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Trajectory of Firebrands in and out of Fire Whirls

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Firebrands which are generated from a fire front and carried by prevailing winds may become a source of spot fires impeding fire control and endangering men and equipment. A normal thermal convection column can only lift small embers which fall relatively close to the fire front (<500 ft), but fire whirls are characterized by high uplift velocities and the ability to generate long distance firebrands. This brief communication addresses itself to the calculation of trajectories of long-range firebrands.

When analyzing the trajectory of firebrands originated from a fire whirl, three regions are considered: region I is the fire whirl core characterized by a solid body rotation; region II is the ambient swirl characterized by a constant angular momentum; and region III extending above the core and swirl zone and beyond the swirl zone where the main force carrying the firebrand aloft is the prevailing wind.

In region I, the trajectory of a firebrand with mass m, drag coefficient C_D, and maximum drag area A, can be defined using cylindrical coordinates (radial r, axial z, and azimuthal θ) by three equations:

$$m\ddot{z} = \left(\frac{1}{2}\right)\rho C_D A\,[(u-\dot{z})^2 + \dot{r}^2 + (W - r\dot{\theta})^2]^{1/2}(u-\dot{z}) - mg, \tag{1}$$

$$m(\ddot{r} - r\dot{\theta}^2) = \left(\frac{1}{2}\right)\rho C_D A\,[(u-\dot{z})^2 + \dot{r}^2 + (W - r\dot{\theta})^2]^{1/2}(-\dot{r}), \tag{2}$$

$$m(r\ddot{\theta} + 2\dot{r}\dot{\theta}) = \left(\frac{1}{2}\right)\rho C_D A\,[(u-\dot{z})^2 + \dot{r}^2 + (W - r\dot{\theta})^2]^{1/2}(W - r\dot{\theta}), \tag{3}$$

where u, W and ρ are fire whirl core axial velocity, swirl velocity and gas density, respectively, calculated in the manner described by Muraszew, Fedele, and Kuby [1].

If a firebrand leaves the side of the fire whirl core, it will enter region II described by the same equations as region I except that in region II there is no gas axial velocity but only a tangential velocity, W, which can be calculated from known ambient circulation, Γ (deduced from meteorological data) by:

$$W = \frac{\Gamma}{r}. \tag{4}$$

In addition, the gas density ρ is replaced by ambient air density of ρ_∞. The radial extent of region II is at a point where the tangential velocity is equal to the average wind velocity and the height of that zone, z_e is equal to the vertical extent of the ambient circulation.

The calculations have shown that the residence time of firebrands in regions I and II was short, usually less than 10 s, and that during this time, which can be considered the ignition period, only a small change in firebrand size and mass occurs. Consequently, mass and size could be assumed constant in regions I and II and equal to the initial conditions.

In region III, the firebrand is burning and its density and size decrease. Tarifa [2] found that in a wind environment a firebrand quickly attains a horizontal velocity equal to the wind velocity and falls at its instantaneous terminal fall velocity. Tarifa's observations led also to a conclusion that for a variety of woods both cylindrical and spherical in shape the ratio of instantaneous terminal fall velocity to initial terminal fall velocity could be represented by a unique analytical function of a parameter Z, which includes firebrand initial shape, size, density, fall velocity, and air density and air viscosity [1]. He also observed from wind tunnel experiments that the flight of a firebrand could be calculated assuming that the firebrand flies at its maximum drag orientation with a constant drag coefficient. With these observations, a trajectory of a firebrand in region III can be calculated:

$$\text{Horizontal distance } x = \int_0^t u_{x\ \mathrm{wind}}\, dt, \tag{5}$$

$$\text{Vertical distance } z = \int_0^t (u_{z\ \mathrm{wind}} - w_f)\, dt. \tag{6}$$

In the above equations, $u_{x\ \mathrm{wind}}$ and $u_{z\ \mathrm{wind}}$ are given and w_f, instantaneous fall velocity, can be calculated from Tarifa's relationship for w_f/w_{f0} assuming that the initial conditions of a firebrand are known. The vertical distance z at which the firebrand enters region III was calculated from region I and II trajectories; hence, the time of flight t and horizontal distance x can be calculated by numerical integration.

