

Fire As A Physical Factor in Wildland Management

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WE USE FIRE to accomplish many goals. Most of our use is based on long years of experience—experience that enables us to predict the results we should obtain from the “feel” of the situation. Research is being conducted, to assist less experienced land managers to understand fire more completely and to provide means for them to predict its effects in given situations. We must better learn to understand and predict all the effects of fire if we are to use fire effectively, or, for that matter, to use fire at all. Recent pressures by various organizations and individuals are directed at air pollution caused by fire. Unless we can effectively demonstrate the reasons we need to use fire as well as its effects on the atmosphere we will find more laws enacted against use of fire.

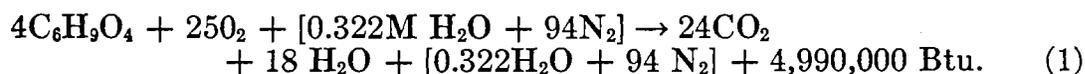
The purpose of this paper is to present a mental model of some physical aspects of fire. Perhaps these can be of use in planning some prescribed fires as well as understanding some effects observed in others. Each fire and therefore its effects are the products of many factors. The basic fuel material, quantity, fuel bed geometry, and moisture content are of elementary importance. Compounding the

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effects of the above factors are atmospheric conditions and movement, and slope. Gradations in all the above factors generally occur both horizontally and vertically, often in an erratic fashion, within the bounds of a prescribed burn, greatly compounding the problem of measuring and understanding fire and its effects.

As a fire progresses, it consumes fuel, releases heat and gases, leaves charred material and ashes, and affects all the biota directly or indirectly to a greater or lesser degree. Combustion of woody fuel has been represented by Byram (1959) as:



Equation 1 represents four basic physical factors in the effects of fire on the environment. First, $\text{C}_6\text{H}_9\text{O}_4$ represents the fuel material which is consumed in a fire. Second, a tremendous amount of heat is produced, the amount given here representing the heat from four pound moles of woody fuel. Third and fourth factors to be considered are the formation of carbon dioxide and water. The water of combustion in addition to the water evaporated in the fuel may have more significance in affecting the biota than has previously been recognized.

Looking at a fire in detail, we might consider an idealized figure or model of fire in relation to the fuel it is consuming (Fig. 1). The head fire under the same fuel conditions as a backfire will have a higher rate of spread and, consequently, a higher rate of energy release. Its flames will be higher and will have higher gas velocities than the backfire. Radiation to fuel in front of the fire will be considerable from the headfire due to its slope and height. The backfire will have relatively little radiative effect from above the fuel in advance of the flame front, but will irradiate the remaining fuel or soil behind it, perhaps contributing to a more complete burn where the lower fuel layers are moist, or to greater soil heating.

Combustion of fuel occurs in four stages. First, heat is transferred to fuel before the fire by radiation, conduction, or convection, the preheating phase of the fire begins. In our normal fuels, conduction is probably of minimal importance and the other two mechanisms are the significant ones, both within the fuel bed and from the

