FIRE RESEARCH STATION
F. R. Note No. 540

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

THE SPREAD OF FIRE IN PINE FUELS IN STILL AIR

by

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SUMMARY

Some of the experiments by Curry and Foss 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 m/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 Foss et al for wood chips. 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 crins 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, to any mill., 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 flames 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 crins.

2. The contribution of flames to the heating.

The mean rate of heat transfer ahead of a vertical flame of height L, emissivity \( \varepsilon \) and black body intensity \( I \) is

\[
q_f = I \varepsilon I L F,
\]

where the dot over \( q \) denotes per unit time, and the index per unit length 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 \( \frac{1}{4} \) for an infinitely wide vertical flame.

The value of \( q_f \) where the suffix \( B \) denotes radiation from the burning zone is

\[
q_B = I \varepsilon B A
\]

where \( I_B \) is the black body intensity emitted from the burning zone, \( \varepsilon_B \) the emissivity of the burning zone and \( A \) the height of the fuel bed. In the experiments performed by Fons et al. the crib was usually 25 cm wide (42 cm at most) and the height usually 12 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 \( \varepsilon_B \) to be taken as unity(1), but for a flame 10 cm thick the emissivity \( \varepsilon_B \) is approximately 0.6(5) so that the ratio \( q_f/q_B \) is approximately 1/20 if \( I \approx I_B \). 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 Fons's crib data(3) a value of \( 8 \times 10^{-4} \) cal cm\(^{-2} \) 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 crins. 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.
\[ \phi = \frac{\sigma A}{1 + \sigma A} \]  
\[ \sigma = \frac{1}{D} \]  
\[ \varepsilon = \frac{\sigma}{\varepsilon D} \]  

If \( A \) fuel elements are in contact apart, the inaccessibility to the air around each is so small that they are in contact with each other except those just above it. To a certain limit the fuel bed which are similar in relation to the thickness \( D \) of the fuel element the convective transfer coefficient \( \varepsilon \) approximates that for a single fuel element. An approximate expression for this can be that the thickness of the boundary layer is the same as the thickness of the fuel. Since from equation (1) this is "\( \phi = \varepsilon A \)" with an error of \( \delta < 2\sigma \).

3.1. The interaction between the cooling from several fuel elements

\[ N_u = 0.53 \left( \frac{G_r P_r}{\varepsilon D} \right)^{1/2} \]

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 0.72.

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

\[ \bar{\sigma} = \frac{D}{0.53 \times 0.72} \left( \frac{G_r}{\varepsilon D} \right)^{1/2} \]

\[ = 2.67 \left( \frac{G_r}{\varepsilon D} \right)^{1/2} \]
The temperature difference between the solid surface and the air outside the boundary layer.

\( \Delta T \) is the mean kinetic viscosity of the gases within the boundary layer.

\( g \) is the acceleration due to gravity

\( \gamma \) is the absolute pressure of the ambient air.

Since \( \Delta T \) depends only on \( L \), the maximum value of \( \Delta T \) 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 \( \sigma \), which is \( \sqrt{\frac{A}{V}} \) for a long cylinder and a long square section stick. Thus

\[
\Delta T \approx 2.9 \sqrt{\frac{1}{g \cdot \frac{\sigma}{L^2}}} \]

So that the requirement \( \Delta T < 2\lambda \) can be written as

\[
\lambda > \frac{1}{2} \left( \frac{g \cdot \sigma}{L^2} \right)^{1/4}
\]

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 \( L \), a relation (14) \( L \) the maximum boundary layer thickness will be given by an equation similar to equation (13) except that \( L \), the height of the crib, replaces \( L \). The condition \( \Delta T < 2\lambda \) can now be written

\[
\lambda > \frac{1}{2} \left( \frac{g \cdot \sigma}{L^2} \right)^{1/4} \]

If this condition is fulfilled the air in the centre of the vertical passages remains unheated. \( D \) is less than 0.1 m. The maximum surface temperature rise of 150°C, \( T_{0} \) is 35°C, \( \sigma \) in 10^6 cm^2/s^2 and \( \gamma \), (appropriate to a mean boundary layer temperature of 150°C), is 0.1 cm/s approximately.

