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THE SPREAD OF FIRE IN FINE FUELS IN STILL AIR

by

P. H. Thomas

SUMMARY

Some of the experiments by Curry and Fons on the spread of fire in thin fuels in still air have been analysed. Except for the thinnest fuel and the most tightly packed beds the rate of spread in all the experiments can be described as between 4 and 8 mg/s per sq. cm of vertical cross section, according to the volume of voids per unit surface area. These results compare closely with those obtained by Fons et al for wood cribs. These have been discussed in a previous report but certain aspects of that discussion are continued here.

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1. Introduction

In a previous report[1] it was shown that the spread of fire along cribs of wood in still air can be accounted for by the transmission of radiation through the fuel bed from the burning zone. In still air the front edge of the burning zone moves forward vertically and this was taken by Fons to imply that the top of the fuel bed did not receive a greater amount of heat than the bottom, that is, the flames above the fuel bed did not contribute significantly to the spread nor, we may add, did the cooling vary significantly throughout the depth of the crib. This report begins by discussing the two assumptions concerning the small contributions of the flame and the uniformity of the cooling conditions within the fuel bed in more detail than hitherto. Also in this report some experimental results obtained by Curry and Fons[2] for the spread of fire in thin fuels in still air are discussed in terms of the heat balance of the fuel bed and are found to give results similar to those for cribs.

2. The contribution of flames to the heating

The mean rate of heat transfer ahead of a vertical flame of height L, emissivity ϵ_f and black body intensity i_f is

$$\dot{q}'_f = i_f.\epsilon_f.L.F.$$

where the dot over q denotes per unit time, and the dash per unit width of fire front, and the suffix f denotes flame. F is the exchange factor between the flame and the top of the fuel bed and is $\frac{1}{2}$ for an infinitely wide vertical flame.

The value of $\dot{q}'_B$ where the suffix B denotes radiation from the burning zone is

$$\dot{q}'_B = i_B \epsilon_B h$$

where i_B is the black body intensity emitted from the burning zone, ϵ_B the emissivity of the burning zone and h the height of the fuel bed. In the experiments performed by Fons et al[3] the crib was usually 25 cm wide (42 cm at most); and the height usually 14 cm (32.5 cm at most). The medium flame height was between 30 and 40 cm so that typical values of F are less than 0.2[4]. The burning zone is wide enough for ϵ_B to be taken as unity[1], but for a flame 10 cm thick the emissivity ϵ_f is approximately 0.04[5] so that the ratio $\dot{q}'_f/\dot{q}'_B$ is approximately 1/20 if $i_f \sim i_B$. It is for this reason that the contribution of the flames could be neglected in comparison with that of the radiation from the burning zone.

3. Cooling in the fuel bed

In the analysis[1] of Fon's crib data[3] a value of 8×10^{-4} cal cm^{-2}s^{-1} deg C^{-1} was assumed for the mean total cooling coefficient in the fuel bed. We now consider this cooling in greater detail.

Indeed, much of this report is devoted to discussing the effective cooling in fuel beds which are more tightly packed than cribs. The reason for doing this is that in the experiments by Curry and Fons[2] to be discussed below, H, the heat transfer coefficient, is not constant for the different fuel beds.

[illegible] a [illegible] distribution of elements of various sizes. Here we [illegible] an [illegible] bed of elements of equal size and define

- σ surface area of fuel per unit volume of solid fuel
- λ volume of solids per unit area of solid
- ϕ volume of solids per unit total volume (porosity)

[illegible]

$$\phi = \frac{\sigma\lambda}{1+\sigma\lambda} \qquad (1)$$

σ and λ are the same symbols as used by Curry and Fons. If the ratio of horizontal spacing to stick size D in units of square sticks is s we have

$$\phi = \frac{s}{s+1} \qquad (1i)$$

$$\sigma = 4/D \qquad (1ii)$$

$$s = \sigma\lambda \qquad (1iii)$$

and [illegible]

$$sD = 4\lambda \qquad (1iv)$$

If the fuel elements are far enough apart, the disturbance to the air around a fuel element does not interact with any other except those vertically above it. This means that for fuel beds which are shallow in relation to the thickness D of the fuel element the convective transfer coefficient is approximately that for a single fuel element. An approximate [illegible] on this condition is that the thickness of the boundary layer is less than the half [illegible] spaces of the solids. Since from equation (iv) this [illegible] is [illegible] λ [illegible] we require $\delta \leq 2\lambda$