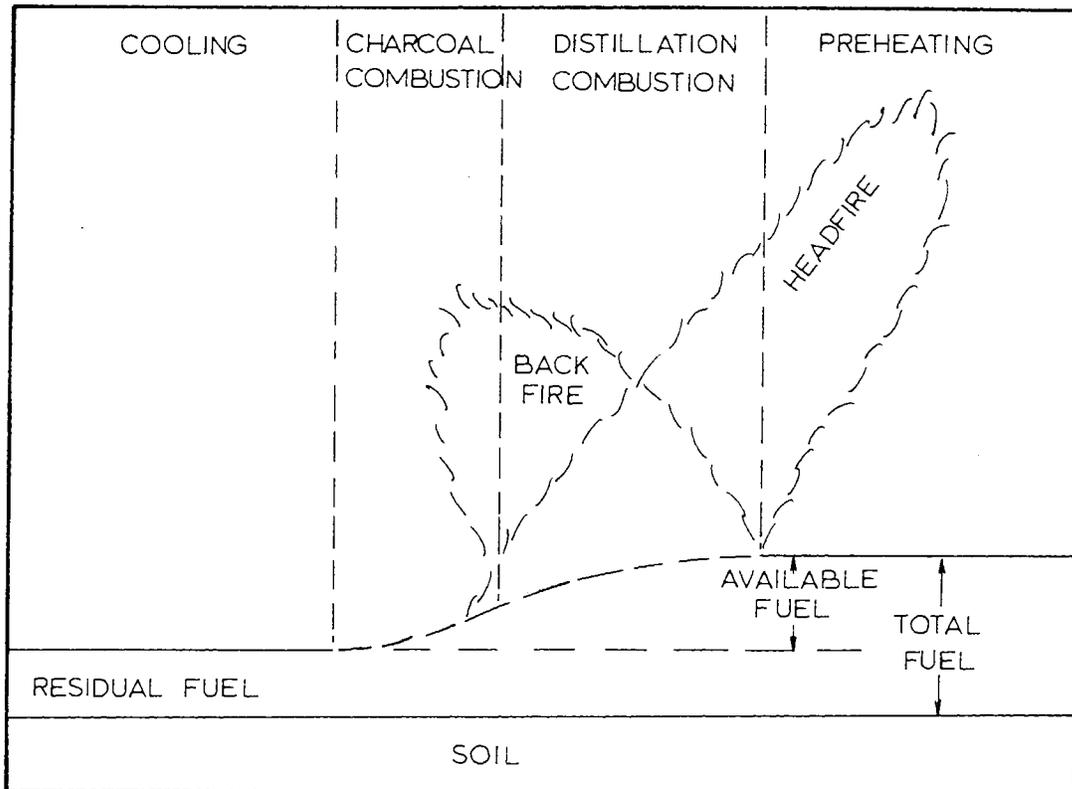


FIG. 1. Stages in fuel combustion. As the fire moves from left to right, the fuel is first preheated and dried. Endothermic and exothermic decomposition occur, releasing gases for the distillation combustion. The flames at any point diminish and charcoal combustion occurs, followed by a gradual cooling of the area.

flames and wind above. In early stages of heating, the energy absorbed by the fuel changes its temperature and moisture content.

As heating of the fuel continues, the second state, that of endothermic decomposition occurs, releasing flammable and non-flammable gases. The third stage of combustion occurs as decomposition becomes exothermic, that is, the energy released exceeds energy absorbed. Flammable gases emitted become concentrated enough to exceed their lower critical flammability level and the flame or distillation combustion stage of the fire occurs.

Finally, the flames pass the region, and charred fuel continues to release energy in glowing or charcoal combustion. Depending on the condition of the fuel, some fuel may remain in the charred condition,

whereas in dry "hot" fires only ash remains. Where subfuels are extremely moist and/or compact, these lower fuels may not even be dried by the fire. The portion of the total fuel consumed by the fire is the available fuel; that remaining after the fire is the residual fuel.

FUEL REMOVAL

Returning to equation 1, we might consider the removal of fuel from the forest floor by fire. The fuel, represented here empirically as $C_6H_9O_4$, may vary somewhat in the ratios of C, H and O. As represented here $C_6H_9O_4$ is not a chemical compound but the ratios of C, H and O in many compounds constituting woody fuels. Carbon, hydrogen, and oxygen constitute most of the fuel; however, they are combined in different ways and in connection with other elements. The other elements are low in percentage but often are quite important as plant nutrients. Generally, a fire may be expected to make available to plants great amounts of the nutrients, either directly or indirectly. Removal of the fuel also has a significant effect on soil temperatures and seedbed conditions, and generally alters the environment of the biota.

Fires may increase pH of soil following fire, but the change may be limited and be of little significance in the pine forests of southeastern United States. The pH of litter as compared to ash is vastly different, however (Fig. 2). In this limited study, litter from a 28-year-old loblolly pine (*Pinus taeda* L.) stand in Montgomery County, Virginia, was separated into fresh litter (dropped the previous fall and winter, collected in March), old litter, and humus or duff. The pH of fuels that were unburned, partially burned, and completely burned were measured, using 4 grams of ground material in 25 grams of distilled water at room temperature (Moore and Johnson, 1967). Each experiment was replicated three times and the averages calculated.

As can be seen in Figure 2, all three fuel portions are fairly acid in the unburned condition. The pH increases somewhat as the material is partially burned, where some parts were ashed, some charred, and some unburned. A large increase occurs in pH as the material is completely ashed, and the possible short time effects of the very

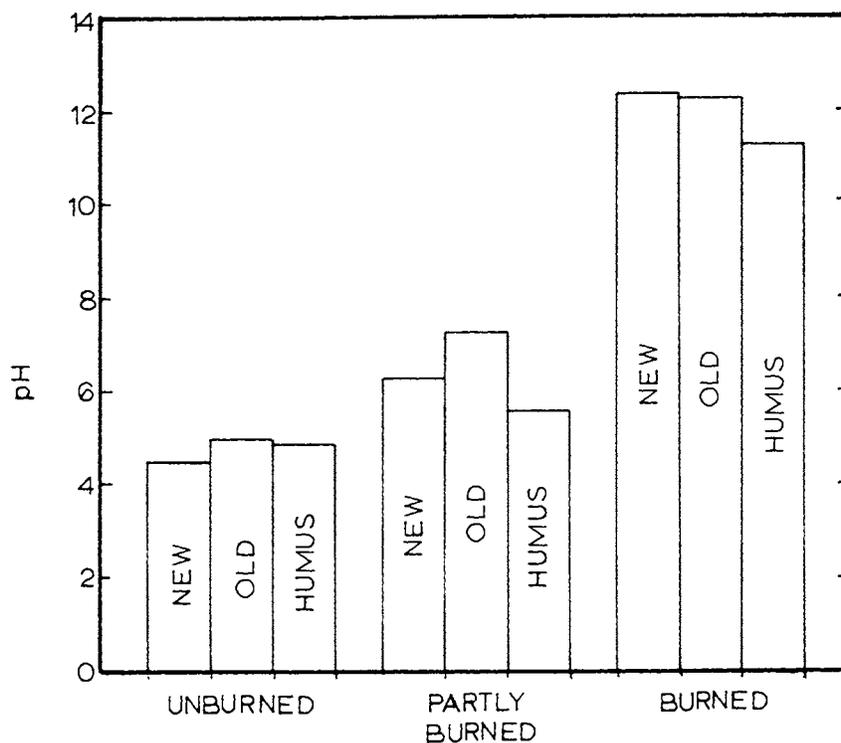


FIG. 2. Values of pH recorded from unburned, partly burned, and completely burned litter from a 28-year-old loblolly pine stand in Montgomery County, Virginia. The pH for all components of the fuel rose from less than 5 to greater than 11 when completely burned.

