

U. S. FOREST SERVICE  
RESEARCH PAPER INT-30  
1966

# FIRE SPREAD CHARACTERISTICS DETERMINED IN THE LABORATORY

by

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# Fire Spread Characteristics Determined in the Laboratory

## INTRODUCTION

A study of the mechanisms of fire spread was conducted from January 1961 to January 1964 by the Fire Physics Research project located at the Northern Forest Fire Laboratory. The research program was supported by the U.S. Forest Service and the National Science Foundation. This report presents the major findings of that study and is part of a continuing program conducted by the Forest Service to obtain a better understanding of forest fires.

Light forest material such as pine needles, leaves, and rotten wood are recognized as the fuels in which fires start and spread in early stages (7, 9, 15).<sup>1</sup> Such fires often burn on the ground in a thin layer of fuel without generating enough heat to carry them into the tree crowns. Running crown fires are dangerous to approach and are therefore difficult to control or instrument for research purposes. The small initial fire burning in a flat bed, however, can be studied successfully in the laboratory.

Moisture content of the fuel and velocity of the air over it are two primary factors that determine the rate of spread and other burning characteristics of a fire. Laboratory research on the mechanisms of fire spread was directed at understanding the influence of these two factors on the behavior of fire in a mat-type fuel bed of randomly placed pine needles.

Past research in forest fuels (8, 10, 11) was hampered by the variability of outdoor weather conditions. Consequently, most of the work in the last decade (5, 13, 14, 17) has been directed toward controlled environmental conditions and controlled fuel bed characteristics. In most of these investigations, fuel particles larger than 0.25 inch thick have been arranged in a geometric pattern. This provides an idealized model which is easily duplicated, but does not represent the randomized arrangement nor the particle size of forest fuels that contribute to the start and early spread of a forest fire. This study of the mechanisms of fire spread is aimed at providing this information.

## PURPOSE

This study was designed to find the relative importance of fuel moisture and wind upon the rate of fire spread in light forest fuels. Systematic investigations of a physical phenomenon often produce an insight into its cause and effect. Through this technique, the authors hoped to gain a better understanding of the basic mechanisms of fire spread, which would enable them to develop hypotheses to be analyzed in future experiments.

Several questions of technique and instrumentation also needed answers. Could a reproducible fuel bed be constructed with pine needles? Could the environmental system of the laboratory maintain stable conditions long enough to complete a test fire? How could flame dimensions be measured consistently? How could the energy released by the fire be measured? What is the best technique for measuring low velocities of air movement?

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<sup>1</sup> Italic numbers in parentheses refer to Literature Cited, page 24.

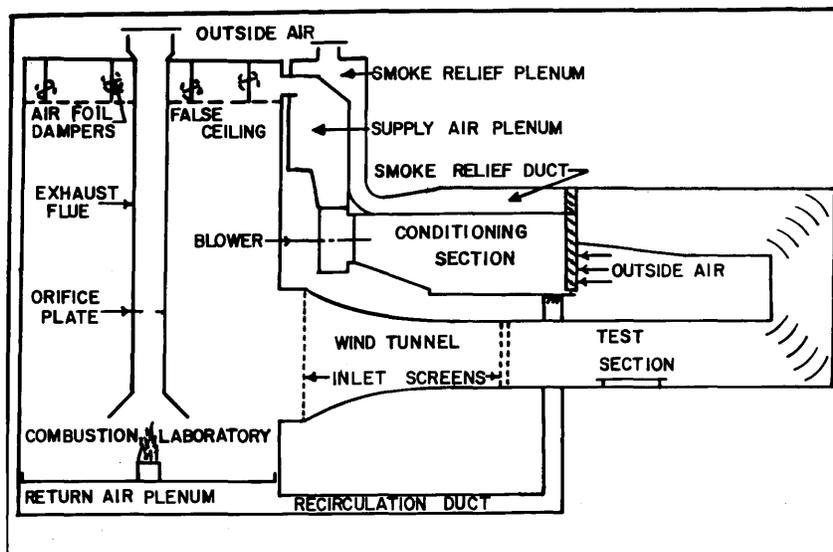


Figure 1. -- Profile section of the combustion research facilities at the Northern Forest Fire Laboratory, Missoula, Mont.

## METHOD

### FACILITIES

These experiments were conducted at the Northern Forest Fire Laboratory in Missoula, Montana. The combustion facilities there consist of two wind tunnels, a still-air combustion laboratory, and an environmental conditioning section (fig. 1). The large wind tunnel has a 10-by 10-foot cross section and is capable of velocities up to 8 m.p.h. The combustion laboratory in which the no-wind experiments were conducted is 66 feet high and 44 feet square. A flue exhaust hood, located in the center of the room, may be raised or lowered to accommodate the size of the fire. The exhaust velocity may be controlled automatically. The air circulated through the combustion laboratory and wind tunnels is conditioned to the desired temperature and humidity in a series of heaters, chillers, and water spray nozzles. The tabulation below describes the range of environmental conditions and limits of control used.

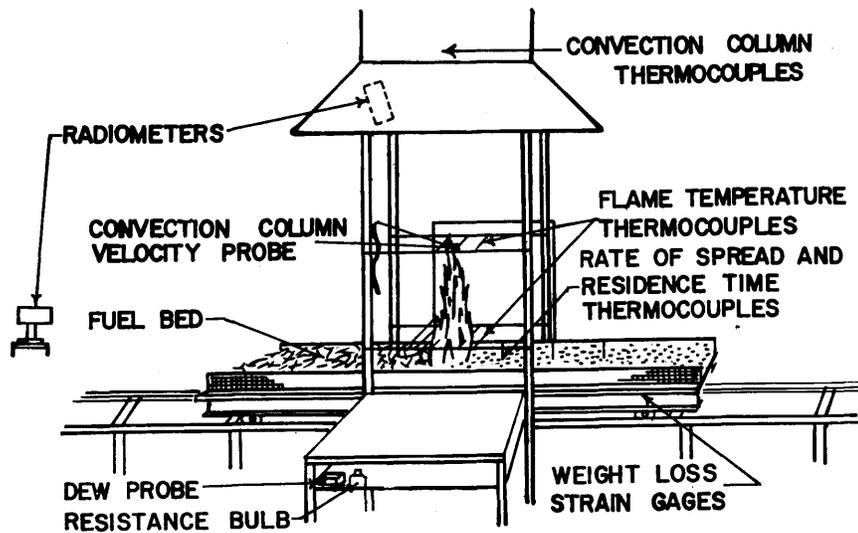
	Range	Control
Relative humidity (percent)	6.4 → 75	±1.5
Air temperature (°F.)	89° → 97°	±1° F.
Air velocity (ft./min.)	0 → 704	±2.0 percent

### EXPERIMENTAL TECHNIQUE

The experiments were conducted in two phases. In the first phase we investigated the effect of fuel moisture on rate of fire spread in still air. In the second, we studied the effect of wind on fire spread with fuels at three distinct moisture content levels.

All primary experiments were conducted on a fuel bed 8 feet long and 1.5 feet wide. The fuel was needles of ponderosa pine and white pine. The fuel was preconditioned for several days at the same air temperature and relative humidity conditions that would prevail during the test burnings. This determined the fuel moisture content. The ponderosa pine needle beds

Figure 2. -- Instrumentation used in the combustion laboratory. A similar arrangement was used in the wind tunnel.



were 3 inches thick and loaded at  $0.5 \text{ lb./ft.}^2$ . The white pine needle beds were 2 inches thick and loaded at  $0.33 \text{ lb./ft.}^2$ . Uniform loading was achieved by spreading 1 pound of needles 1 inch deep over 4 feet of the 8-foot bed. Successive layers were added until loading was completed by techniques for collecting and processing already described by Schuette (16). Additional information concerning initial experiments and determination of fuel bed size was published by Anderson (1).