3.1. The interaction between the cooling from several fuel elements

3.1.1. Convection loss

McAdams[6] gives the heat transfer by natural convection from long horizontal cylinder

$$N_u = 0.53\,(G_r . P_r)^{1/4} \qquad (2)$$

where N_u is the Nusselt Number for the cylinder diameter

G_r is the Grashof Number for the cylinder diameter

P_r is the Prandtl Number of the fluid which for air is 0.7

Equation (2) then corresponds to a mean thickness for the thermal boundary layer of

$$\bar{\delta} = \frac{D}{0.53 \times 0.7^{1/4}} (G_r)^{-1/4}$$

$$= 2.07 \left(\frac{g\theta}{\nu^2 T_0 D}\right)^{-1/4} \qquad (3)$$

where θ is the temperature difference between the solid surface and the air outside the boundary layer.

ν is the mean kinematic viscosity of the gases within the boundary layer

g is the acceleration due to gravity

and T_o the absolute temperature of the ambient air

Since $\bar{\delta}$ depends only on $D^{\frac{1}{4}}$ the maximum value of δ is approximately 1.33 times the mean value, but in view of the extent of the approximations to be made in what follows, this is neglected, as is the difference in shape between squares and cylinders. The above expression can be written in terms of the surface to volume ratio σ which is $4/D$ for a long cylinder and a long square section stick. Thus

$$\bar{\delta} \doteqdot 2.9\left(\frac{T_o \nu^2}{g \theta \sigma}\right)^{1/4} \qquad (4)$$

so that the requirement $\delta < 2\lambda$ can be written as

$$\lambda \left(\frac{g \theta \sigma}{T_o \nu^2}\right)^{1/4} > 1.5 \qquad (4i)$$

We shall refer to this as condition A. If, instead of regarding each fuel element in isolation, we consider the crib as consisting of a group of vertical tubes, square in section, of side 2λ (equation (1iv)) the maximum boundary layer thickness will be given by an equation similar to equation (3) except that h, the height of the crib, replaces D. The condition $\delta < 2\lambda$ can now be written

$$\lambda \left(\frac{g \theta}{h T_o \nu^2}\right)^{1/4} > 1.5 \qquad (4ii)$$

If this condition is fulfilled the air in the centre of the vertical passages remains unheated. θ is less than θ_s, the maximum surface temperature rise of 300°C, T_o is 300°K, g is 981 cm/s^2 and ν (appropriate to a mean boundary layer temperature of 150°C) is 0.3 cm^2/s approximately

The two conditions (4i) and (4ii) that have now been obtained are then

$$\lambda \sigma^{1/4} > 0.15 \text{cm}^{\frac{3}{4}} \qquad (5i)$$

$$\lambda h^{-1/4} > 0.1 \text{cm}^{\frac{3}{4}} \qquad (5ii)$$

The above conditions can also be written

$$s > 0.5/D^{2/4} \qquad (6i)$$

and

$$s > 0.5\, h^{1/4}/D \text{, h and D in cm} \qquad (6ii)$$

In many of the cribs used by Fons et al.[3] D was 1.3 cm, S was 2–3 and h ~ 14 cm. Cribs with such values satisfy the above conditions, so that the convection heat transfer does not approximate to that in packed beds. With caution we may [illegible] value to approximate to that in free space. The [illegible] between using D and h as characteristic lengths for evaluating [illegible] transfer coefficient is the ratio $(h/D)^{\frac{1}{4}}$ a factor about 2. An [illegible] of the convective part of H for a single stick is approximately [illegible] x [illegible] cal cm^{-2}s^{-1}degC^{-1}. If only the two vertical surfaces of each stick [illegible] considered as cooling surfaces and the boundary layer is that due to a height, h [illegible] cooling coefficient for all four surfaces is about 1 x 10^{-4} cal cm^{-2}s^{-1}degC^{-1}.

