A Basic Approach to Fire Injury of Tree Stems

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FIRE HAS COME to be widely used as a tool in wildland management, particularly in the South. Its usefulness in fire hazard reduction, removal of undesirable trees, and changing of cover types has been demonstrated. We are continually trying to improve fire use, however, by learning more of the specific effects of fire on different species of plants.

Most fire effects studies are conducted by observing conditions following one or more fires. In the study described here, the approach has been to measure the separate factors involved in fire injury, and then to predict the effect of a given fire on tree stems.

Some phases of the study are complete, whereas much more information is needed in others. The purpose of this paper will be not to describe in detail any part of the study, but to outline the approach taken.

The problem has been considered in three parts. First, there is the heat pulse to which the stem is subjected. This heat pulse is the high temperatures produced by the fire. Second are the stem characteristics. This part consists of the thermal properties of bark and wood, and also bark thickness, bark fissuring, and stem diameter. Third are lethal temperatures. Although these have not yet been studied at the laboratory, consideration has been given to use and manipulation of lethal data taken from the literature.

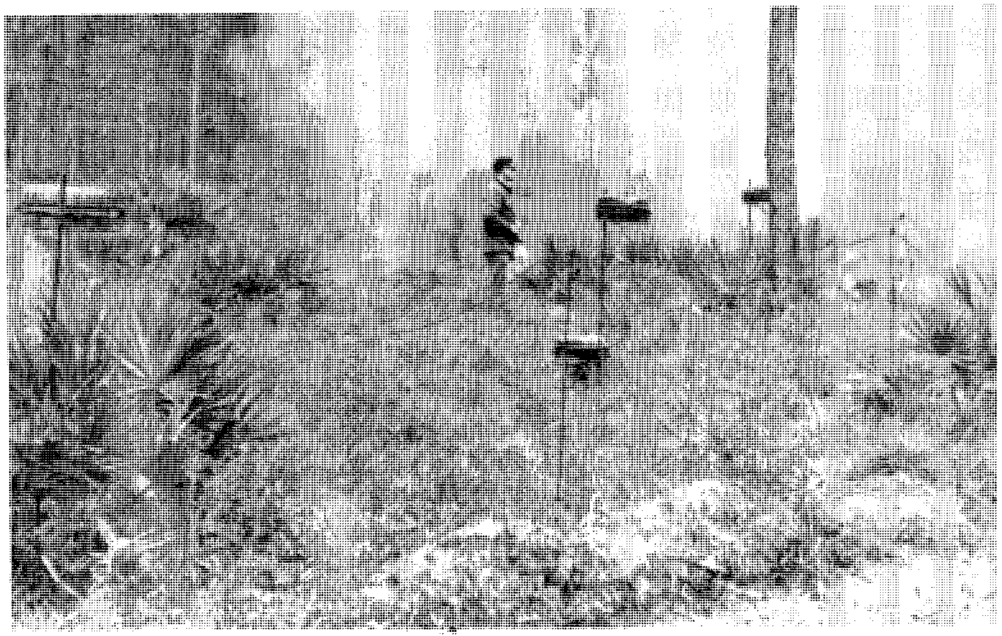

Fig. 1. Installation for measuring fire heat pulse. In addition to the themocouples for indicating the fire time-temperature relations, roasters filled with water were used as calorimeters to indicate heat output.

FIRE TEMPERATURES

Heat input to the surface of the bark is governed by fire temperatures and their durations. Whereas many investigators have measured maximum forest fire temperatures, little work has been done on variation of temperature with time as a fire passes.

Fire temperatures were measured in palmetto-gallberry fuels in south Georgia. Chromel-alumel thermocouples were used as sensing elements, the temperatures being indicated on pyrometers located outside the burn plot. Lead-in cables were buried in the early part of the study, but a high temperature insulation was found, permitting above ground connections. Thermocouple junctions were located on poles at one and four feet above the ground (Fig. 1) at three locations within each plot. As the fire passed each measuring pole, a switching arrangement allowed measurements to be obtained from the next. The two pyrometers were read at three-second intervals, providing almost continuous curves for both the one and four foot elevations.

Head and backfires were measured for each of three levels of fuel accumulation. Difficulties in measurement of fuel consumption, however, made it necessary to group the fires by rate of spread only.