Fuel beds were ignited at one end across their entire width by means of an alcohol trough. In the absence of wind the fuel bed was moved on a track at the same rate as the fire progressed (fig. 2). This kept the flame centered under the exhaust hood and overhead instrumentation. In the wind tunnel, the fuel bed was stationary 2 feet above the floor. A ground plane surrounded the bed and was held flush with the top surface of the fuel.

In the wind tunnel a boundary layer trip fence or air spoiler was placed on the ground plane 1 foot ahead of the fuel bed. The spoiler started a wake that developed quickly into a turbulent boundary layer over the entire fuel bed. Without the spoiler, the free-stream air passed directly over the surface of the pine needles in the first portion of the fuel bed. As a consequence the rate of spread was four to seven times faster over the first half than over the last half of the fuel bed. The spoiler prevented this acceleration and permitted the fire to stabilize within the first 2 feet. (For further explanation of this phenomenon and results of boundary layer investigation with a hot wire anemometer, see Appendix B.)

#### INSTRUMENTATION

The instrumentation was designed to eliminate need for visual observations. However, visual observations of rate of spread and flame dimensions were used until the instrument system was proved reliable. Similar instrumentation (fig. 2) was used in the combustion laboratory and the wind tunnel; provisions were made for the fact that the flame front was stationary in the combustion laboratory but mobile in the wind tunnel.

Weight-loss system. -- A system for weighing the fuel bed continuously during the fire was developed to permit the energy release rate of the fire to be determined. The original system

used four cantilever beams with a strain gage on the top and bottom of each beam. The gages were arranged in a Wheatstone bridge circuit. The output of the bridge was amplified and recorded on a strip chart recorder. An improved version of the system incorporates force rings in place of the cantilever beams (3).

The recorded trace of weight loss was linear with time during the steady state of the fire. The slope of the trace began decreasing when the fire reached the end of the bed, and was essentially flat when the flames ceased. This indicated that most of the fuel is consumed in the fire front, and not in the afterburning and glowing combustion.

Fuel bed thermocouples.--Thermocouples of 30-gage chromel-alumel wire were placed in the fuel bed one-fourth inch beneath the upper surface of the pine needles (4). The thermocouples were spaced 9 inches apart along the longitudinal centerline of the fuel bed and were used primarily to locate the leading and trailing edges of the fire. The thermocouple signal was recorded continuously on strip chart oscillograph recorders. When the fire reached the thermocouple, the recorder trace rose sharply. When the rear of the fire passed over the thermocouple, the trace became erratic and finally dropped. The drop indicated that the major flame front had passed.

From these traces, the rate of spread of the fire was determined by the time required for the flame front to travel the 9 inches between thermocouples. Residence time of the fire, i.e., the time flaming exists at one point, was taken as the difference between rise time and drop time of the thermocouple. The flame depth of the fire, i.e., the distance from the leading edge of the flame to the trailing edge, was computed by multiplying rate of spread by residence time.

Radiometers.--Gier & Dunkle<sup>2</sup> directional radiometers were used to measure irradiance from the fires. In the wind tunnel, only overhead measurements were made. In the combustion laboratory, measurements were taken with an instrument 18 feet in front of the fire.

Photographs.--Several photographic techniques were tried for recording flame dimensions. The best results were obtained with Plus-X film with 1-second exposure at f:11. Flame height, flame length, and flame angle were measured from the photographs. Flame depth measured from photographs was shorter than flame depth obtained by thermocouple techniques when the fire was being driven by wind.

Environment monitors.--Air temperature was measured with a platinum resistance bulb. Dewpoint temperature was measured with a salt-saturated heater bobbin and a resistance bulb. Air velocity was measured with pressure probes connected to a microdifferential transducer and amplifier.

## RESULTS

The results were analyzed with the object of exploring phenomena and relative influences of various parameters. No hypotheses were tested, but empirical formulas were developed to demonstrate the effects of wind and fuel moisture on the fire. The results of these tests, together with the studies by others, are beginning to reveal the characteristics of fires and should eventually lead to an understanding of the basic laws governing fires.

A complete list of the results for each fire is presented in Appendix B.

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<sup>2</sup>Trade names are used for identification only and do not imply endorsement or recommendation by the U.S. Forest Service.

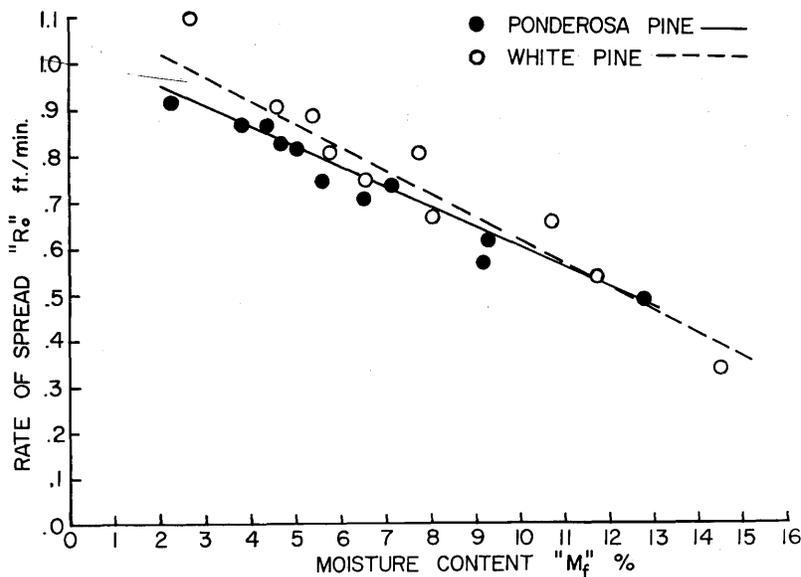


Figure 3.--Correlation of experimental values of rate of spread and prediction equation.

#### INFLUENCE OF MOISTURE IN ABSENCE OF WIND

We noted early in the program that the rates of spread in both kinds of fuel were strikingly similar (1). A regression analysis over the range of fuel moistures used showed that a linear relation gave the best fit with the data (fig. 3). The equations for rate of spread are:

$$\text{ponderosa pine} \quad R_o = 1.04 - 0.044 M_f \quad (1)$$

$$\text{white pine} \quad R_o = 1.12 - 0.051 M_f \quad (2)$$

where:

$R_o$  = rate of spread in ft./min., and

$M_f$  = fuel moisture content, fraction of oven-dry weight.

Equations (1) and (2) may be made dimensionless by dividing both sides of the equation by the rate of spread at  $M_f = 0$ .

$$\text{Thus for ponderosa pine} \quad \frac{R_o}{R_{M_f=0}} = 1 - 0.0423 M_f \quad (3)$$

$$\text{and for white pine} \quad \frac{R_o}{R_{M_f=0}} = 1 - 0.0455 M_f \quad (4)$$

These equations show that the rate of spread in our ponderosa pine needle fuel beds decreased by 4.23 percent for each 1-percent increase in fuel moisture. Rate of spread in white pine needle fuel beds decreased by 4.55 percent for each 1-percent increase in fuel moisture. If the effect of moisture remains linear as moisture content increases, the ponderosa pine needles would not sustain a rate of spread at a fuel moisture of 24 percent in the still air environment. Similarly, the limit for white pine needles would be 22 percent.