Cribs of the same height but of 0.6 cm ($\frac{1}{4}$ in) sticks could also be regarded as fulfilling the conditions (5i) and (5ii). In some of the cribs of [illegible] cm ([illegible] in) wood used by O'Dogherty and Young(7) h was 120 cm. These also satisfy the above conditions so long as 's' is 2 or over. However, since there is a considerable range of behaviour between a "packed bed" and "free space" convection transfer it would be unwise to regard such conclusions and the numerical value of H obtained from the above arguments as more than rough approximations.

5.1.2. Radiation loss

The radiation incident at any point ahead of the fire has been calculated(1) on the assumption that there is no reradiation from the heated solid surfaces. These are at a temperature below 330°C so that any reradiation would be less than 0.16 cal cm^{-2}s^{-1} which is about 8-16 per cent of the estimate of 1-2 cal cm^{-2}s^{-1} for the incident radiation. The temperature rise above ambient was shown to follow the same exponential law as the level of radiation and because of the non-linear way that radiation depends on temperature the reradiation decreases more rapidly with distance than does the incident radiation, so that the above estimate of 8-16 per cent is a maximum estimate and as a first approximation the reradiation can be treated separately from the incident of radiation.

Although there is some radiation exchange within the fuel bed, the only loss is from the upper and lower surfaces of the fuel bed and this is a smaller fraction of the whole the deeper the fuel bed.

The maximum possible radiation loss is equivalent to a heat transfer coefficient of 0.16/330, i.e. 5 x 10^{-4} cal cm^{-2}s^{-1}degC^{-1}, making a total of 9 x 10^{-4} cal cm^{-2}s^{-1}degC^{-1} for a single isolated element.

Treating the crib as a series of square tubes of side 4λ and height h allows the radiation loss from the two ends to be calculated. The distance between stick centres is $4\lambda + 4/\sigma$ so that the product of the square area enclosed by neighbouring sticks and the intensity i_R reradiation from unit surface of wood is

$$2(4\lambda + 4/\sigma)^2 i_R$$

The total surface corresponding to each square tube is

$$4(4\lambda + 4/\sigma) h$$

so that the fraction of radiation loss through the open ends is

$$r = \frac{2\lambda}{h}\left(1 + \frac{1}{\sigma\lambda}\right)$$

For the values of λ, σ and h used by Fons et al r is at most about [illegible] so that the loss is equivalent to a mean radiation transfer coefficient of about [illegible] x 10^{-4} cal $cm^{-2} s^{-1} degC^{-1}$, a total loss of at least 1.[illegible] x 10^{-4} cal $cm^{-2} s^{-1} degC^{-1}$ compared with about 5 x 10^{-4} cal $cm^{-2} s^{-1} degC^{-1}$ for a single isolated fuel element. These are approximate lower and upper limits respectively for the heat loss expressed as a transfer coefficient per unit surface of wood in the cribs used by Fons et al. In a previous report(1) a value of 8 x 10^{-4} cal $cm^{-2} s^{-1} degC^{-1}$ was taken.

5.2. The fuel beds used by Curry and Fons

Curry and Fons(2) studied fire spread in beds of unordered fuel elements, i.e. they used no special arrangement of fuel, as with cribs. The range of values of λ and σ were $0.[illegible] < \lambda < 0.8$ cm and $6.5 < \sigma < 100$ cm^{-1}. One would expect that there would be fewer large vertical channels through such a fuel bed than there are in cribs and because of this the flow through the fuel bed may more appropriately be treated as flow through a "packed bed". To illustrate this we consider the probability that a small object rising vertically will pass freely through the bed without striking part of the solid. This will overestimate the probability for a small volume of heated air to rise freely by neglecting the finite size and expansion of the eddy. For a crib, the horizontal cross-sectional area of the vertical passages in the notation of this paper is a fraction f_1 of the whole base area where