basic ash on soil flora and fauna as well as chemistry may be considerable. First, the availability of some nutrients may be drastically altered. Secondly, a less acid environment may reduce fungal activity and increase bacterial activity. One offshoot of this may be a greatly accelerated activity of nitrogen-fixing bacteria in the first $\frac{1}{4}$ to $\frac{1}{2}$ inch of the soil where most nitrification is thought to occur. We would like to emphasize that these results are not in contradiction to our previous statement that pH change of soil may be limited and of little significance. The differences lie in the materials analyzed, and timing of the analysis. We have measured pH of the litter or fire residue *not* that of the soil. We justify this procedure by considering very short term effects in the surface layers of the soil, not on long term effects on several inches of soil.

TEMPERATURES

The high temperatures of a fire are one of the most important physical factors to be considered. We might begin by considering the rather generalized view of a fire (Fig. 3). Here, isotherms, or lines of equal temperature, would form closed areas similar to contour elevation lines on topographic maps. Around the bottom and sides of the flame, the temperature gradients would be extremely steep, and the lines tend to merge into one. Above the flame in the convection column, a gradual reduction in temperature occurs. Cooling occurs due to radiative loss and turbulent mixing along the edges of the column. In actuality, one would expect the temperature at any point in the column, but particularly along the edges, to fluctuate drastically since the entrainment of cool air into the column occurs in a rolling, eddy-type motion. Over a period of time, however, the time average of temperature across the column might be expected to produce a fairly smooth curve with the highest temperatures in the interior of the column. The flatness of the curve would be affected by the degree of turbulence occurring in the column.

Surface temperature of a solid object exterior to the flame convection may be considerably higher than the air temperature due to the absorption of radiation. Fons *et al.* (1960) have shown radiation from a fire to represent a considerable portion of the released energy. Radiation occurs from all objects above absolute zero. Due to the fourth power radiation law and the high temperature in the flame or convection column, the net exchange is toward the cooler object. Heating due to radiation can be of significance in fire effects as well as behavior.

Switching from the situation considering the fire at a fixed position, let us consider the exposure of points fixed in space as the moving fire passes. Any point on an object above the fuel bed will be exposed, first to radiant heat, then to convective heating by the gases of the column, and finally to a combination of radiation and limited convection as gases rise from the burned-over area. The curves of Figure 4 represent the average temperatures recorded by thermocouples at 1 and 4 feet above ground for palmetto-gallberry [*Serenoa repens* (Bartr.) Small—*Ilex glabra* (L.) Gray] fuels in south Georgia.

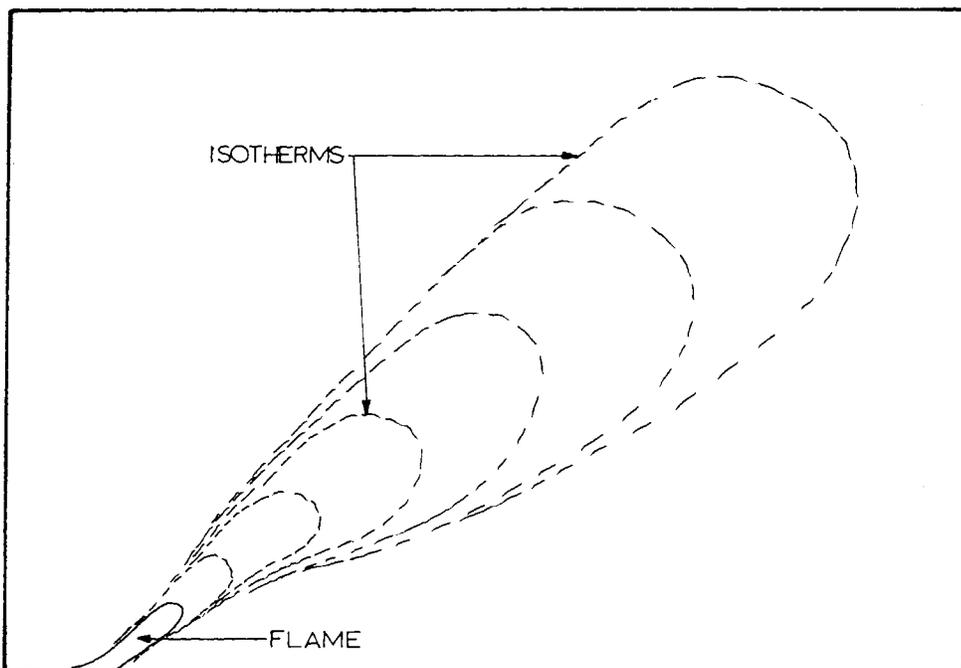


FIG. 3. Idealized isotherms in the convection column above a fire. Temperature decreases as distance above the flame increases. At any instant of time the isotherms, in actuality, would be quite irregular due to turbulence in the column, but time-averaged isotherms would be quite smooth as depicted here.