The similarity of the equations for these two fuels is surprising because of the contrast in flame size. The ponderosa pine beds burned with flames 3 to 4 feet high, and the fuel was well burned out. The white pine beds burned with flame heights closer to 1 foot high, and considerable unburned fuel was left beneath the ashes on the surface. Even though the equations are similar, we should not expect that they will predict rate of spread over the wide variety of compactness and fuel geometry that can be found in the field.

#### EFFECT OF WIND UPON RATE OF SPREAD

Ponderosa pine. -- A plot of the logarithm of rate of spread in ponderosa pine needle fires against air velocity on a linear scale produced a straight line graph for each fuel moisture level. The equation for rate of spread in ponderosa pine needles assumes the form:

$$R_{pp} = R_0 e^{rU} \quad (5)$$

where:

$R_{pp}$  = rate of spread in ponderosa pine needles, ft./min.

$R_0$  = rate of spread at  $U = 0$ , ft./min.

$U$  = air velocity, ft./min.

$r$  = constant, min./ft.

$e$  = base of natural logarithms.

A regression analysis for each moisture condition gave  $r$  values of:

0.00389 at  $M_f = 4.5$  percent

0.00376 at  $M_f = 7.3$  percent

0.00362 at  $M_f = 9.6$  percent

A weighted average  $r$  value = 0.0038.

Substituting the average value of  $r$  and the equation for  $R_0$  gives

$$R_{pp} = (1.04 - 0.044 M_f) \exp 0.0038U. \quad (6)$$

Equation (6) is plotted using the experimental points in figure 4. The equation predicts rate of spread from  $U = 0$  to at least  $U = 700$  ft./min. where  $U$  is the free-stream air velocity above the boundary layer of the fuel. A linear relation with moisture is predicted by equation (6).

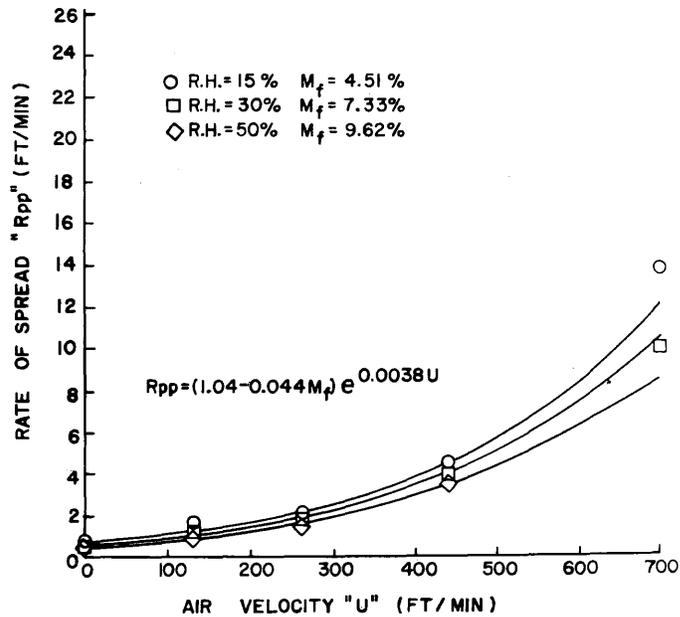
White pine. -- The rate of spread of fire in white pine needles also increases as windspeed increases, but at a faster rate than in ponderosa pine needles. An exponential equation can be fitted to the data (fig. 5), but it is good for free-stream air velocities only up to 440 ft./min. The equation is

$$R_{wp} = R_0 e^{0.006U}, \quad (7)$$

substituting for  $R_0$  gives

$$R_{wp} = (1.12 - 0.051 M_f) \exp 0.006U. \quad (8)$$

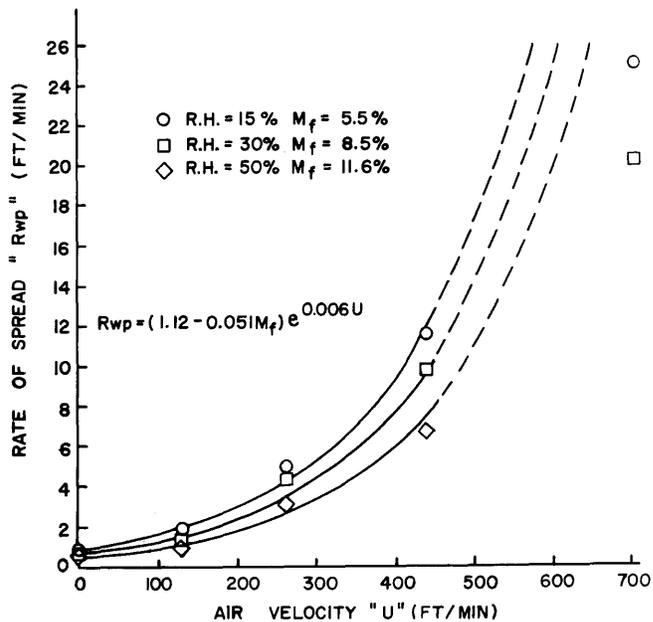
Figure 4.--Influence of air velocity upon rate of spread at three fuel moisture levels in ponderosa pine needles.



A more elaborate equation fits the data up to 704 ft./min.; however, it is easier to compare coefficients if the equations are of the same form.

If we assume the exponential curve is the correct form for describing rate of spread with wind, then the deviation of the data from the curve at 704 ft./min. is probably due to a cooling effect of the increased windspeed. Possibly there is an upper limit to air velocity in which fire can burn without being blown out. Such a limit would be at a lower velocity for small flames. The white pine fire with its small flame may show the effects of this limit even though rate of spread is still increasing. Comparative flame sizes of ponderosa pine and white pine may be seen in figures 6 and 7 at 704 ft./min. and 15 percent relative humidity.

Figure 5.--Influence of air velocity upon rate of spread at three moisture levels in white pine needles