$$f_1 = \left(\frac{\sigma\lambda}{1+\sigma\lambda}\right)^2$$

For an unordered bed a measure of this probability is given by the attentuation of a light ray and this is approximately

$$f_2 = e^{-\alpha \ell}$$

where α can be taken as

$$\alpha = \frac{\sigma}{4(1+\sigma\lambda)}$$

The unordered bed is most like an ordered one when λ is large and σ small, and taking the appropriate extreme values σ = 6.5 cm^{-1} and λ = 0.8 cm the maximum value of the ratio f_2/f_1 is 0.10 (the actual values of f_1 and f_2 being 0.70 and 0.070 respectively). For the values λ = 0.8 cm and σ = 3 cm^{-1} appropriate to cribs of ½ in square wood sticks spaced 1½ in apart which lie outside the above range of λ and σ, f_1, f_2 are 0.5 and 0.1 respectively. Because f_2 is small it is unrealistic to consider these beds as having vertical passages allowing an unrestricted flow of air, and in the following section the convection through beds of unordered fuel of the kind used by Curry and Fons is considered in terms of the flow through packed beds. It is of interest to note in passing that because f_1 and f_2 differ the free burning of such beds may also differ.

3.3. Cooling in the fuel beds

Because the temperature of the fuel elements varies with their distance ahead of the fire front a simple estimate of the heat transfer conditions in the fuel bed can only be very approximate.

3.3.1. Radiation loss

The variation of temperature rise on the fuel surface assuming no cooling is theoretically[1]

$$\theta_s = \theta_i e^{-\frac{\sigma x}{4(1+\sigma\lambda)}} \qquad (7)$$

where θ_i is the temperature rise causing ignition

and x is the distance ahead of the fire front. If the top surface of the fuel bed is assumed to have the same distribution an upper estimate of the total radiation loss from this surface per unit width of fire front is

$$\dot{q}'_R = 1.37 \times 10^{-12} \int_0^\infty \{(T_0 + \theta_s)^4 - T_0^4\} \, dx \qquad \text{cal cm}^{-1}\text{s}^{-1}$$

where T_0 is the ambient absolute temperature. This loss is

$$\dot{q}'_R = 1.37 \times \frac{4(1+\sigma\lambda)}{\sigma} \times 10^{-12} \left\{ 4T_0^3\theta_i + 3T_0^2\theta_i^2 + \frac{4}{3}T_0\theta_i^3 + \frac{1}{4}\theta_i^4 \right\} \qquad \text{cal cm}^{-1}\text{s}^{-1}$$

For $T_0 = 300^\circ$K and $\theta_i = 300$ degC this becomes $0.38 \left(\frac{1}{\sigma}+\lambda\right)$ cal cm^{-1}s^{-1}. The largest value of $\frac{1}{\sigma}+\lambda$ in these experiments was about 1.1 cm making the radiation heat loss about 0.42 cal cm^{-1}s^{-1}. The depth of the fuel bed was 15 cm so that the heat loss expressed per unit cross section of the advancing front is less than 0.03 cal cm^{-2}s^{-1} which is negligible compared with the forward radiation flux which will be shown below to be over 1 cal cm^{-2}s^{-1}.

3.3.2. Convection loss

If heated air leaves the fuel bed vertically at a mean velocity ω with a temperature θ_e the convective loss for unit width of fire front is

$$q'_c = \int_0^\infty \rho_{ge} \, c_A \, \theta_e \, \omega \, dx \qquad (8)$$

ω is calculated as volume per unit base area of fuel bed.

ρ_{ge} is taken as the air density and c_A as the specific heat of air, and the suffix e denotes exit conditions.

Since ω varies with x we shall calculate ω for a bed in which the solids are at a uniform temperature rise of θ_g and in which the air flow is entirely vertical. We shall neglect all pressure variation and all inertia terms in the equation of motion, and equate the loss of pressure due to the resistance to flow to the buoyancy head. We shall also assume that the fuel elements can be treated in terms of their specific surface, disregarding any effect of their shape.