The two conditions (14) and (15) that have now been obtained are then

\[
\lambda > \frac{1}{2} \left( \frac{g \cdot \sigma}{L^2} \right)^{1/4} \]

The above conditions can also be written

\[
s > 0.5 / D^{1/4} \]

and

\[
s > 0.5 \frac{1}{D^{1/4}}, \text{ h and D in cm} \]

In many of the cr1bs used by Fons et al. (1) \( D \) was 1.3 cm, \( s \) was 2.5 and \( h = 14 \) cm. Cell, with such values satisfies the above conditions, so that the convection heat transfer does not approximate to that in packed beds. With caution we may
of the face height but of 0.6 cm (1 in) sticks could also be
regarded as fulfilling the conditions (54) and (55). In some of the cubs
of 1.4 m (5 ft) and 2.1 m (7 ft) by O’Sheperty and Young(7) h was 120 cm. These
at least satisfy the above conditions so long as ‘a’ is 2 or over. However,
not a fair measure of the range of behaviour between a “packed bed” and
the “free space” correction factor it would be unsafe to regard such conclusions
and the normal value of H obtained from the above arguments as more than
with great caution.

1.2. Radiation loss

The radiation incident at any point ahead of the fire has been calculated(1)
under the assumption that there is no reradiation from the heated solid surfaces.
These are at a temperature below 100°C so that any reradiation would be less than
0.4% which is about 8-6 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
make the non-radiative part of the fall of radiation and because of the
assumption of no radiation by solid on temperature the reradiation decreases
down rapidly with distance and the incident radiation, so that the above
estimate of 8-6 per cent is a maxima estimate and as a first approximation
the reradiation can be treated separately from the incident radiation.

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

The maximum possible radiation loss is equal to a heat transfer
coefficient of 0.16 W/cm2 K, i.e., 5 × 10−4 W cm−2 deg−1, making a total of
7 × 10−4 W cm−2 deg−1 for a single isolated element.

Treating the fuel as a series of square tubes of side L and height h
above the radiation loss from the two ends to be calculated. The distance
between adjacent tubes is 2L+4/6 so that the product of the square area
enclosed by neighbouring tubes and the intensity of radiation from unit
surface of wood is

\[ 2(4L+4/6)^2 \]

The total surface corresponding to each square tube is

\[ 4(4L+4/6)^2 \]

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

\[ \gamma = \frac{2L}{h} \left( 1 + \frac{1}{a} \right) \]
For the values of $\lambda$, $\sigma$, and $\frac{f_1}{f_2}$ used by Farcy et al., the area is equivalent to a heat radiation transfer coefficient of $0.005 < \lambda < 0.01$ cm$^{-1}$ at least for a fuel bed covered with about $5 \times 10^{-2}$ cm$^{-1}$ of wood, or for single isolated fuel elements. These are approximate lower and upper limits respectively for the heat loss expressed as a transfer coefficient per unit surface of wood in the crib used by Farcy et al. In a previous report(1) a value of $5 \times 10^{-2}$ cm$^{-1}$ was taken.

4. The final beds used by Curry and Fones

Curry and Fones(2) studied fire spread in beds of unordered fuel elements, i.e., they used no special arrangement or fuel, as with cribs. The range of values of $\lambda$ and $\sigma$ were $0.005 < \lambda < 0.01$ cm$^{-1}$ and $\sigma = 6.5 < \sigma < 16$ 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 fire through the fuel bed may move more appropriately in treating the flow through a "packed bed". To illustrate this we consider the probability that a small object rising vertically will pass finally through the bed without striking part of the solids. This will overestimate the probability for a small volume of heated air to rise freely by reducing the chance of formation of the eddy. For a crib, the horizontal inter-sectional area of the vertical passages in the relation of this power to a fraction $f_1$ of the whole bed can be shown