To obtain the information on the size and mass of a firebrand at impact, an expression describing the burning law of a firebrand in flight must be introduced. This expression was derived from tests carried out by the Forest Research Lab in Missoula [1] and it defines the ratio of instantaneous average firebrand density, ρ_f, to its initial density, ρ_0, for cylindrical shapes as a function of time by the equation:

$$\frac{\rho_f}{\rho_{f0}} = e^{-\frac{t}{D_0^2 \cdot k}}, \tag{7}$$

with

$$k = 929(43.3 - 1.87 w_f + 0.01 w_f^2),$$

where w_f is in ft/s; time t, in sec; and initial firebrand diameter, D_0, in ft. Knowing ρ_f/ρ_{f0} and w_f/w_{f0} from Tarifa's relationship, the diameter of the firebrand at time t can be calculated from $D/D_0 = (w_f/w_{f0})^2 \cdot \rho_{f0}/\rho_f$.

The density law for flat plates (representing bark pieces) was experimentally found to be:

$$\frac{\rho_f}{\rho_{f0}} = e^{-\frac{t}{h_0 \cdot k}}, \tag{8}$$

with

$$k = 30.48(126 + 59 w_f - 0.8 w_f^2),$$

where h_0 is flat plate thickness in ft.

Further observations in the Missoula experiments regarding flat plate burning indicated that there is little change in plate thickness, the burning taking place at the edges. The ratio of instantaneous to initial terminal velocity for flat plates does not follow Tarifa's relationship but can be ex-

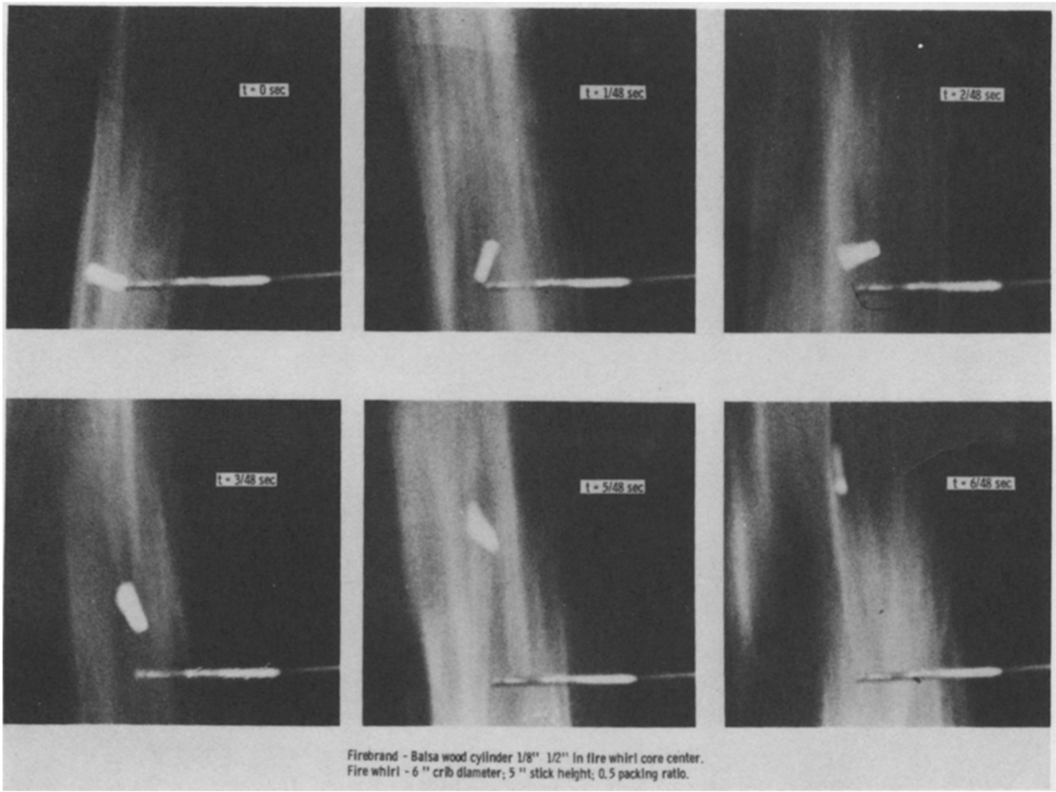

Fig. 1. Firebrand trajectory experiments.

pressed by:

$$\frac{w_f}{w_{f0}} = \left(\frac{\rho_f}{\rho_{f0}}\right)^{1/2} \tag{9}$$

To verify the calculation of fire whirl core trajectory (region I), firebrands were introduced into the experimental fire whirl discussed in Ref. [1]. Balsa sticks of 1/16 in and 1/8 in cross section, 1/2 in long were introduced at various points of the core and their motion was photographed with a movie camera at 48 frames/s, as shown in Fig. 1. The distance traveled was compared with calculated data indicating good agreement, as for example shown in Fig. 2.