Ergun[8] defines the pressure drop across a packed bed of height Z for a velocity ω as

$$\Delta P_1 = \rho_g \omega^2 Z f_k \cdot \frac{1-p}{p^3} \cdot \frac{1}{d_e} \qquad (9)$$

where
$$f_k = 1.75 + \frac{150(1-p)\nu}{\omega d_e} \qquad (10)$$

ν = the kinematic viscosity of the hot gases

and
$$d_e = \frac{6}{\sigma} \qquad (11)$$

$\frac{\omega}{p}$ is the actual mean velocity of the gases in the bed. ρ_g is the density of the gases. Equating this loss of head to the buoyancy gives

$$f_k \cdot \frac{1-p}{p^3} \cdot \frac{\omega^2}{d_e} \rho_g = g \, \Delta\rho \qquad (12)$$

where $\Delta\rho$ is the difference in gas density between inside and outside the fuel bed. For an ideal gas

$$\frac{\Delta\rho}{\rho_g} = \frac{\theta_g}{T_0} \qquad (13)$$

Substituting for p, d_e and $\frac{\Delta\rho}{\rho_g}$ equation (12) becomes

$$\frac{(1+\sigma\lambda)^2}{\sigma^2\lambda^2} \omega^2 \left(1.75 + \frac{25\sigma\nu}{\omega(1+\sigma\lambda)}\right) = 6 g \frac{\theta_g}{T_0} \lambda$$

$$\text{i.e.} \quad \omega = \frac{\sqrt{\frac{42 g \theta_g \lambda^3}{T_0} + 625\nu^2} - 25\nu}{3.5\lambda\left(1 + \frac{1}{\sigma\lambda}\right)} \qquad (14)$$

It may be noted here that the gain in momentum per unit area of this flow from zero velocity is $\rho_g \omega^2 \left(1 + \frac{1}{\sigma\lambda}\right)$ which is less than $\frac{6 \rho g \theta_g \lambda}{T_0 \, 1.75}$. It is because $\frac{6\lambda}{1.75}$ is at most $\frac{6}{5}$ that the momentum terms can be neglected compared with the buoyancy and the drag. The neglect of pressure variation within the fuel bed can be justified only if, as here, the bed is deep in relation to the width of the rising plume of air. The rise in temperature of the air at exit from the upper surface of the fuel bed over the initial temperature difference θ_g between the heated fuel and the cold air may be estimated from data for the heat transfer for forced convection, and it can be shown that the heat transfer for all the combinations of σ and λ in these fuel beds is high enough for the air to be in effect heated to the fuel surface temperature. Thus if θ_g is taken as 300°C and ν as 0.52 cm²/s, ω is $\frac{3.7}{\lambda(1+\frac{1}{\sigma\lambda})}\left(\sqrt{1 + 2400\lambda^3} - 1\right)$ in c.g.s. units which for the values of λ used by Curry and Fons is less than 55 cm/s. Lower temperatures give [illegible] [illegible]. The maximum Reynolds No. with respect to the particle $\left(\frac{6u\rho}{\mu\sigma}\right)$ for the low σ σ equal to about 6 cm^{-1} is then about 100. The Colburn-Chilton coefficient j_H is therefore about 0.2 (see, for example, Spalding[8]). For air with a Prandtl No. of 0.7 the value of Log $\frac{\theta_s}{\theta_s - \theta_0}$ is therefore $\frac{\sigma j_H h}{6}$ i.e. about 3. Larger values of σ giving lower values of Reynolds number give even higher values of $\frac{\sigma j_H h}{6}$. It follows that for the purpose of these calculations $\theta_e \sim \theta_s$ so that the heat loss per unit cross section of the fire front is from equation (8)

$$q''_L = \frac{q'}{h}$$

$$= \frac{2[\ldots] c_A \rho_0}{3.[\ldots] h \lambda (1 + 1/6\lambda)} \int_0^\infty \frac{T_0 \cdot \theta_s}{T_0 + \theta_s} \left\{ \sqrt{\frac{42 g \lambda^3 \theta_s}{625\, \nu^2 T_0} + \nu^2} - \nu \right\} dx \qquad (15)$$