The curves for 5 chains per hour spread were recorded on backfires. The peaks at the 1-foot elevation were drawn so the peaks coincided. At the 4-foot elevation, the peaks are displaced from the 1-foot peaks by a time factor depending on flame slope and rate of spread. It should be noted that the greater the rate of spread, the higher the recorded peak temperature. The highest peaks recorded on individual fires in this study were around 1000°C or 1800°F , for the most rapidly moving fires, but are lower here due to averaging of many fires.

Time-temperature curves such as those in Figure 4 have often been considered to be fire or flame temperatures. The recorded temperatures are not flame temperature, however, but merely reflect the heat balance attained by the sensor. To understand this more completely, let us consider the following heat balance equation for a sensor in the flames:

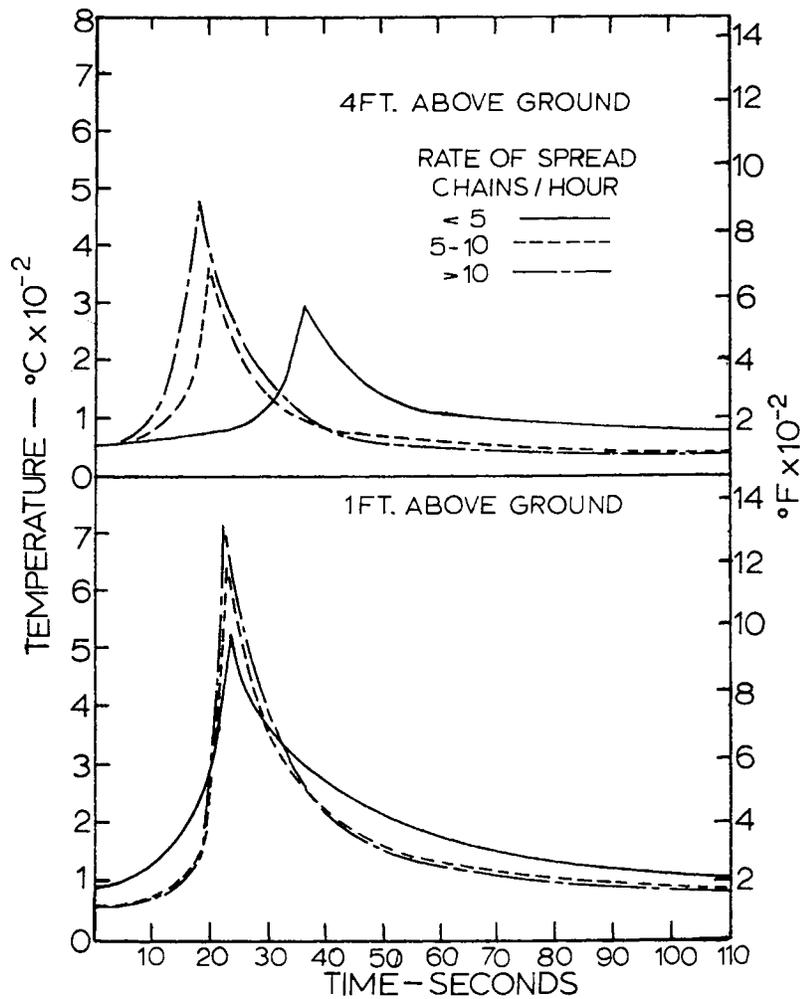


FIG. 4. Smoothed time-temperature records obtained by thermocouple from prescribed fires in palmetto-gallberry fuel in south Georgia. Note that fires with higher rates of spread indicate a higher temperature, probably due to higher gas velocities by the thermocouples.

$$q_C + q_{GR} = q_R + q_K \quad (2)$$

where q represents a heat flux or amount of heat transferred per unit time, and the subscripts represent the following:

C = convective transfer from the flame to the sensor

GR = radiation from the hot gases of the flame to the sensor

R = radiation from the sensor to the surroundings (trees, forest floor, atmosphere)

K = conduction along the leads of the thermocouple sensor away from the sensing junction.

The left side of equation 2 thus represents processes transferring heat to the sensing element; those on the right away from the junction. In the small flames in which the temperatures of Figure 4 were recorded, q_{GR} would be relatively small, and q_K was reduced by exposing a portion of the thermocouple wire to the same temperature. Thus, the important transfer processes are q_C and q_R .

To approach a "true" flame temperature, we should maximize q_C and minimize q_R . In general terms, these factors are dependent on the following relationships:

$$q_C \propto V^x, x < 1 \quad (3)$$

$$q_R \propto (T_{TC}^4 - T_s^4) \quad (4)$$

where

V = flame gas velocity and x is a fractional exponent

T_{TC} = absolute temperature of the thermocouple

T_s = absolute temperature of the surroundings.

The obvious answer to obtain a better indication of flame gas temperature is to increase gas velocity and the temperature of the surroundings. This is often accomplished by placing a series of concentric shields around the thermocouple and drawing gases through the shields and past the thermocouple by a vacuum system. The resulting apparatus is called a shielded-aspirated thermocouple. Such an apparatus was constructed and cribs of white fir [*Abies concolor* (Gord. and Glend.) Hoopes], similar to those of Fons *et al.* (1960) in Project Fire Model, were burned at 8–12 percent moisture content (Fig. 5). The cribs were placed on sheet asbestos which in turn rested on a rack of dead rolls. The rolls allowed the flame to be centered alternately under the shielded-aspirated thermocouple and an exposed thermocouple. A funnel-shaped outer shield aided in concentrating the flame and in reducing the amount of cold air drawn in from the surroundings. Temperatures were recorded on a potentiometric recorder.

