind direction has been seen to increase the rate of advance 20-fold. Such behaviour and range of values of V can be readily duplicated by an expression such as (11), based on a form of (10) perhaps intermediate between (10a) and (10b).

Although Figure 2 shows V plotted through the whole range of A from 0° to 180°, flame radiation is probably of most importance for flame angles between about 30° and 90°. For vertical and backing flames the controlling propagation mechanism is heat transfer through the fuel bed, while at the other extreme flames tilted close to the surface lick the fuel directly.

In the absence of field data, a simple laboratory experiment was carried out to test the effect of flame angle alone on the rate of advance. Beds of red pine needles (*Pinus resinosa* Ait.) were burned on an asbestos pad in a tray 48 inches long, 30 inches wide and 2 inches deep. The flame angle was varied by simply tilting the tray in a series of 5° steps up to 35°. The fuel loading was held at 0.06 $g/cm^2$ and the fuel moisture close to 10 per cent. Since in the steeper positions the flame leaned toward the fuel bed, actual flame angles down to about 25° were obtained. Rate of advance and spot measurements of flame radiation were recorded.

According to expression (11), plotting rate of advance V against (1 + cos A) should yield a straight line of slope $\frac{1}{1 - n}$ on log-log paper. A graph of the actual rates, shown in Figure 4, is a curve, but some adjustment of the two upper points is permissible because of differences in flame radiation intensity E. The flames of intermediate rate radiated with about 0.7 to 0.8 cals/cm-sec, whereas readings on the two fastest were 0.9 and 1.1. Theoretical rates of advance for these latter two, adjusted to a common level of 0.8, were plotted. A line of slope 3 can then be fitted reasonably well to the upper five points, ignoring the lower three on the grounds that their rates of advance were reinforced appreciably by radiation through the fuel bed. The equation for this line is

$$V = 0.224\ (1 + \cos A)^3 \qquad (12)$$

This can be recast in the form of (11), with $w = 0.06\ g/cm^2$, $M = 10$ per cent, $E = 0.8\ cals/cm^2\text{-sec}$, as follows:

$$(wV)^{1/3} = \frac{48\ E\ (1 + \cos A)}{(6.2M + 98)} \quad \text{.................. (12a)}$$

which is equivalent to (11a) if the fuel absorptivity e is taken as equal to 0.24.