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

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

$$f_1 = e^{-x}$$

where $x$ can be defined as

$$x = \frac{\sigma}{\lambda}.$$ 

The unordered bed is most like an ordered one when $\lambda$ is large and $\sigma$ small, and taking the appropriate extreme values $\sigma = 0.4$ cm$^{-1}$ and $\lambda = 0.8$ cm$^{-1}$ at the minimum value of the ratio $f_1/f_2$ is 0.10 (the actual values of $f_1$ and $f_2$ being 0.70 and 0.65 respectively). For the values $\lambda = 0.8$ cm$^{-1}$ and $\sigma = 3$ cm$^{-1}$ appropriate to cribs of $\lambda$ in square wood sticks spaced $1\frac{1}{2}$ in apart which lie outside the above range of $\lambda$ and $\sigma$, $f_1$, $f_2$ 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 Fones 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. Cooling in the fuel bed

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

3.1. Radiation losses

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

\[
T_r = T_0 e^{-\frac{r}{1 - \infty}}
\]  

where \( \theta_0 \) is the temperature rise causing ignition and \( \infty \) 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

\[
Q_R = 1.37 \times 10^{-3} \int_0^\infty \left( T_a + \theta_0 \right)^4 - T_0 \theta_0^4 \, d\theta
\]

where \( T_0 \) is the ambient absolute temperature. This loss is

\[
Q_L = 1.37 \times \frac{4 (1 + \lambda)}{3} \times 10^{-12} \left\{ \frac{4}{3} T_a^3 \theta_0 + 3 T_a^3 \theta_0^3 + \frac{1}{8} T_a \theta_0^4 \right\}
\]

For \( T_0 = 300^\circ \) and \( \theta_0 = 500 \) deg C this becomes \( 0.4 \times \frac{(1 + \lambda)}{3} \) cal cm\(^{-1}\) s\(^{-1}\).

The largest value of \( \frac{1}{3} + \lambda \) in these experiments was about 0.1 cm making the radiation heat loss about 0.15 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 0.003 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\(^{-1}\).

3.1.2. Convection loss

If heated air leaves the fuel bed vertically at a mean velocity \( \omega \) with a temperature \( \theta_c \), the convective loss for unit width of fire front is

\[
Q_c = \int_0^\infty \rho_{air} C_A \theta_c \omega \, d\theta
\]

\( \omega \) is calculated as volume per unit base area of fuel bed.

\( \rho_{air} \) is taken as the air density and \( C_A \) as the specific heat of air, and the suffix e denotes exit conditions.
for \( \nu = \omega \) values with \( \Theta \) we shall calculate \( \omega \) for a bed in which the solids are of a uniform temperature rise of \( \Theta \), and in which the air flow is entirely isothermal. 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 force. We shall assume that the fuel elements can be treated in terms of their specific surface, disregarding any effect of their shape.

Equation (9) defines the pressure drop across a packed bed of height \( z \) for a velocity \( \omega \) as

\[
\Delta Z = \rho \omega^2 \int_{0}^{Z} \frac{1-p}{1} \frac{dZ}{P}
\]

(9)

where \( \int_{0}^{Z} \frac{1-p}{1} \frac{dZ}{P} = \frac{1-p}{1-p} \),

(10)

\( \nu = \) the kinematic viscosity of the hot gases

and \( \Theta_0 = \frac{\rho_0}{\rho} \)

(11)

\( \omega \) is the actual linear velocity of the gases in the bed. \( \rho \) is the density of the gases. Equating this loss of head to the buoyancy gives

\[
\int_{0}^{Z} \frac{1-p}{1} \frac{dZ}{P} = \frac{\rho_0}{\rho} \Delta Z
\]

(12)

where \( \Delta Z \) is the difference in gas density between inside and outside the fuel bed. For an ideal gas

\[
\frac{\Delta Z}{\rho_0} = \frac{\Theta_0}{\mu}
\]

(13)

Substituting for \( \rho \), \( \mu \), and \( \Delta Z \), equation (12) becomes

\[
\left( \frac{12 \chi}{\sigma} \right)^{2} \omega^2 \left( 1 - \frac{3 \Theta_0}{\sigma} \right) = \frac{\Theta_0}{\mu} \Delta Z
\]

\[
\omega = \sqrt{\frac{42 \chi \Theta_0}{\sigma} + 625 \Theta_0^2 - 25 \Delta Z}
\]

(14)