The effects of shielding and aspirating a thermocouple were quite dramatic (Fig. 6). To the left of the figure the fire was started, and temperatures were recorded alternately from the shielded-aspirated

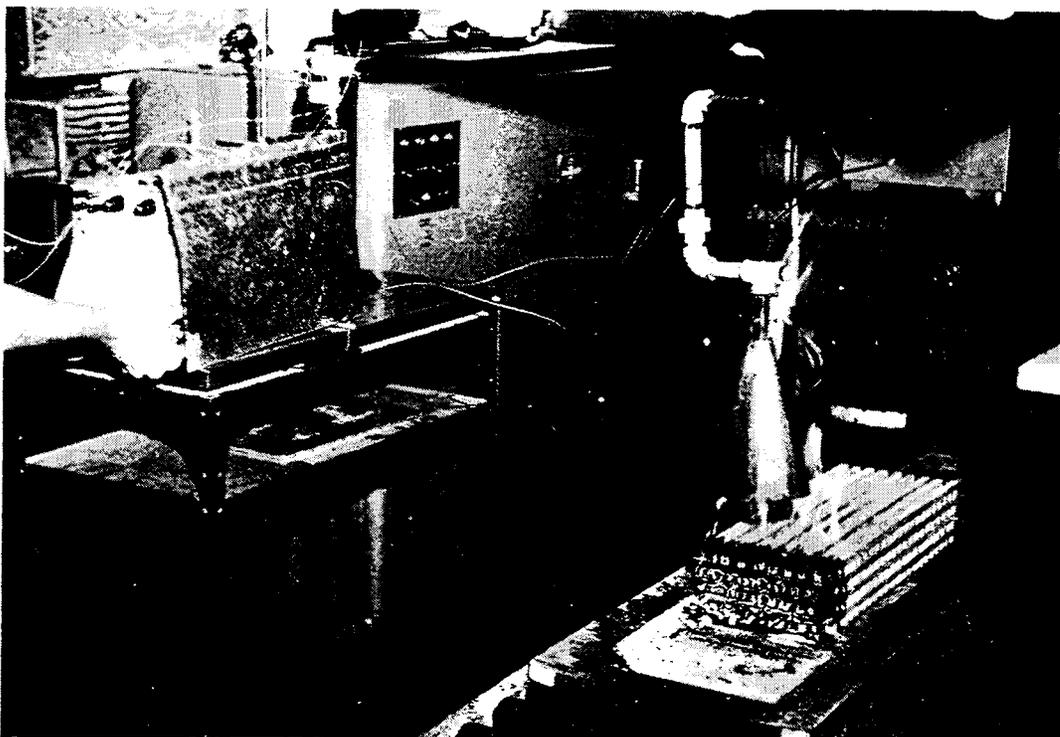


FIG. 5. Laboratory apparatus for recording shielded-aspirated thermocouple temperatures and exposed thermocouple temperatures in flames from a crib of white fir wood.

chromel-alumel thermocouple (SA) and an identical non-shielded, non-aspirated thermocouple (NA). The SA thermocouple recorded peaks greater than 1100°C (2100°F), whereas the peaks for the NA thermocouple were around 870°C or 1600°F .

The peak temperatures recorded on the SA thermocouple still lie somewhat below those calculated from thermocouple errors (Martin, 1963a), and a considerable amount of temperature fluctuation occurs. It is possible that the thermocouple did not reach the temperature of the hottest gases due to its finite size. It is also possible, however, that the aspiration causes an increased temperature over normal flame temperatures due to increased mixing. The fluctuation in temperature could be due to varying temperatures within the flame or to drawing of excess cooler air from the surroundings. It is further interesting to note that the 1600°F recorded on the NA thermocouple corresponds with temperatures often given for woody fuel flame tempera-