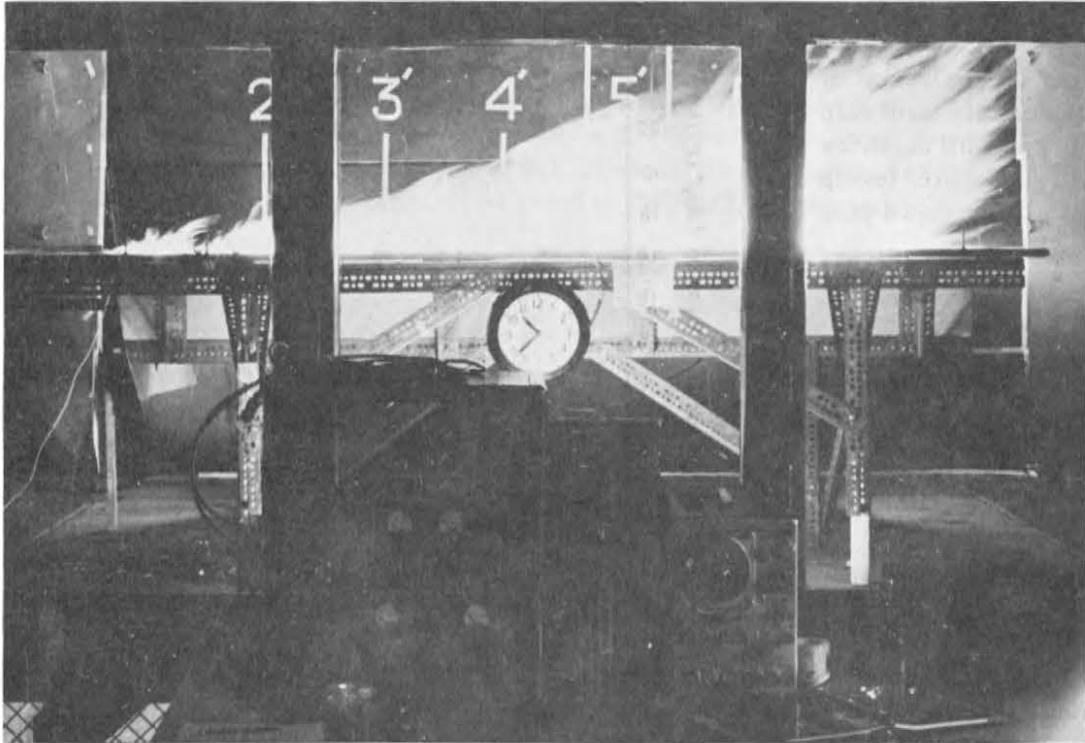


Figure 6. --Flame size in ponderosa pine needles at 704 ft./min. airspeed.

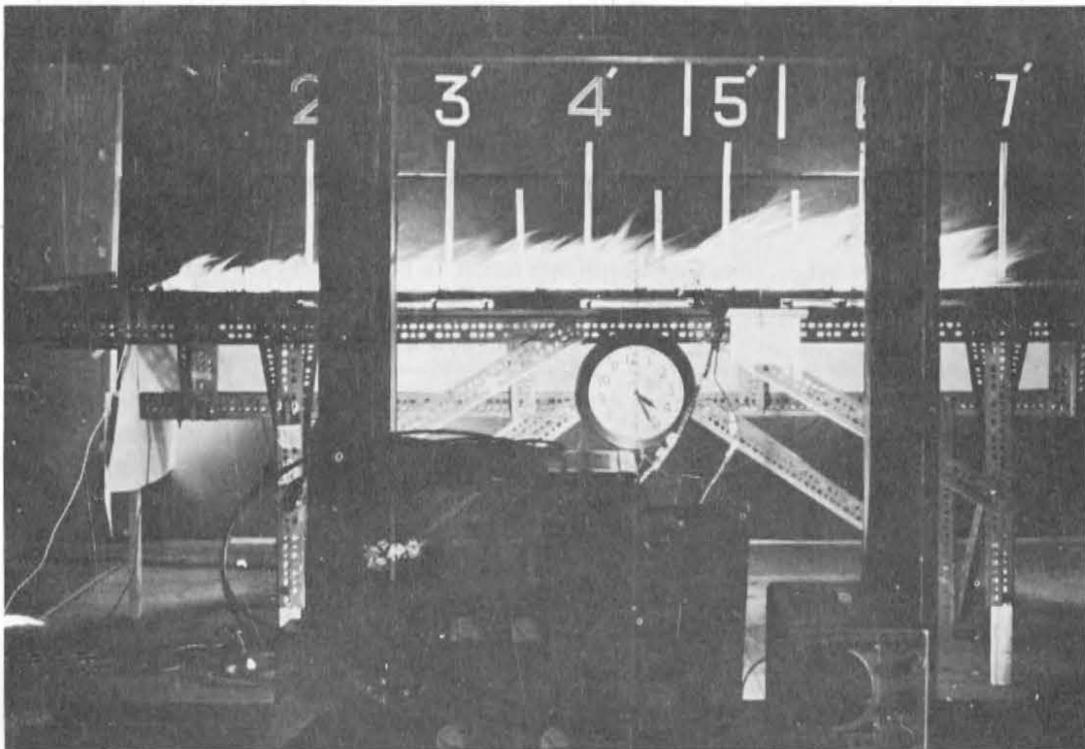


Figure 7. --Flame size in white pine needles at 704 ft./min. airspeed.

## DISCUSSION OF RATE OF SPREAD

The experiments demonstrated that fuel moisture and wind do affect rate of spread and showed the relative magnitude of that effect in a specific fuel bed. We have not shown how these parameters exert their influences on the fire, however. Some insight into the processes involved may be obtained from the following observations.

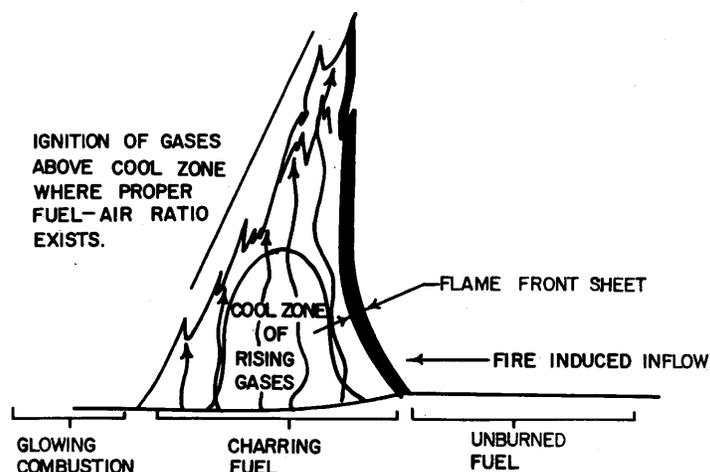
It is not difficult to picture moisture as a dampening agent which must be driven from a fuel before its temperature can be raised to ignition point. Just how the heat gets to the fuel to drive out the moisture by radiation, convection, or mass transport is not clear and is a matter of controversy among some fire researchers. We must answer this question before we can successfully develop mathematical models for rate of spread.

A fuel bed with a propagating fire burns much differently in the absence of wind than in the presence of wind. In the absence of external air movement, the fire creates an indraft and moves against this airflow into the unburned fuel. The leading flame surface is a thin, well-defined sheet (fig. 8). The base of this sheet forms in the gases issuing from the newly ignited fuel. If there is any preheating of the fuel ahead of the fire, it must be due to radiation because there is no mass transport (firebrands) and the convective flow is toward the fire, not away from it. The radiation source may be from either the overhead flames or from within the fuel bed.

Wind creates a much more complex situation. Wind tips the flame forward, and sporadic burning occurs at the base of the flame where it contacts the unburned fuel (fig. 9). This burning appears to play a key role in propagation of the fire. Observation of this phenomenon with high-speed motion pictures and visual observation of many laboratory fires indicate that the sporadic flames are caused by an accumulation of ignitable gases which have collected at the surface of the fuel bed just ahead of the fire. The fire itself provides the pilot flame that ignites the gases--which burn in a direction away from the fire, and appear as a jet of hot gas issuing from the fire.

The source of the unburned gases is not clear, but may be very important in forming a mathematical model of rate of spread. Gases may be formed in the actively burning portion of the fuel bed and may be blown forward through the fuel to rise in front of the fire; they may not ignite before reaching the surface because of an improper fuel/air ratio. They may be a product of pyrolysis of the unburned fuel ahead of the fire.

Figure 8.--Flaming zone combustion characteristics in the absence of wind.