The value of ν and its variation with temperature is not of great importance if

$$\frac{42\, g\, \lambda^3\, \theta_s}{625\, T_0\, \nu^2} >> 1$$

With this condition and equation (7) we then obtain from equation (15)

$$q''_L = \frac{100\, c_A \rho_0 \theta_1}{3.[\ldots]\, h} \sqrt{\frac{42 g \lambda^3 \theta_1}{625\, T_0}} \int_0^\infty \frac{e^{-\frac{1}{2}y}}{1 + e^{-y}}\, dy \qquad (16)$$

The infinite integral is $2 - \pi/2$ so that

$$q''_L = 12.3\, C_A\, \rho_0\, \theta_1 \left(\frac{\lambda}{h}\right) \sqrt{\frac{42 g \lambda \theta_1}{625\, T_0}} \qquad (17)$$

with $\rho_0 = 1.3 \times 10^{-3}$ g/cm^2, $C_A = 0.24$ cal $gm^{-1}\,{}^{\circ}C^{-1}$, $h = 15$ cm $\theta_1 = T_0 = 300°$ we obtain

$$q''_L = 0.62\, \lambda^{3/2} \qquad (18)$$

4. Experiments by Curry and Fons

Data from Fig. 13 in the report by Curry and Fons have been replotted in Fig. 1. In the region where $\lambda < 0.3$ the rate of spread decreases rapidly with λ and σ in a way suggesting that a different regime of behaviour obtains. In this connection, it is of interest that Palmer[10] has obtained smouldering rates for $\lambda \ll 0.1$ cm of approximately 0.45 mg $cm^{-2}\,s^{-1}$ - an order of magnitude smaller than the values for $\lambda > 0.3$. This regime of burning is of less immediate interest and it is with the region $\lambda > 0.3$ that we are most concerned here.

For these values of λ the data given by Curry and Fons may be correlated by the lines shown in Fig. 1

$$R\rho_b = (7.8 - 3.6\lambda) \ \mathrm{mg\ cm^{-2}\,s^{-1}} \qquad (19)$$

except that the rates of spread for the thinnest fuel, woodwool (Excelsior), are substantially in excess; no explanation is offered for this discrepancy at present. $C\theta_s$ is taken as appropriate to a moisture content of 8.8 per cent. Thus the change in enthalpy represented here for a dry material by $C\theta_s$ is for wet wood

$$C_m \theta_s = C\theta_s + h_w + m\Delta H$$

where C is the specific heat of dry wood 0.3[illegible]

h_w is the heat of wetting 16 cal/g

m is the moisture content by wt.

ΔH is the enthalpy difference between water at, say, 20°C and the temperature at which the vapour leaves the fuel bed.

Some of the last vapour leaves sufficiently far ahead of the fire front for its temperature to be taken as 100°C. The last vapour may not leave until the fire front has reached it and the effective mean value may not be the same for all combinations of σ, λ etc. However, we shall take ΔH as 620 cal/g and then put $C_m \theta_s$ 160 cal/g for $m = 0.088$.

i.e. an effective C_m of 160/280 i.e. 0.57 cal $g^{-1}\,degC^{-1}$

Equation (19) can then be written as

$$R\rho_b C_m \theta_s = (1.3 - 0.6\lambda) \ \mathrm{cal\ cm^{-2}\,s^{-1}} \qquad (20)$$

which may be compared with a theoretical equation for thin fuels obtained in a previous report(1). For small heat loss this took the approximate form

$$R\rho_b C_m \theta_s = i_B - 2.67\, H\theta_i \qquad (21)$$

and hence it is possible to identify the intensity of radiation emitted by the burning zone i_B as 1.3 cal $cm^{-2}\,s^{-1}$. This is a reasonable value of the same order as that obtained from examination of the data for spread in cribs. The value calculated for q_L^* from equation (18) differs in form from the value derived from equation (20) viz 0.6λ if the variation in λ is regarded as the consequence of a variation in cooling loss. The actual magnitudes, however, are of the same order. Thus over the range $0.3 < \lambda < 0.9$ cm the coefficient of λ viz $0.62\,\lambda^{\frac{1}{2}}$ varies from 0.34 to 0.59 compared with the experimental value of 0.6. Errors will be incurred in making use of such a treatment of the variation in β and ω with distance ahead of the fire front, but the results do suggest nevertheless that the variation of $R\rho_b$ with λ could be a consequence of the variation in the cooling loss.