Three rate-of-spread categories are shown in Figure 2. Of the three categories, the 5-10 and >10 chains per hour are head fires burning under different fuel and weather conditions. The <5 category consists of backfires. The peaks of all three categories are made to coincide at the one-foot level, and represent averages for the number of fires indicated.

The highest peaks at both one and four feet were recorded for the highest rate-of-spread fires. The four-foot peaks precede or follow the one-foot peaks by an amount dependent on wind and rate of spread. The backfires demonstrate a slower temperature decline following the peak, giving a somewhat different curve shape than the head fires.

The temperature curves presented in Figure 2 are somewhat lower

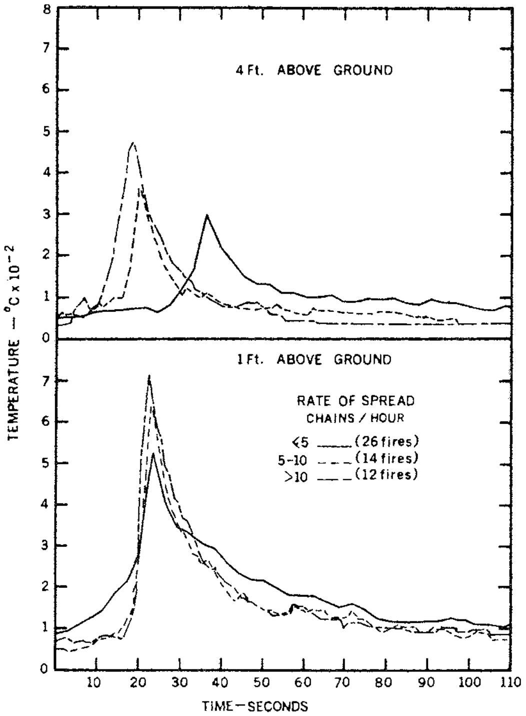

Fig. 2. Fire time-temperature curves for various rates of spread in palmetto-gallberry fuels.

than true gas temperatures. From consideration of the heat gain and heat loss of each thermocouple, the difference is due primarily to radiation losses. The difference between actual and recorded fire temperatures is related directly to the fourth power of the absolute temperature and inversely to a function of the gas velocities around the thermocouple. Correction of the error would accentuate the peaks of all curves and have the greatest effect on curves where the gas velocities are least, that is, in the slower spreading fires.

It should be pointed out that the fire time-temperature curve is not the same as the bark surface time-temperature curve. Just outside the bark surface a temperature gradient occurs due to the surface transfer resistance. The amount and nature of the temperature gradient depend on temperature and properties of the gas and surface. In effect, the recorded time-temperature curves lie somewhere between true gas temperature and bark surface temperature.

Although errors occur in the fire temperature measurements, the curves are very useful as a first approximation. Future measurements will be directed toward evaluating and correcting the errors and toward measuring fuel and weather variables.

STEM CHARACTERISTICS

Once the heat input to the bark surface is known, thermal properties of the stem must be known in order to predict temperatures that will occur in living tissues. Thermal properties of wood are well known (Rowley, 1933; Wangaard, 1939; MacLean, 1941), but data on bark were obtained in this study (Martin, 1963a; 1963b).

Three thermal properties of a material are important in considering heat transfer through it. Thermal conductivity is the ability of a material to transmit heat and is expressed in terms of the amount of heat conducted across a unit area per unit time per unit temperature gradient. Specific heat is the ability of a material to absorb heat in terms of the heat absorbed per unit mass per unit temperature change. Thermal diffusivity is the ratio of thermal conductivity to the product of specific heat and density. Its value indicates the rate at which temperatures change within the material when its surface temperature changes. Thermal properties of a material are affected by many factors. In this study on bark, density, moisture content, and temperature accounted for most of the variation in thermal properties, regardless of species.

Thermal conductivity of bark was measured by the heated probe method, a method well adapted to small specimens of irregular shape. Bark from three pine and seven hardwood species was used in the testing. Thermal conductivity in the transverse plane was first correlated with density and moisture content, and the regression equation:

$$k = [5.026\rho + 13.241\rho_m - 0.202] \times 10^{-4}$$

where k = thermal conductivity, cal/cm sec °C.