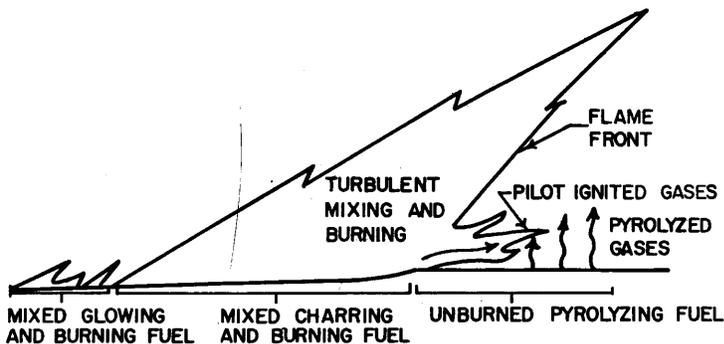


Figure 9.--Flaming zone combustion characteristics in the presence of wind.

If they are combustible gases from unburned fuel ahead of the fire, then this fuel must be receiving sufficient heat to drive the gases off before it is engulfed by the fire. Again the heat may come from several sources--radiant heat from the fuel bed, radiant heat from the overhead flame which is now tipped forward very close to the fuel, or it may be convective heat carried by the wind blowing through the fire. Mass transport of firebrands was not observed in laboratory fires but may be very important in natural uncontrolled fires. Some simple experiments were conducted to answer some of these questions.

Heat shield.--The most straightforward method of observing the effect of radiation is to shield the unburned fuel so that radiation from the flame cannot heat it. A horizontal sheet of asbestos was placed above the fuel bed in the combustion laboratory just high enough to permit the fuel bed to be moved under it without scraping the needles out of position. The fuel bed was ponderosa pine needles, 3.5 feet wide, 8 feet long, and 3 inches deep. Burned in still air, the rate of spread in the first half of the bed (which was not shielded) was 1.18 ft./min. When the fire reached the 4-foot mark, the bed was positioned so the shield stayed just ahead of the flame but did not touch it. The rate of spread decreased to 0.72 ft./min. Blocking the radiation from the flame thus reduced the rate of spread by 39 percent. Interestingly, the fuel burnout was much more nearly complete when the fire was slowed by the shield than when it was unimpeded. This was very evident to the eye because ash content changed from black residue to grey ash where the fire had been slowed.

A similar experiment was performed in the wind tunnel with the air velocity at 5 m.p.h., air temperature at 90° F., and relative humidity at 14.5 percent. The ponderosa pine needle fuel bed was standard size--1.5 feet wide, 8 feet long, and 3 inches deep. The shield was moved so that it stayed 1 to 1.5 inches ahead of the fire. The rate of spread was 1.42 ft./min., whereas without the shield it would have been 4.5 ft./min. The shield therefore reduced rate of spread by 68.5 percent. This reduction cannot be attributed solely to radiation, however, because convective heat would also be blocked from the fuel downwind from the fire.

Needle temperature.--In a second experiment, a 5-mil (.005-inch) chromel-alumel thermocouple was placed inside the fascicles of a hollowed-out ponderosa pine needle; the needles were held tightly around the thermocouple with fine thread wrapped around the fascicle needle. The thermocouple inside the needle provided a temperature history of whatever heat impulse was received by the needle. Because of the low mass of the needle and the small size of the thermocouple, the temperature response was reasonably fast.

The needle was placed on the surface of the fuel bed. In still air, any temperature rise in the needle must be attributed to radiation because the induced airflow caused by the fire is toward the fire; hence no convective heat could be carried from the fire to the needle.

Figure 10 shows the temperature rise of a needle which was placed 7 feet in front of the fire. The ponderosa pine needle fuel bed was of standard size. The average flame height was 3.74 feet. Even though the instrumented needle was 7 feet from the end of the fuel bed where the fire was ignited, the temperature began to rise immediately when the fire had burned 6 inches into the bed and the flames were 1 to 2 feet high. The temperature continued to rise as the fire burned closer and the temperature measured inside the needle passed the boiling temperature of water when the fire was still 1 foot away. This test clearly shows that radiation from the flame can preheat the needle while it is two flame lengths away. When it is close to the fire, radiation from the fuel within the bed may also be contributing to the temperature rise. The combined effect is sufficient to drive the moisture out of the fuel and raise the temperature toward ignition point before the fire engulfs the fuel. The surface temperature of the needle would be hotter than the temperature measured inside the needle. It is reasonable to assume that products of pyrolysis would also be coming from the needle during the preheating.

A fire being driven by wind is more difficult to analyze because the airflow is from the fire toward the unburned fuel. The needle temperature indicates only the total heating and cannot separate the methods of heat transport. To make this separation, an aspirated thermocouple was placed just beneath the surface of the fuel next to the instrumented needle. To assure rapid response, the aspirated thermocouple was made of 1-mil wire; the housing was 3-mil brass shim stock covered with insulation. The tube with the thermocouple inside was oriented vertically so that the thermocouple would respond only to a small collimated portion of the flame when it was directly overhead. Air was drawn off the surface of the fuel bed and pulled past the thermocouple with a vacuum pump and hoses.

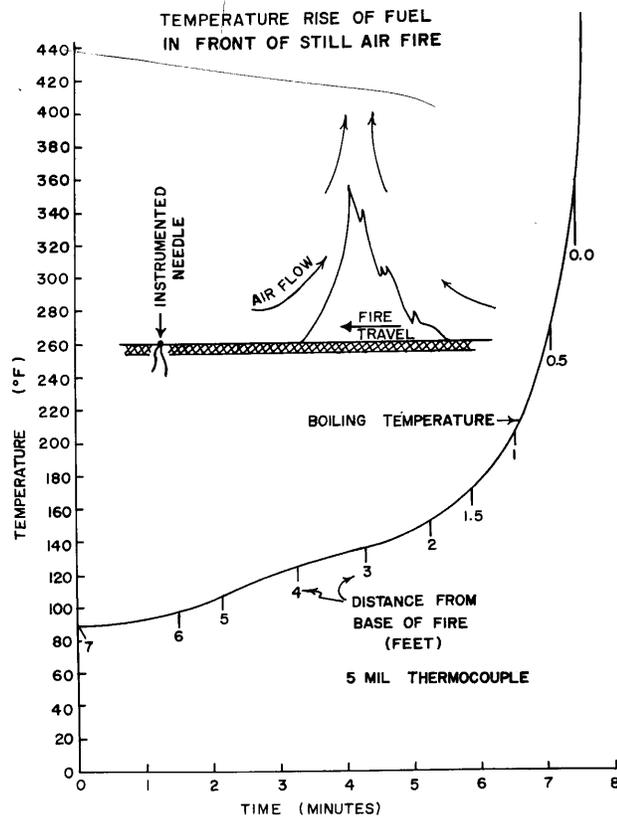
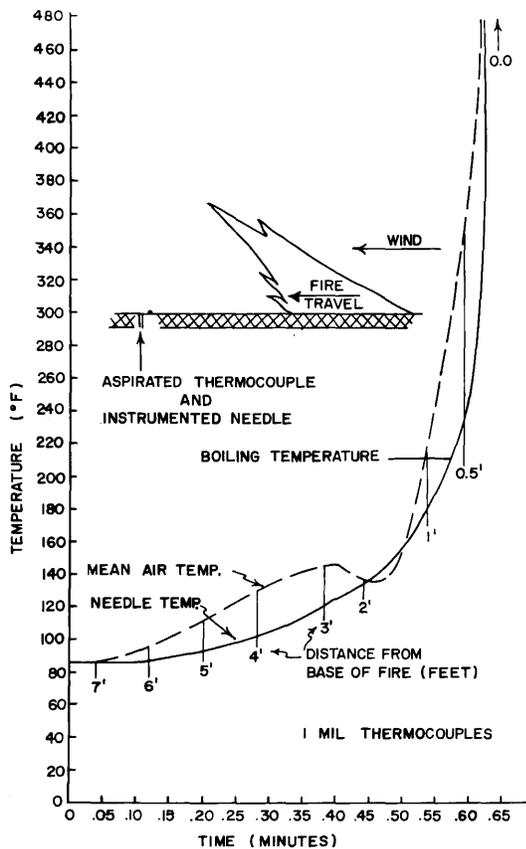


Figure 10.--Temperature rise of fuel in front of still-air fire.