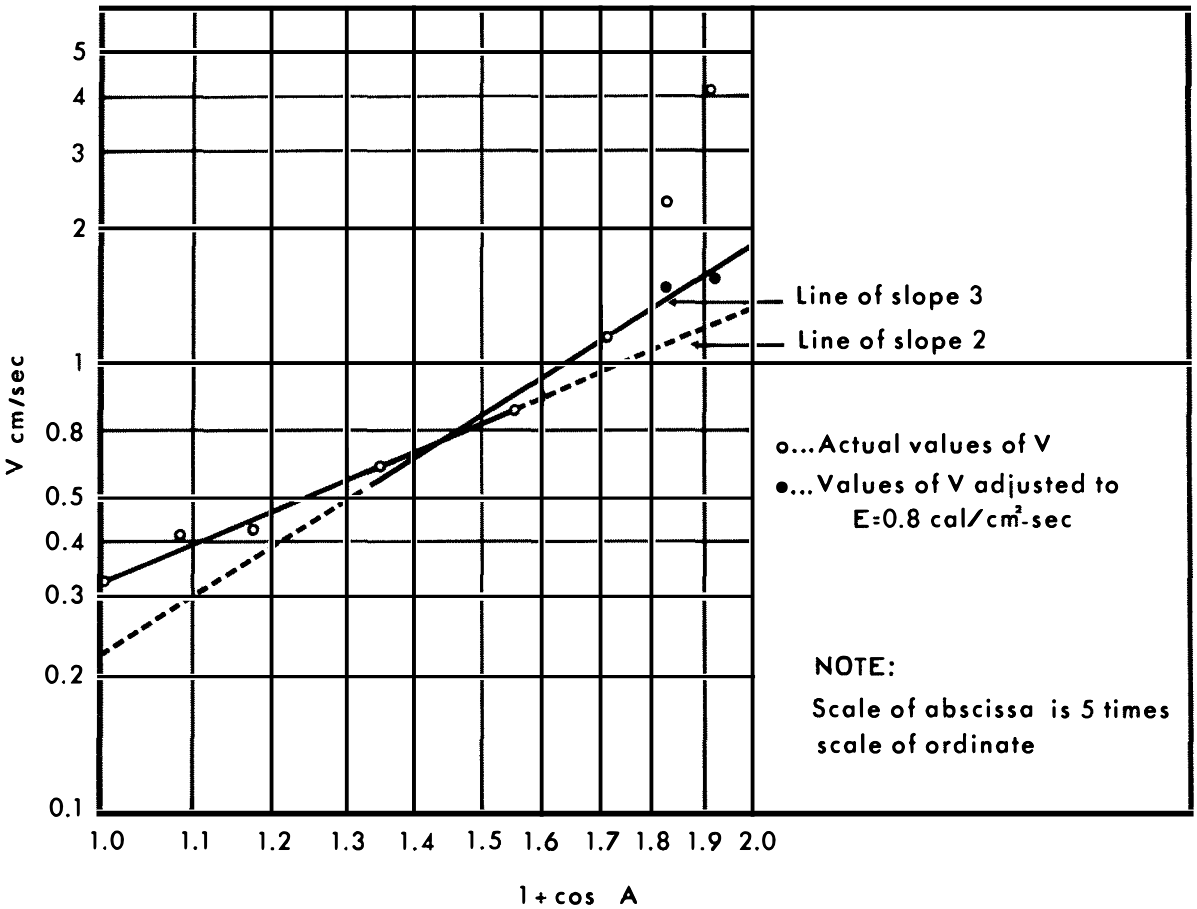


*Figure 4. Experimental effect of varying the flame angle A on the rate of advance V in trays of red pine needles in the laboratory.*

Alternatively, a line of slope 2 can be drawn through the lower five points in Figure 4, assuming that the three points representing the fastest rates of advance were displaced upward owing to higher radiation intensities E. This line has the equation

$$V = 0.324\ (1 + \cos A)^2 \quad \text{.................. (13)}$$

which, when recast in the same manner as (12), becomes

$$(wV)^{\frac{1}{2}} = \frac{28\ E\ (1 + \cos A)}{(6.2M + 98)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (13a)$$

By setting e equal to 0.28, expression (13a) can be made equivalent to the version of (11) based on (10a).

Probably the true interpretation of this experiment lies somewhere between the two extremes represented by expressions (12a) and (13a). Either way the values obtained for e are similar, and indicate that the calculated amount of radiation reaching the fuel ahead of the fire is quite adequate for the assumed ignition mechanism, with ample allowance for various losses.

## SUMMARY AND CONCLUSIONS

A simple theory for the propagation of surface fires by flame radiation alone is given by expressions (5), (9) and (11). The ingredients are: 1) an expression for the radiation dose received by a fuel element as the flame approaches and reaches it, 2) an energy balance between this quantity and the energy required for a simple ignition process, and 3) published relations linking flame length with energy output. Several complicating factors were ignored for simplicity's sake.

The theory does not incorporate the effect of radiation through the fuel bed (important at low rates of advance), but it does offer an explanation of the combined effects of fuel moisture content and flame angle once flame radiation becomes dominant. Since surface fires driven by moderate winds are common in the forest, good use could be made of a theory for their behaviour that is reasonably valid without being unwieldy. The present result can hardly be regarded as proven but does suggest much the sort of fire behaviour often observed in the forest.

## SOMMAIRE ET CONCLUSIONS

Un exposé théorique simple de la propagation des incendies de surface par rayonnement calorifique est fourni par les équations (5), (9) et (11). Les éléments symbolisés sont: 1) une équation exprimant la quantité de chaleur absorbée par une matière combustible quelconque lorsque les flammes s'en approchent et l'atteignent; 2) l'équilibre énergétique entre cette quantité de chaleur et la quantité de chaleur nécessaire pour déclencher les flammes; 3) les formules déjà publiées et traitant de l'énergie calorique dégagée, en fonction de la hauteur des flammes. Afin de simplifier les calculs, l'auteur n'a pas fait entrer en ligne de compte un certain nombre de facteurs.

Les formules ne tiennent pas compte de l'influence du rayonnement calorifique à travers la couche combustible (pourtant importante dans les cas de faible vitesse de propagation), mais elles offrent toutefois une explication de l'effet combiné de la teneur en eau de la couche combustible et de l'angle d'inclinaison des flammes, dès que leur rayonnement calorifique devient l'élément dominant. Étant donné que les feux de surface poussés par un vent modéré sont les plus fréquents en forêt, les formules pourraient se révéler précieuses pour prévoir le comportement des incendies, sans pour cela être par trop compliquées. Les formules proposées n'ont pas encore été beaucoup éprouvées, mais elles se fondent toutefois sur les données qui correspondent le mieux au comportement du feu le plus souvent observé en forêt.

## LIST OF SYMBOLS

A - angle between flame and unburned fuel bed
c - specific heat of dry fuel, cal/g
e - absorptivity of fuel to radiation
E - radiation intensity emitted by flame, $cal/cm^2$-sec
F - radiation configuration factor
h - latent heat of evaporation, cal/g
k - constant
L - flame length, cm
M - moisture content of fuel, per cent of dry weight
n - fractional power relating energy output to flame length
Q - radiation dose incident on fuel, $cal/cm^2$
q - energy required for ignition, $cal/cm^2$
R - radiation intensity received by fuel, $cal/cm^2$-sec
t - time, sec
$T_o$ - initial fuel temperature, °C
$T_i$ - fuel ignition temperature, °C
V - rate of advance of fire front, cm/sec
w - weight of fuel per unit area, $g/cm^2$
W - wind speed, cm/sec

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