Hence the term in λ in equation (20) can be provisionally identified with the term in H in equation (21)

$$\text{i.e.} \quad H = \frac{0.6\lambda}{2.67 \times 300} = 7.5 \times 10^{-4}\,\lambda \qquad (22)$$

For the cribs used by Fons et al, where the sticks are spaced 1¼ in apart, λ is 0.8 cm and equation (22) gives the estimated H as 6×10^{-4} cal cm^{-2}s^{-1} degC^{-1} which is a little less than the 8×10^{-4} cal cm^{-2}s^{-1} degC^{-1} assumed in analysing the data on cribs. The estimate of i_B varies approximately as the square root of H and no correction has been made for this change in the choice of H in reference (1).

5. Discussion and Conclusion

We have in fact correlated much of the data reported by Curry and Fons for horizontal spread of fire in still air at a fixed moisture content. The exceptions are principally the thinnest fuel and the most tightly packed beds where the behaviour regime would be expected to be different anyway. The value at λ equals 0.[illegible] cm is 5.0 mg cm^{-2}s^{-1}.

The correlation of crib data(1) gave an estimate of $H\theta_i/i_B$ as 0.175 and a value of i_B of about 1.4 cal cm^{-2}s^{-1}. Equation (21) applies for these materials so that the value of R expected when C_m is taken as corresponding to [illegible] per cent moisture viz: 0.67, is 4.3 mg cm^{-2}s^{-1} in reasonable agreement with the above value. It is probably sufficient for practical purposes to regard R/ℓ as 6 ± 2 mg cm^{-2}s^{-1} over a wide range of thickness and fuel spacing for most practical purposes.

6. Acknowledgements

The author wishes to thank his colleagues, Dr. Simms and Mr. Wraight, for assistance with the calculations and for undertaking the experiments with wood shavings referred to in this report.

7. References

(1) THOMAS, P. H., SIMMS, D. L. and WRAIGHT, H. G. "Fire Spread in Wooden Cribs" Joint Fire Research Organization F.R. Note 537/1964.

(2) CURRY, J. R. and FONS, W. L. "Forest Fire Behaviour Studies". Mech. Eng., 1940, 62 (3), 219-225.

(3) FONS, W. L., CLEMENTS, H.B., ELLIOTT, E. R. and GEORGE, P. M. Project Fire Model, Summary Progress Report II, Forest Service, U.S. Dept. Agriculture, Southern Forest Fire Laboratory, Macon, Georgia, 1962.

(4) HAMILTON, D. C. and MORGAN, W. R. Radiation Interchange Configuration Factors. U.S. National Advisory Committee for Aeronautics Technical Note [illegible]6. Dec. 1952.

(5) HESELDEN, A. J. M. Unpublished data.