If the temperature rise of the needle is to be attributed to convective heating from the air passing over it, then the air temperature must be hotter than the needle. For this test a 1-mil thermocouple was placed inside the needle--instead of the 5-mil used in the "no wind" test. The needle was hollowed sufficiently to allow the thermocouple to be positioned just beneath the surface. The needle and inlet to the aspirated thermocouple were placed 7 feet from the forward edge of an 8-foot fuel bed. The bed was 3.5 feet wide and 3 inches deep with ponderosa pine needles. The free-stream air velocity was 5 m.p.h., air temperature was 90° F., and relative humidity was 12.5 percent. Fuel moisture content was about 4 percent. Even though 1-mil thermocouples were used in both the aspirated thermocouple and the needle, the response of the needle thermocouple to heat impinging on the surface would be slower than that of the aspirated thermocouple because of the time necessary for the heat to be conducted from the surface of the needle to the thermocouple.

The temperature trace from the two thermocouples (fig. 11) shows that the air temperature began to rise almost immediately. The needle temperature began to rise when the fire was still more than 6 feet away. Except for a dip in the curve when the fire was 1.5 feet from the instruments, the air temperature remained higher than the needle temperature. If it is assumed that the lag of the needle temperature was not enough to account for the difference in temperatures, then the air temperature was indeed hotter than the needle and capable of transferring heat to it. This test does not rule out radiant heat transfer because the needle temperature is responsive to both types of heating. It would have eliminated convective preheating if the air temperature had been cooler than the needle temperature.



Note also the sharp increase in both temperatures as the fire comes close and the flame comes overhead. Boiling temperature of the needle was passed when the fire was about 8 inches from the needle. The chart did not extend to ignition temperature of 608° F., but both temperatures were heading for it simultaneously. During this portion of the fire, the sporadic burning at the surface was close upon the needle and possibly touching it. The high temperature of the needle before the fire reached it presents the possibility that preheating releases combustible gases ahead of the fire.

Figure 11.--Temperature rise of air and fuel in front of wind-driven fire.

## SUMMARY OF DISCUSSION

The thermocouple inside the needle shows that preheating of the fuel begins at a considerable distance (two or more flame lengths) ahead of the fire. The temperature of the needle passes boiling temperature of water before the fire reaches it. Heating in the absence of wind must result from radiation because the direction of airflow is from the needle toward the fire. In the presence of wind, preheating may be caused by both convection and radiation. Fires burning in wind exhibit burning on the surface of the fuel ahead of the main flame front. This burning is in gases which have accumulated there from an unknown source. Possibly these gases may result from pyrolysis in the fuel ahead of the fire or from the combustion zone within the flame.

The mechanism of fire spread in fine fuels may be described as a series of ignitions in which the temperature of fuel ahead of the fire rises, slowly at first as the water is expelled and then rapidly as the fire draws close. In a steady state fire, the fuel reaches pilot ignition temperature simultaneously with the arrival of the fire.

### CHARACTERISTICS OF RATE-OF-SPREAD CURVES

There has been considerable conjecture about the shape of the rate-of-spread curve in a wind-influenced fire. Thomas and Pickard (19) have shown in crib fires that as windspeed increases, its effect on rate of spread progressively decreases. They show that this effect of windspeed appears to approach a limit as wind velocity increases. Byram et al. (6) at the Southern Forest Fire Laboratory in Macon, Georgia, have shown a linear increase in rate of spread as air velocity increases in crib fires. Velocities thus far tested have not been high enough to indicate whether a limiting value will be approached. Our tests with two similar mat-type fuel beds have produced curves that increase as wind velocity increases. Perhaps they too will approach a maximum rate of spread at a higher velocity. It seems reasonable to assume that an upper limit exists. For large outdoor fires, however, the upper limit may fall outside the atmospheric range of wind velocities. Similarly, increasing rate-of-spread curves were found in the lodgepole pine and Douglas-fir logging slash fires,<sup>3</sup> and by Fons (11) in outdoor ponderosa pine fires. These curve shapes are shown in figure 12.

This diverse behavior may be explained by the surface area-to-volume ratio of the fuel particles,  $\sigma$ , and the porosity,  $\lambda$ , of the fuel bed. Fine fuels, such as pine needles, have a large surface-to-volume ratio. They have a short ignition delay time, and individual needles, once ignited, sustain combustion. Emmons (9) shows how the surface-to-volume ratio is important in preheating fuel elements by radiation. A large value of  $\sigma$  also facilitates better convective heat transfer. Table 1 shows the rate of spread of several fuels having different values of  $\sigma$  and  $\lambda$  at the same air velocity and having nearly the same fuel moisture content. Recent work at the laboratory indicates the burning characteristics may be related to the product of the fuel particle surface area-to-volume ratio and the fuel bed porosity ( $\sigma\lambda$ ). This is a non-dimensional parameter. A plot of the data in table 1 vs. ( $\sigma\lambda$ ) is shown in figure 13.

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<sup>3</sup> Anderson, Hal E., Arthur P. Brackebusch, Robert W. Mutch, and R. C. Rothermel. Mechanisms of fire spread research progress report no. 2 (field study). U.S. Forest Serv. Res. Pap. INT-28, 1966. (In press.)

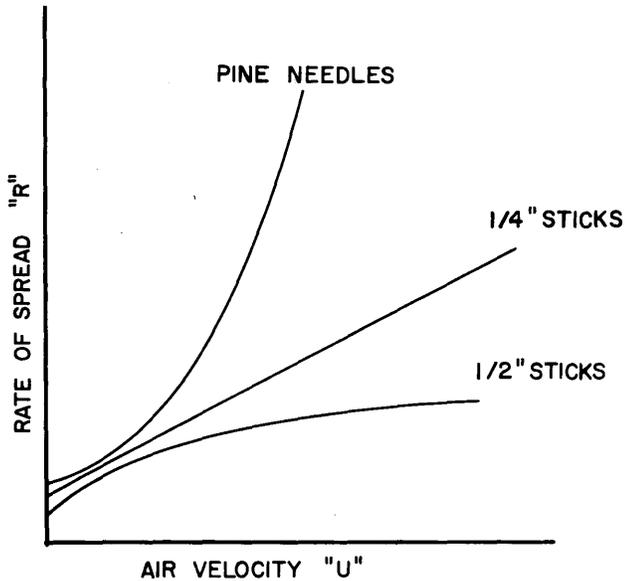


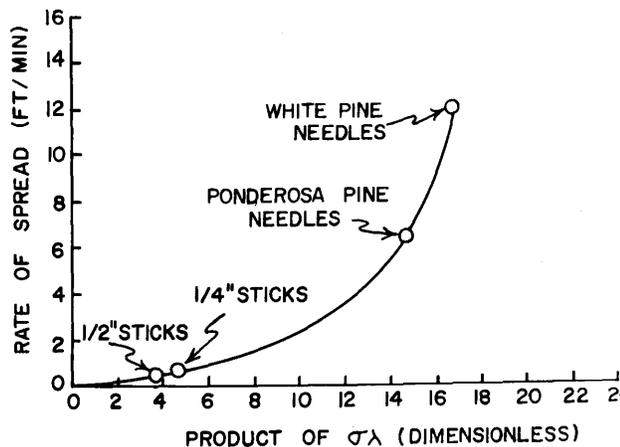
Figure 12.--Possible curve shapes for rate of spread in wind as influenced by size of fuel particles.