ρ = bark density at current moisture content, gm/cm^3
ρ_m = moisture density, gm/cm^3

accounted for 98.1 percent of the variation in conductivity. To this equation was added a temperature coefficient of conductivity, as indicated in paired tests at different temperatures, giving the equation:

$$k = [5.026\rho + 13.241\rho_m + 0.0078t - 0.397] \times 10^{-4} \qquad (1)$$

where t = temperature °C.

This equation expresses thermal conductivity in terms of physical properties of the bark and can be used for other species of bark that are not radically different in structure and composition from those used here. Supplementary tests showed that longitudinal conductivity is always greater than tangential conductivity. In the transverse plane, tangential conductivity is usually greater than radial conductivity. The ratios of longitudinal to tangential conductivity were about 1.1:1, nowhere near the 2:1 or 3:1 ratios reported for wood (Wangaard, 1939; MacLean, 1941).

Specific heat of dry and moist specimens was measured by a standard laboratory test ASTM C351-54T (Am. Soc. Test. Matl., 1958). Measurements indicated that bark has about the same specific heat as wood, and the effect of temperature on bark specific heat was assumed to be the same as that for wood (Dunlap, 1912). Specific heat of dry bark then becomes:

$$C_p = 0.264 + 0.00116t \qquad (2)$$

where C_p = specific heat, cal/gm °C.
t = temperature, °C.

The specific heat of bark containing moisture is somewhat higher than the addition of bark and water heat capacities due to heat of sorption. This elevation was also measured in this study with the following results:

$$\begin{aligned} \triangle C &= 0.083\ M \text{ for } O \leq M \leqq 20.27 \\ \triangle C &= 0.083 \text{ for } M > 0.27 \end{aligned} \tag{3}$$

where $\triangle C$ = elevation of specific heat, cal/(gm dry bark) °C.
M = moisture content, gm H_2O/gm dry bark

Thermal diffusivity of bark was calculated from equations (1), (2), and (3), plus the specific heat of water. The results indicate that thermal diffusivity is nearly constant over wide ranges of density, moisture content, and temperature. For studies in which diffusivity alone can be used, an average value of 13×10^{-4} cm^2/sec would probably be best to use.

In order to apply the measured thermal properties to living tree stems, knowledge of moisture distributions across tree stems was needed. As obtained from field sampling and from the literature, the ranges in moisture distribution patterns shown in Figures 3 and 4 were obtained. All species have low moisture contents in the outer bark. As the phloem is approached, moisture content increases, with a large jump occurring near the last formed periderm, or cork layer. Hardwoods display a gradient in moisture content within the phloem, but the pines do not. Moisture content drops as we proceed inward from the cambium to the center of the tree.

Combining moisture contents with bark and wood density we find the tree stem consists of a shell of bark low in thermal conductivity and specific heat, around an inner core of high conductivity and specific heat. This central core may be very significant in tree resistance due to its ability to absorb and conduct heat. The diameter of a tree stem will thus play an important role in fire injury.

In addition to moisture distribution and density, bark thickness and fissuring will be important in fire injury of tree stems. Using data from the Lake City Research Center, bark thickness of Longleaf and Slash Pine was shown by multiple regressions to be dependent primarily on diameter of the tree at the point of measurement. This

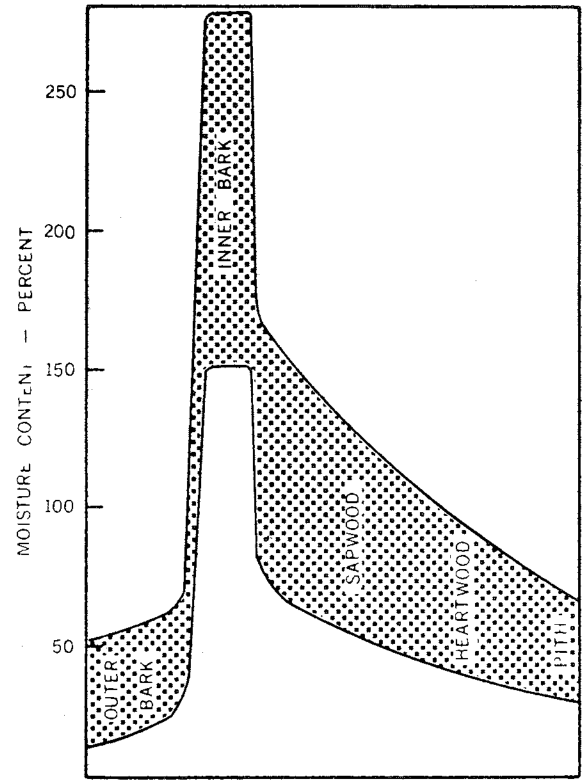

Fig. 3. Range in moisture content distribution in cross-section of pine stems showing values found in this study and previous studies by other investigators.

almost constant relationship between inner and outer bark diameter will greatly simplify the evaluation of heat flow into stems. Bark fissuring will have to be considered in later phases of the study as measures of its importance are developed.