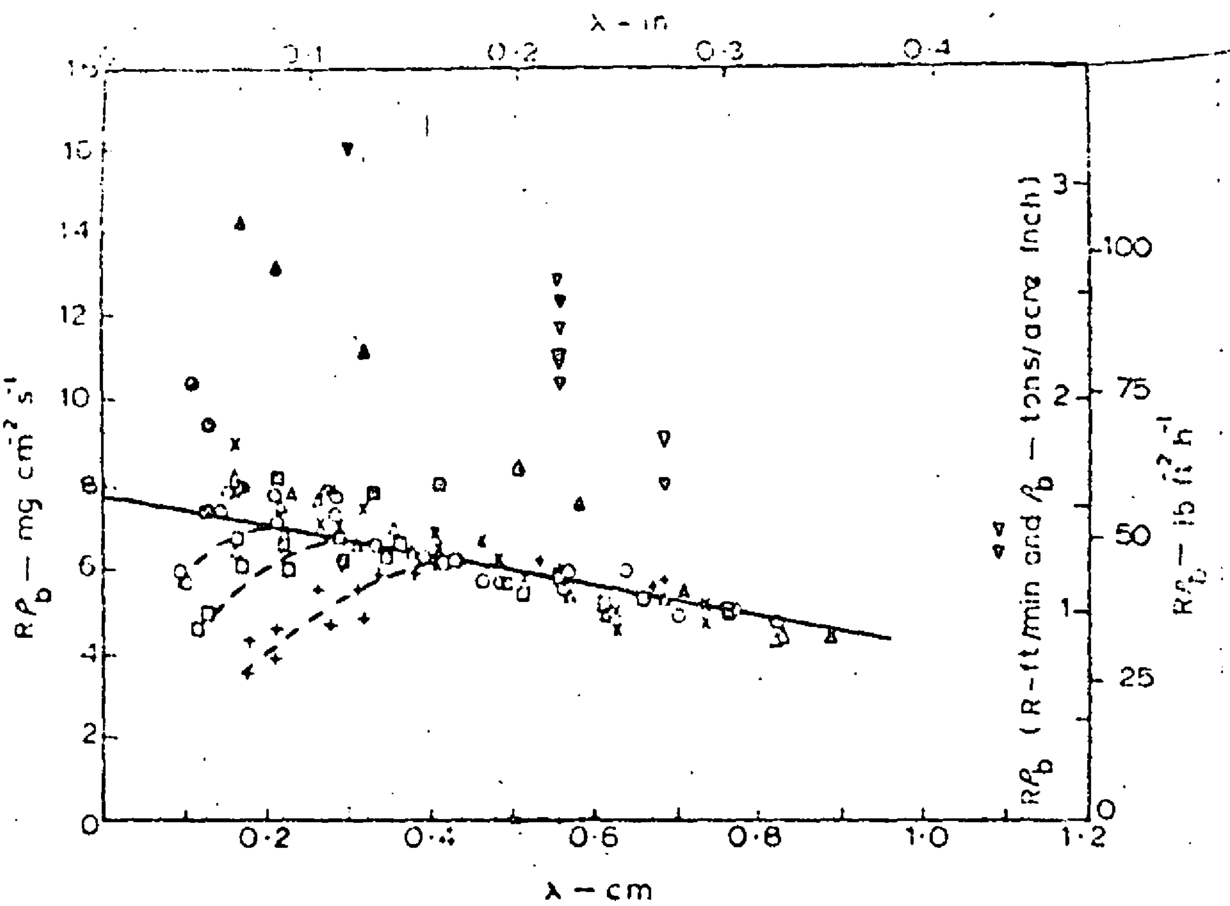
(6) McADAMS, W. H. Heat Transmission. McGraw-Hill Book Co., Inc., 2nd Ed., 1942.

(7) O'DOHERTY, M. J. and YOUNG, R. A. Unpublished Data.

(8) ERGUN, S. Chem. Eng. Progress, 1962, 48 (5) 89 and 227.

(9) SPALDING, D. B. "Some Fundamentals of Combustion". Butterworth Scientific Publications, London 1955.

(10) PALMER, K. Combustion and Flame, 1957, 1 129.



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

+	0·62 cm (0·25 in) sticks	*
□	0·26 cm (0·10 in) sticks	*
○	0·16 cm (0·06 in) sticks	*
△	0·11 cm (0·04 in) sticks	*
x	0·09 cm (0·04 in) sticks	*
■	Ponderosa pine needles	*
●	Lodgepole pine needles	*
▽	Sugar pine needles	*
▲	Poplar excelsior (wood shavings)	*
▼	Wood shavings J.F.R.O.	

* Curry and Fons data

FIG.1. SPREAD OF FLAME IN FINE FUELS

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