Table 1.--Fuel particle size and fuel bed porosity used in these and other fire experiments

Fuel	Fuel surface-to-volume ratio	Fuel bed void volume-to-surface area ratio <sup>1</sup>	( $\sigma\lambda$ )	R at U = 600 ft./min.
	$\sigma$ ft. <sup>2</sup> /ft. <sup>3</sup>	$\lambda$ ft. <sup>3</sup> /ft. <sup>2</sup>	Dimensionless	Ft./min.
White pine needles	2,790	$6 \times 10^{-3}$	16.7	12.0
Ponderosa pine needles	1,741	$8.46 \times 10^{-3}$	14.7	6.5
1/4-inch sticks	192	$2.47 \times 10^{-2}$	4.74	0.775
1/2-inch sticks	96	$3.86 \times 10^{-2}$	3.70	0.456

<sup>1</sup> Meanings of the terms "compactness," "porosity," and the symbol  $\lambda$  are sometimes confused. The porosity of a fuel bed is defined as the void volume of the bed divided by the surface area of the fuel in the bed and is represented by the symbol  $\lambda$  with the units ft.<sup>3</sup>/ft.<sup>2</sup>. Compactness is the reciprocal of porosity. The void volume of the fuel bed is the total geometric volume minus the volume occupied by the fuel. The surface area of the fuel is that of all the fuel within the volume.

Figure 13



## RELATION BETWEEN FIRE BEHAVIOR AND ENERGY RELEASE RATE

Fire increases the temperature of the air associated with it and thereby lowers its density. Buoyancy causes the less dense air to rise and thus form the familiar convection column. If wind is present, the vertical buoyancy forces compete with the horizontal wind force, and the flame tilts away from the vertical. The amount of tilt depends on the relative magnitude of the fire and wind forces. We are very much interested in the amount of tilt and the amount of heat that is carried horizontally, because of the resultant preheating in the unburned fuel and the increase in rate of spread (fig. 14). Unfortunately the vertical forces that a fire generates over its entire area are difficult, if not impossible, to measure or compute. However, the energy rates of the fire and wind can be measured and these energy values may help to explain fire behavior.

The conservation of energy relationship for the fire may be written:

$$E_{\text{potential}} = E_{\text{combustion}} + E_{\text{residue}} + E_{\text{loss}} \quad (9)$$

where:

$E_{\text{potential}}$  = heat content of the fuel

$E_{\text{combustion}}$  = heat released by the fire

$E_{\text{residue}}$  = heat content of the unburned fuel and ashes

$E_{\text{loss}}$  = heat content of unburned fuel in the convection column.

Since the potential energy of the fuel is equal to the weight of the fuel multiplied by the heat content per unit weight, the change in weight is proportional to the energy released by the fire.

$$\Delta \text{ wt.} \approx E_{\text{potential}} - E_{\text{residue}} = E_{\text{combustion}} + E_{\text{loss}} \quad (10)$$

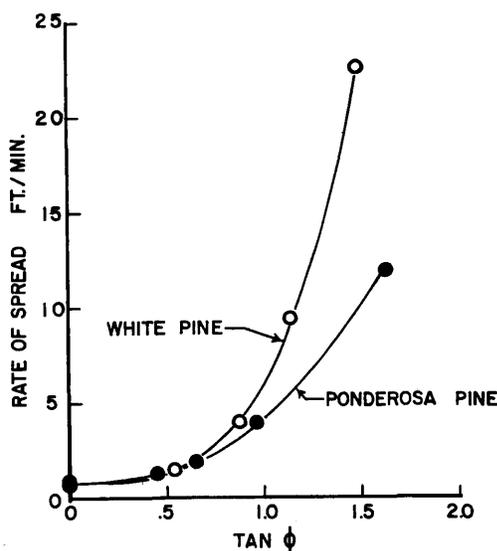


Figure 14.--Relation of flame angle and rate of spread under influence of air velocity.

Fons (12) showed that under no-wind conditions E loss is approximately 5 percent of the potential energy of the fuel. Assuming that E loss remains small with wind, E combustion =  $\Delta$  wt.  $\times$  heat content of fuel. Since we are interested in rate changes rather than total changes, the rate of weight loss is used and gives the rate of combustion (B.t.u. per minute). The energy release rate per unit area of burning fuel may now be defined as the equivalent unit energy release rate,  $E_R$ , and is obtained by dividing the combustion rate by the combustion area.

$$E_R = \frac{(\text{Weight loss rate}) (\text{Energy equivalent of fuel})}{(\text{Combustion area})} \text{ B.t.u./ft.}^2/\text{min.} \quad (11)$$

The energy rate per unit area of the wind tunnel airstream equals the dynamic pressure times the air velocity. The tangent of the flame angle should then be proportional to these two quantities:

$$\text{Tan } \phi \approx \frac{qU}{E_R J} \quad (12)$$

where:

- $\phi$  = flame angle
- $q$  = dynamic pressure of airstream lb./ft.<sup>2</sup>
- $U$  = air velocity ft./min.
- $E_R$  = equivalent unit energy release rate B.t.u./ft.<sup>2</sup>/min.
- $J$  = mechanical equivalent of heat ft. lb./B.t.u.

Tan  $\phi$  plotted against  $qU/E_R J$  (fig. 15) is a straight line on log log paper, with no evidence of dependence upon moisture or species for all conditions under which fires were burned. This relation also shows a correlation to rate of spread when a sufficiently wide fuel bed is used.

The relation  $qU/E_R J$  may also prove to be a valuable dimensionless parameter for scaling indoor fires to outdoor fires.

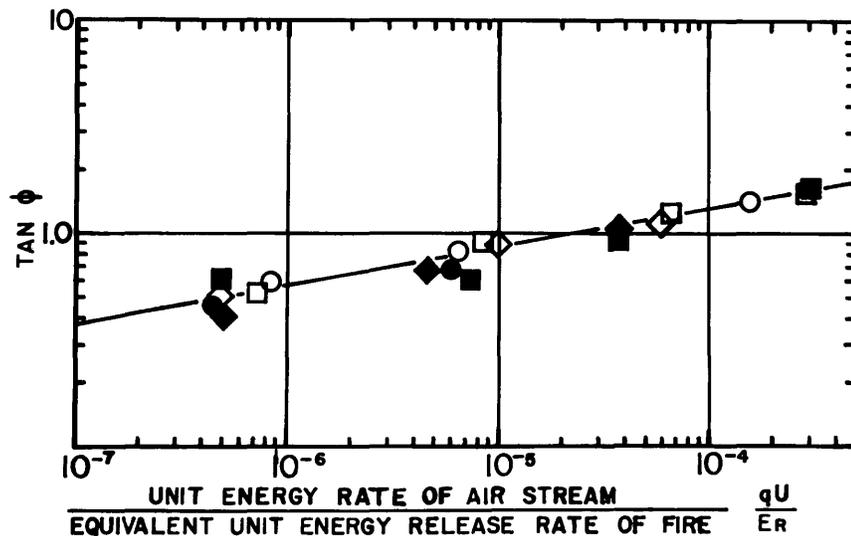


Figure 15.--Dependence of Tan  $\phi$  upon unit energy rate of fire and airstream.