It may be noted here that the part in momentum per unit area of this flow from zero velocity is \( \frac{1}{2} \omega^2 \left( 1 + \frac{3 \Theta_0}{\sigma} \right) \) which is less than \( \frac{3 \Theta_0}{\sigma} \). It is because \( \frac{3 \Theta_0}{\sigma} \) is in effect \( \frac{1}{2} \) 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 plane of air. The rise in temperature of the air at exit from the upper surface of the fuel bed over the initial temperature difference \( \Theta_0 \) between the hot-fuel and the cold air may be estimated from that for the heat transfer for forced convection, and it can be shown that the heat transfer for all the combinations of \( \sigma \) and \( \lambda \) in these fuel beds is high enough for the air to be in effect heated to the fuel surface temperature. Thus if \( \Theta_0 \) is taken as 300°C and \( \sigma \) as 0.64, \( \Delta Z \) is \( \chi \left( \frac{12 \chi}{\sigma} \right)^{2} \), \( \omega \) is \( \chi \left( \frac{12 \chi}{\sigma} \right) \left( 1 + \frac{3 \Theta_0}{\sigma} \right) \) in cgs units which for the values of \( \chi \) used by Curry and Fans is less than 55 cm/s. Lower temperatures give
The heat loss per unit area of the fire front is given by equation (8)

\[ q'' = \frac{2}{A} \int_{0}^{\infty} \left( \frac{T_0}{T_0 + \Theta_0} \right) \left( \frac{42 \varepsilon \lambda \Theta_0}{0.5 \gamma} \right) \frac{\alpha}{\Theta_0} \left( \frac{2 g \lambda \Theta_0}{6 \gamma \Theta_0} \right) \text{d}x \]

The value of \( \gamma \) and its variation with temperature is not of great importance if

\[ \frac{42 \varepsilon \lambda \Theta_0}{0.5 \gamma} \approx 1 \]

In this condition and equation (17) we then obtain from equation (15)

\[ q'' = \frac{100 \varepsilon \lambda \beta_0 \gamma_1}{0.5 \lambda} \sqrt{\frac{2 \varepsilon \lambda}{\Theta_0}} \int_{0}^{\infty} \frac{e^{-\frac{x^2}{2}}} {1 + e^{-y}} \text{d}y \]

The infinite integral is \( e^{-\pi/2} \) so that

\[ q'' = 0.62 \alpha_0 \lambda^{1/2} \]

where \( \alpha_0 = 1.3 \times 10^{-2} \text{ cm}^3 / \text{cm}^2 \), \( g = 0.2 \text{ g/cm}^3 \), and \( \lambda = 550 \text{ cm}^{-1} \), \( \lambda = 15 \text{ cm} \), \( \Theta_1 = T_0 = 300^\circ \)

We obtain

\[ q'' = 0.62 \lambda^{1/2} \]

4. Experiments by Curry and Yous

Data from Fig. 13 in the report by Curry and Yous have been replotted in Fig. 4. In the region where \( \lambda < 0.3 \) the rate of spread decreases rapidly with \( \lambda \), while with \( \lambda > 0.3 \) a more gradual decrease is observed, suggesting a different regime of behaviour. In this connection, it is of interest that Palmer (10) has obtained similar results for \( \lambda < 0.1 \) and for \( \lambda > 0.3 \). This regime of burning is of less interest and it is with the region \( \lambda > 0.3 \) that we are most concerned here.
For these values of \( \lambda \) the data given by Curry and Fons may be correlated by a formula shown in Fig. 1:

\[
R_{\lambda} = (1.5 - 3.6\lambda) \text{ cal cm}^2\text{s}^{-1}
\]

(9)

except that the rates of spread for the instant fuel, woodwool (Excelsior), are substantially in excess: no explanation is offered for this discrepancy at present. \( \epsilon \phi \) is taken as appropriate to a moisture content of 6.8 per cent. Thus the values in entirely represented here for a dry material by \( \epsilon_0 \phi \) is for wet wood

\[
\epsilon_e \phi_e = \epsilon_0 \phi_0 \cdot \epsilon_w + m \Delta H
\]

where \( \epsilon \) is the specific heat of dry wood \( 0.44 \)
\( \epsilon_0 \) is the heat of wetting to cal/g
\( m \) is the moisture content by \( \% \).
\( \Delta H \) is the enthalpy difference between water at, say, 20°C and the temperature at which the vapour leaves the fuel bed.