Using calculated data from Muraszew et al, [1] for real life fire whirls with three different heights (2000, 3000 and 4000 ft), trajectories of a flat plate simulating a piece of Ponderosa pine bark were computed in region III and the results are

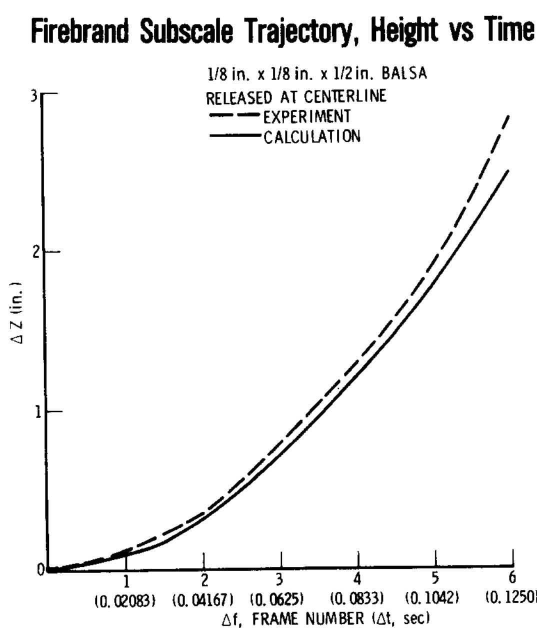

Fig. 2. Firebrand subscale trajectory, height vs. time.

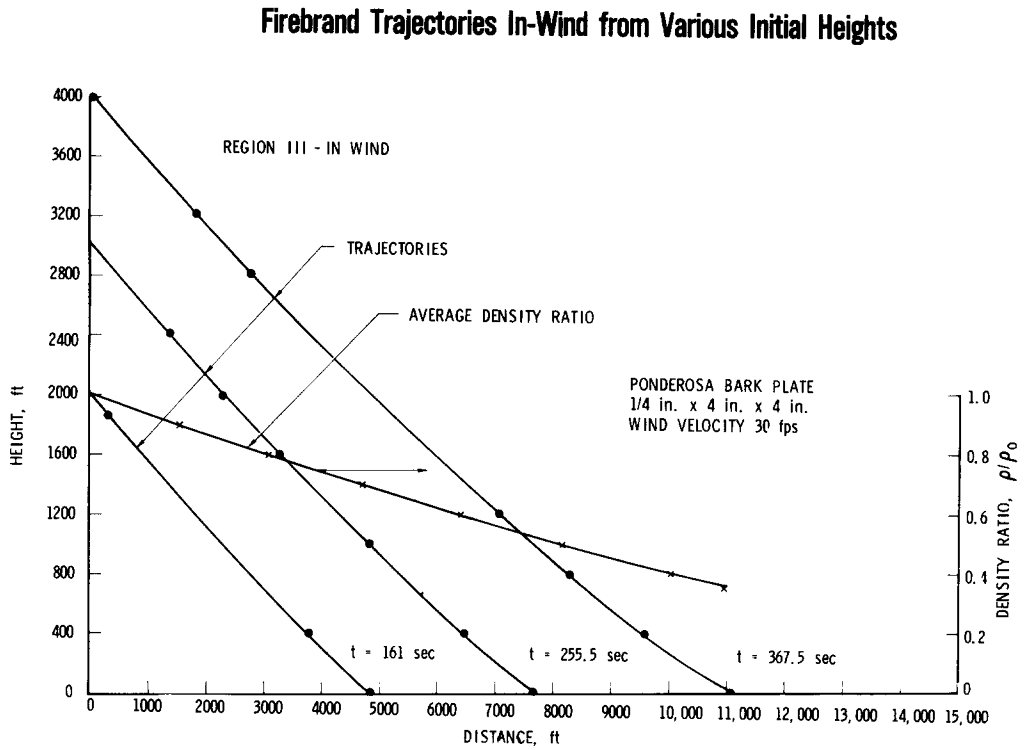

Fig. 3. Firebrand trajectories in wind from various initial heights.

shown in Fig. 3. It can be seen that when firebrands are lofted to heights of several thousands of feet, they may travel distances of several miles from the main fire front in burning condition and then upon impact may initiate spot fires. The bark plates are particularly dangerous because of their low density (hence low fall velocity) and slow burning rate which allows them to glow for a long time. This was confirmed by a number of observations [3].

The analytical approach presented above enables calculation of trajectories and conditions at impact of firebrands lifted by fire whirls.

Calculation of trajectories from two-dimensional convection columns above a fire front based on the same methodology was presented in an earlier report [4]. These convection columns have usually low uplift velocities and small size firebrands are lifted which fall (depending on prevailing wind) only a few hundred feet from the fire front.

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