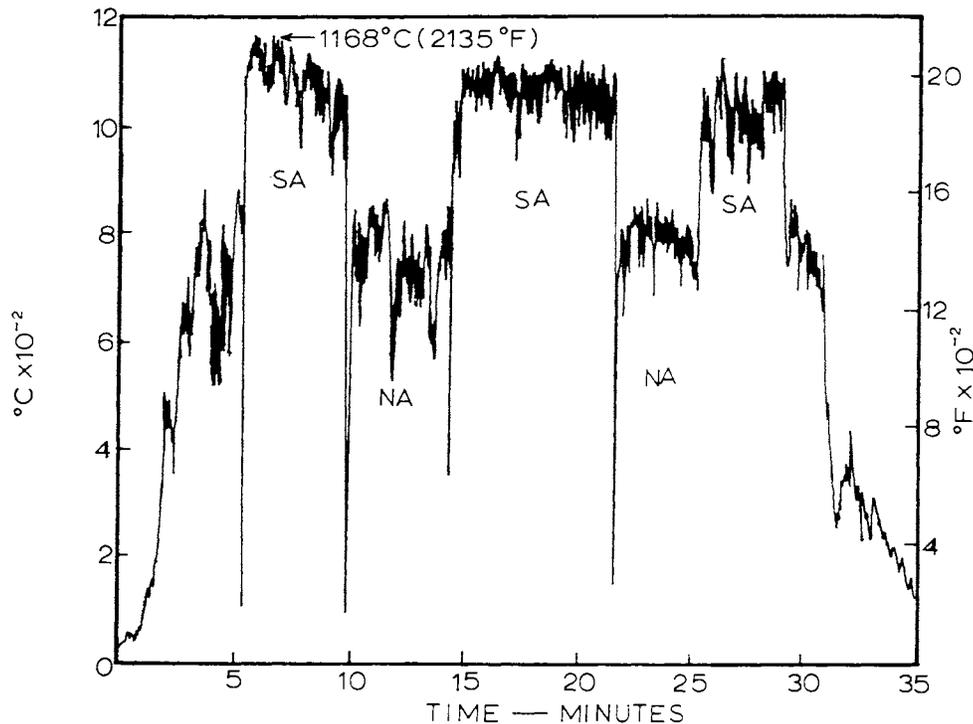


FIG. 6. Temperatures recorded alternately on a shielded-aspirated thermocouple (SA) and a non-shielded, non-aspirated thermocouple (NA) in flames of white fir wood.

tures. The curves of Figure 4 recorded in the field can still be useful in evaluating fires and fire effects as they reflect the ability of the fire to transfer heat. For practical situations it might be easier to evaluate heating of objects directly from the curves than to work from the actual gas temperatures.

MOISTURE

Moisture is present in gases from a fire due to drying of moist fuels and to water produced by combustion. Some prescribed burners have occasionally noticed more scorch of live needles after burning moist fuels than after burning dry fuels. Second, moist heat has been shown to be important in the germination of hard legume seeds (Martin and Cushwa, 1966; Cushwa *et al.*, 1968).

In Figure 7, saturated vapor pressure of water is plotted against

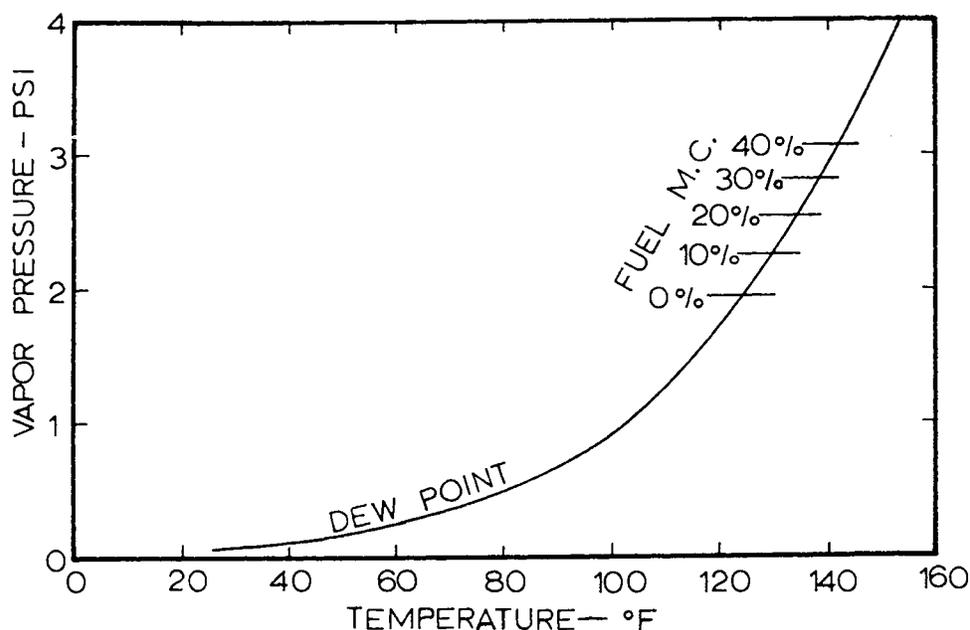


FIG. 7. Dew points calculated for complete stoichiometric combustion of woody fuel using Byram's equation (1). Oven-dry fuel yields a dew point of about 120°F, with dew point increasing as fuel moisture content increases.

temperature. This line represents the dew point, or the temperature at which water vapor will condense, simultaneously releasing its high heat of vaporization. Using Byram's equation (Eq. 1), the vapor pressure for combustion of oven dry woody fuel was calculated and is shown as a horizontal line for 0 percent M.C. The vapor pressures were then calculated for fuel moisture contents at 10 percent M.C. intervals and are shown as a series of horizontal lines. This figure would indicate, then, that the dew point of the gases from combustion of oven dry fuel would be around 120°F and that from fuel at 30 percent M.C. near 140°F. It is interesting to note that as temperature is increased in this range the time many plant tissues can withstand high temperature changes from several minutes to about 1 minute.