None of the last vapour leaves sufficiently far ahead of the fire front for its temperature to be taken as 0°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 \( \sigma, \lambda \) etc. However, we shall take \( \Delta H \) as 6.0 cal/g and then put \( \epsilon_0 \) \( \phi_0 \) = 15 cal/g for \( m = 0.085 \).

... an effective \( \epsilon_0 \) of \( 1/\lambda \Delta H \) i.e. 0.57 cal cm\(^2\) degC\(^{-1}\)

Equation (9) can then be written as

\[
R_{\lambda} \epsilon_e \phi_e = (1.5 - 3.6\lambda) \text{ cal cm}^2\text{s}^{-1}
\]

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

\[
R_{\lambda} \epsilon_e \phi_e = \epsilon_0 \phi_0 \cdot (1 - 0.67 \lambda \Delta H)
\]

(20)

and here it is possible to identify the intensity of radiation emitted by the burning zone \( \lambda_0 \) as 1.4 cal cm\(^2\) degC\(^{-1}\). This is a reasonable value of the same order as that obtained from examination of the data for spread in orbits. The value calculated for \( \phi_e \) from equation (18) differs in form from the value derived from equation (9) if the variation in \( \lambda \) is regarded as the consequence of a variation in cooling loss. The actual magnitudes, however, are of the same order. Thus over the range 0.6 < \( \lambda < 0.9 \) the coefficient of \( \lambda \), viz 0.67 \( \lambda \) \( \Delta H \) varies from 0.67 to 0.9 compared with the experimental value of 0.6. Errors will be incurred in making use of such a treatment of the variation in \( \lambda \) and \( \Delta H \) with moisture ahead of the fire front, but the results do support nevertheless that the variation of \( R_{\lambda} \) with \( \lambda \) could be a consequence of the variation in the cooling loss.
where \( x = \frac{\text{cal}}{\text{deg}} \) in equation (26) can be provisionally identified with the term \( f \) in equation (19).

\[
N \cong 0.67 \times 10^{-4} \lambda \text{ cal} \text{ cm}^{-2} \text{ deg}^{-1}
\]

For the same fuel as in 
\( f \) in equation (26) gives the estimated \( f \) as \( 6 \times 10^{-4} \) cal cm\(^{-2}\) deg\(^{-1}\) which is a little less than the \( 6 \times 10^{-4} \) cal cm\(^{-2}\) deg\(^{-1}\) assumed in analyzing the data on fuels. The estimate of \( f \) varies approximately as the square root of \( H \) and no correction has been made for change in the choice of \( f \) in reference (4).

4. Discussion and Conclusion

We have in fact correlated much of the data reported by Curry and Fans for extinction of spread of fire in still air at a fixed moisture content. The extinctions are principally the thinnest fuel and the most tightly packed beds where the behaviour results would be expected to be different anyway. The value of \( f \) equals 0.2 mg cm\(^{-2}\).

The correlation of data gives an estimate of \( \frac{\text{cal}}{\text{deg}} \) as 0.175 and a value of \( y \) of about \( 1 \times 10^{-4} \) cal cm\(^{-2}\). Equation (27) applies for thickness as that the value of \( f \) expected when \( y \) is taken as corresponding to 10 per cent moisture v/v (0.07, 0.4) mg cm\(^{-2}\) in reasonable agreement with the above values. It is probably sufficient for practical purposes to regard \( \frac{\text{cal}}{\text{deg}} \) as 6 x 10\(^{-4}\) cal cm\(^{-2}\) over a wide range of thickness and fuel spacing for practical purposes.

5. Acknowledgements

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

6. References


(5) HEDGIN, A. J. W. Unpublished data.

(1) CROOKHART, M. J. and YOUNG, R. A. Unpublished Data.
\[ R = \text{Rate of spread of fire} \]
\[ \rho_D = \text{Bulk density of fuel bed} \]
\[ \lambda = \text{Volume of voids in fuel bed} \]
\[ A = \text{Surface area of solids in fuel bed} \]

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
- Δ 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**