The next step in the problem is to evaluate heat flow into a tree stem. Even the simplest of situations we might encounter represent complicated heat flow problems. From a solution, a family of curves such as those shown in Figure 5 would be obtained. Due to the surface transfer coefficient, the bark surface does not attain as high a peak as does the fire, and its peak temperature is attained as the fire temperature drops below it. From that point onward the bark surface

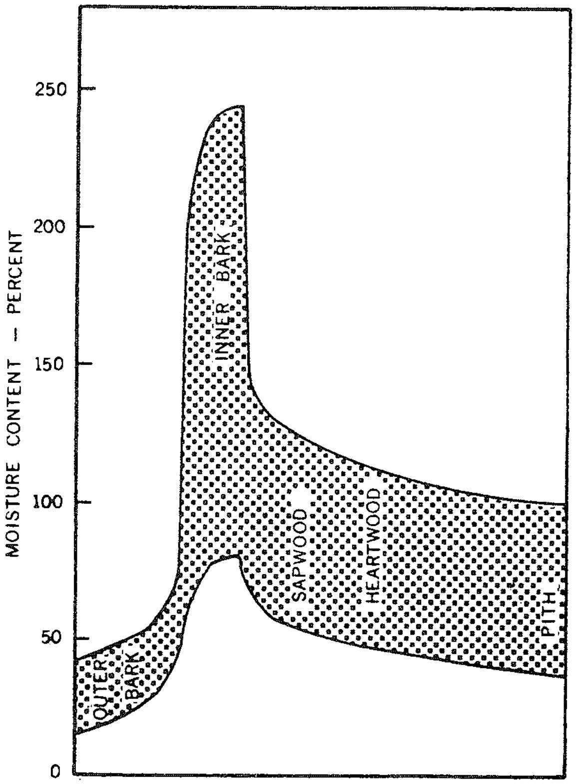

Fig. 4. Range in moisture content distribution in hardwood stems showing range of values found in this study and previous studies by other investigators.

remains somewhat higher than the surrounding air, and both temperatures drop slowly, eventually approaching ambient temperature. Temperature curves within the tree lag behind the surface temperature and their peaks are greatly reduced. The amount of lag and temperature reductions will depend on position in the stem and on stem characteristics.

Initial solutions of heat flow will probably be by use of electrical analogy and be followed by measurements on stem sections. One important difference between the solutions and the curves shown here is that in actual solutions temperature, time, and position will be represented by dimensionless numbers—powerful tools of the engineer. It is through the use of analogies and dimensionless numbers that valuable insights to fire injury of tree stems may be gained.

LETHAL TEMPERATURES

Lethal temperatures of plant tissues have been studied by many investigators. For the most part, data from these studies may be fitted to a semi-logarithmic line of the nature:

$$t = a - b \ln T$$

where t = temperature
$\ln$ = natural logarithm
T = time

By this equation, the temperature to effect kill is inversely proportional to the logarithm of the time of exposure at that temperature. Silen (1960) presented his data for Douglas-fir on a semi-logarithmic chart, and his data for the first indication of injury would give the equation:

$$t = 59.44 - 2.291 \ln T$$

where t is in °C and T is in minutes.
This equation may be manipulated to give.

$$\frac{1}{T} = e^{0.433t - 25.91} \tag{4}$$

Letting $1/T$ equal L, we have the contribution to injury for each minute of exposure to any temperature t. This equation is very useful for evaluating whether or not injury should occur when the tissue is exposed to varying temperatures.

The application of these data to the killing of tree stems would then proceed as follows. We have a fire with a predicted time-temperature curve as shown in Figure 5. An enlarged view of cambial temperature is shown as the flatter curve in Figure 6. If we then substitute the temperature at several times in equation (4) the more peaked curve in the figure is obtained, with its scale reading from the right. If the area under this curve exceeds a value of one, the

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