Consider the effect of dew point on a pine needle exposed to the convection column. Let's assume that the gas velocity is the same and the temperature about 150°F in both cases. In the first case let the dew point be 120°F as obtained from a dry fuel. Up to 120°F,

moisture will be condensed on the needle surface, releasing the high heat of vaporization and contributing to a rapid heating of the needle. As the needle is heated above 120°F, however, the needle would be able to evaporate or transpire moisture, thus maintaining its temperature somewhat surrounding gas temperatures, due again to the high heat of vaporization. Considering the second case with a dew point of 140°F, as might be obtained from more moist fuel, the needle would be brought quickly to 140°F before it was able to lose moisture and reduce its rates of heating.

The dew points and effects covered above have not been studied experimentally and represent conjecture on our part. In actuality, the dew point could be lower for any fuel moisture content if:

- 1) the ratio of C to H in the fuel were higher
- 2) air is entrained into the convection column
- 3) if all the moisture from pyrolysis or drying were not all contained in the gases.

On the other hand, the dew points may be higher if:

- 1) the ratio of C to H in the fuel were lower
- 2) one considers that the early stages of combustion involve proportionately more water as a product than the later stages of charcoal combustion, together with the fact that much of the gas from the charcoal combustion may not be in the column.

At the present time, the above calculations might help to explain scorch from moist fuels, but experimentation would be needed to verify the calculations.

Moisture has also been shown to be important in breaking the seedcoat dormancy of several legume seeds. Seed from these plants would ordinarily be at or near the soil surface. The seeds also are quite sensitive to temperatures above 100°C (212°F) (Fig. 8). The moisture, from both pyrolysis and drying, might play a role in two ways with respect to the seeds. First of all, the vapor could diffuse downward and condense on the seeds. At temperatures above about 60°C (140°F), the mucilaginous material on the seedcoat becomes quite soluble in water, and the seedcoat dormancy is broken as a result.

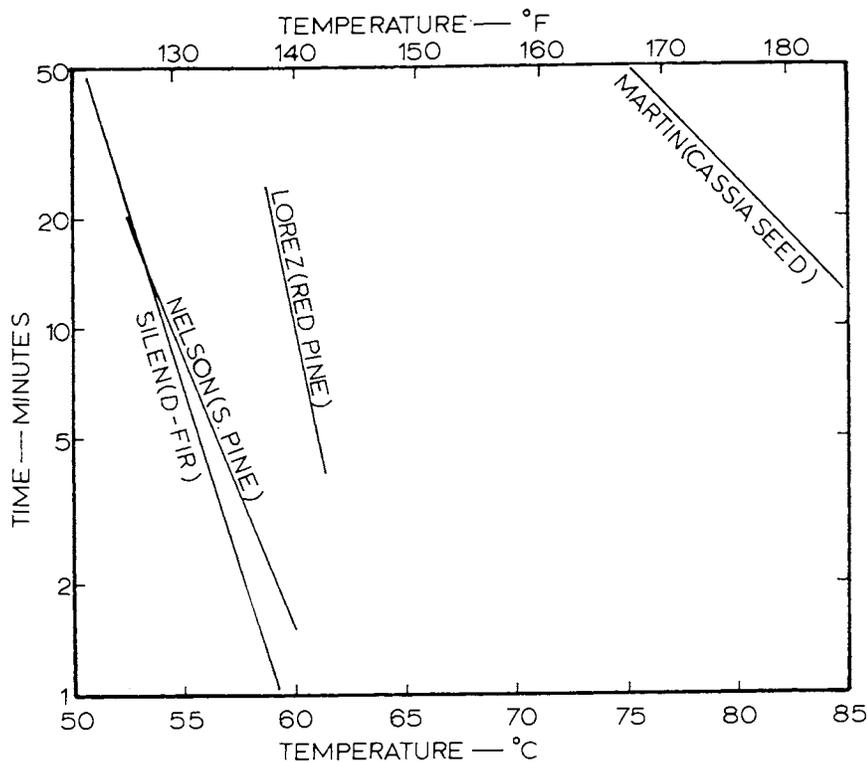


FIG. 8. Lethal time-temperature factors for plant tissues as determined by several investigators. Time is plotted logarithmically and the relationships for any investigation approach a straight line.

Further, moist fuel or soil layers immediately adjacent to the seeds may act as a temperature buffer, not going above 100°C until dried.

LETHAL TEMPERATURES

The time a living tissue can withstand high temperatures is inversely proportional to some function of the temperature to which exposed (Fig. 8). Many people have used a semi-logarithmic form to express the relationship, as:

$$t = a - b \ln T \quad (5)$$

where t = temperature

T = time

a & b = constants for the individual tissue considered.

As can be seen in the figure, different tissues would have different

time-temperature relationships. In addition, the same or similar tissues may have different sensitivities to high temperature, depending on the condition of the tissue at the time of testing.

One important factor to consider, especially in relation to dew point in the convection column is the change in time to cause injury between 120 and 140°F. The data of Lorenz (1939) for red pine, Nelson (1952) for southern pine needles, and Silen (1960) for Douglas-fir seedlings lie in this range. Some differences occur between tissues, and may be due to actual differences in tissue sensitivity or to differences in techniques or criteria for evaluation.

The time-temperature relationships for injury to tissues are generally determined by rapidly raising the tissue to a constant high temperature, maintaining this temperature for a given length of time, and then rapidly lowering the temperature. From this, one is able to obtain the type of curves given in Figure 8. We have already indicated in Figure 4, however, that temperatures from a fire are changing rapidly. Any tissue heated by this shape of heat pulse, whether exposed or isolated by bark, litter, or soil, would also have a continuously varying temperature. If one makes the assumption that the contributions to injury of tissue of temperatures above some critical temperature are additive, then equation 5 may be converted into a rate equation, giving (Martin, 1963):

$$\frac{1}{T} = e^{\left(\frac{1}{b}t - \frac{a}{b}\right)} \quad (6)$$

Thus, knowing the time-temperature curve to which tissue is exposed, and having determined the constants a and b for the tissue, one can expand the exposure curve by equation 6. The area under the expanded curve would indicate whether or not injury should occur. In limited laboratory studies on *Cassia nictitans* seed, we have not been able to demonstrate whether or not this approach is valid.

Finally, we might consider the effects of isolation on the temperatures to which an object is exposed (Fig. 9, Greenstone, 1958). In this computer-calculated figure for a semi-infinite solid—an ideal solid with a flat surface but extending indefinitely behind that surface—all parameters are plotted in dimensionless form, making the curves useful for any number of situations. The dimensionless temperature

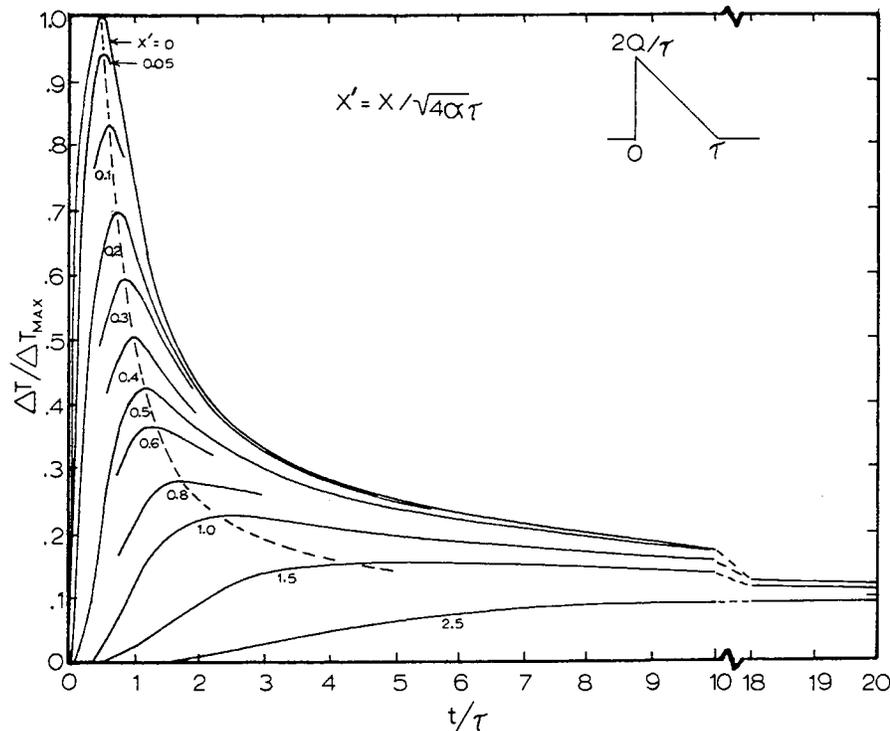


FIG. 9. Dimensionless diagram of the effect of position on the time-temperature curve a material would experience when the surface is exposed to a descending-ramp heat pulse. Curves were calculated by computer for a semi-infinite solid (from Greenstone, 1958).

T/T_{\max} on the ordinate indicates the ratio of the temperature at any time or point to the maximum attained at the surface. Time t/τ on the abscissa is dimensionless where τ is the length of time the radiant heat pulse existed. The dimensionless position, X' , within the solid is given as the ratio of an actual position divided by the square root of $4\alpha T$, where α is the thermal diffusivity of the material. The heat pulse used to calculate the curves is a descending-ramp type curve, depicted in the upper right hand corner, beginning at $t = 0$ and ending at $t = \tau$. Each curve represents the dimensionless time-temperature curve at any dimensionless point within the solid. The very rapid decline in maximum temperatures at points within the solid illustrate the importance of a protective layer over temperature-sensitive tissues. Thus limited depths of bark, litter, soil or other material offer a tremendous amount of protection to living material.

Using an approximate value for the thermal diffusivity of soil ($\approx 9 \times 10^{-4}$ cm²/sec) and a τ of 2 minutes, $\frac{1}{4}$ inch of soil would have a dimensionless position value X' of approximately 1, and $\frac{1}{2}$ inch of soil a value of approximately 2. The peak temperatures at these depths would be only about one-quarter and one-eighth as high, respectively, as at the soil surface.

The curves and calculations used in estimating the effect of isolation on temperature are only approximate calculations. Variability in surface temperatures and soil, as well as other factors, were not taken into account. The importance of the protecting duff or soil layers in protecting living tissues is demonstrated, we feel, by these calculations.

SUMMARY

In this paper we have attempted to illustrate some physical factors of importance in the use of fire. Although we have ignored the factors affecting fire variability and behavior, the principles discussed should contribute to a better understanding of fire effects and, hopefully, to better use of fire.

ACKNOWLEDGMENT

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