The flame angle and the rate of spread have been shown to depend upon the combustion rate per unit area of the fire. Similarly,  $E_R$  can be shown to be dependent upon wind. Figure 16 shows a reduction of  $E_R$  as air velocity increases. An analysis of variance did not indicate a significant difference in  $E_R$  for the fuel moistures used in these experiments. The independence of  $E_R$  to fuel moisture is less obvious in the absence of wind. Without wind, the flame depth is shallow, and edge effects are stronger. Further testing with a wider range of fuel moisture and a better determination of combustion area may show a dependence of  $E_R$  upon fuel moisture.

A simple regression analysis of  $E_R$  on  $U$  produces the equations:

$$\text{ponderosa pine} \quad E_R = \frac{3240}{1+0.0069U} \quad (13)$$

$$\text{white pine} \quad E_R = \frac{2740}{1+0.0088U} \quad (14)$$

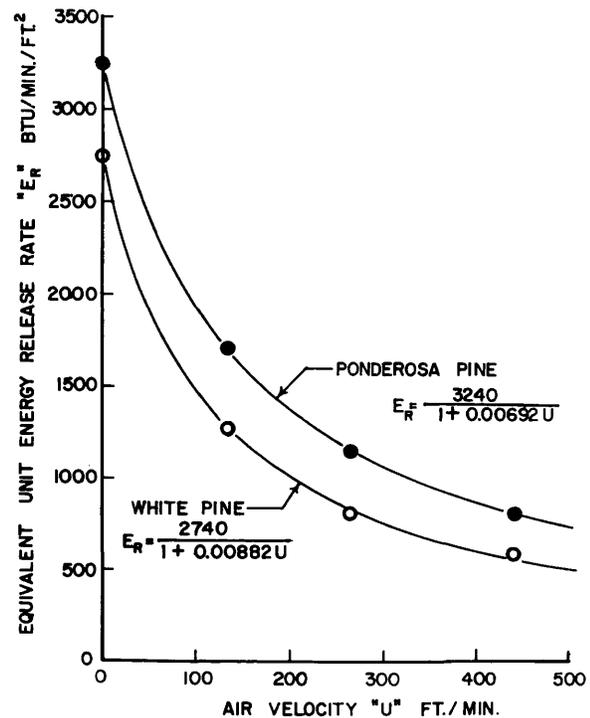
where:

$E_R$  = equivalent unit energy release rate B.t.u./ft.<sup>2</sup>/min.

$U$  = air velocity ft./min.

Further study is needed to develop a hypothesis that will relate  $E_R$  to fuel bed loading, fuel particle size, fuel bed compactness, and air velocity.

Figure 16. --Influence of air velocity upon equivalent unit energy release rate.



A cursory look at fires would not indicate that  $E_R$  should decrease as air velocity increases. In mat-type fuel beds, this decrease is explained by the fact that as air velocity increases, combustion area increases faster than total heat release from the fire. It is true that total heat output of the fire, after first decreasing slightly, increases with additional air velocity; but at the same time the fire is burning over a much larger area and not burning as deep--thereby lowering the heat output per unit area. In fuel beds such as ours, that are restricted in width, the combustion area is directly proportional to flame depth, where flame depth is the distance from the leading edge of the fire to the rear of the fire front. The fire front does not include residual burning behind the main fire. The relation between flame depth and rate of spread is shown in figure 17. In this figure, moisture and wind influences have already shown their effect on rate of spread, and they are not apparently separable.

While flame depth is increasing, the vertical depth of burn into the fuel bed is decreasing. At 704 ft./min. (8 m.p.h.) unburned needles could be found in the lower layers of the ponderosa pine fuel beds. Unburned needles could not be found when air was moving slower. Data on burning depth are presented only in the data summation tables of this paper, pages 31-34.

If the fuel bed porosity,  $\lambda$ , were high enough to permit burnout of fuel to the full depth even in very high air velocities, combustion rate might increase faster than flame depth and  $E_R$  would not decrease as air velocity increases. Again, the need for more research on fuel bed parameters  $\lambda$  and  $\sigma$  becomes apparent.

#### FIRE CHARACTERISTIC CURVE

The preceding discussion has shown a relation between the rate of unit energy release of the fire and the resulting flame angle in the presence of wind. This relation indicates that if  $E_R$  is large the flame will not be tipped and rate of spread will be small. As wind increases, the flame tips, and rate of spread increases as  $E_R$  decreases. A plot of rate of spread versus

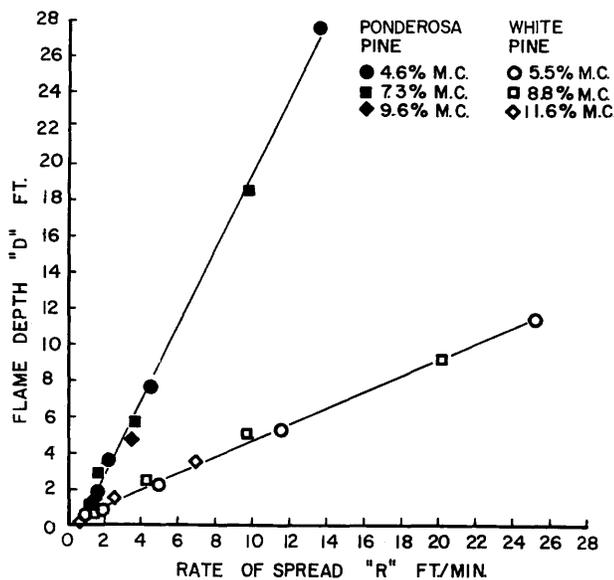


Figure 17.--Influence of moisture and air velocity on rate of spread and flame depth.

$E_R$  confirms this and produces the fire characteristic curve shown in figure 18. Fires that have a very low and nearly constant rate of spread, a large ratio of flame length to flame depth, and a high unit energy release rate are at one end of this curve. These characteristics are similar to those of a fire storm, which is a high-intensity stationary fire. At the other end of the curve are fires that show a very rapid rate of spread, a low ratio of flame length to depth, and a low but nearly constant rate of unit energy release. These are the characteristics of runaway fires that burn in fine light fuels. This curve illustrates the rapid increase in rate of spread that results when the convection column weakens and tips because the unit energy release rate is low.

The knee of the curve (transition zone) marks the area of minimum values for several important fire characteristics--including flame length, total energy release rate, and the peak irradiance (measured by an overhead radiometer). Presence of the transition zone may reflect a change in the mechanism of rate of spread as was discussed earlier (see figures 8 and 9).

This is the only curve that could be found that relates rate of spread of both fuels to a common parameter along the same line. Each point on the curve represents a single velocity at which all values of fuel moisture for that velocity are averaged. The effects of varying size of the fuel particles and configuration of the fuel bed upon this curve will be very interesting to see.

#### DIFFUSION FLAME ANALYSIS

The general principles of diffusion flame theory presented by Thomas (18, 20) applied to fires in mat-type fuel beds (2, p. 18) if the characteristic length,  $D$ , in equation (15) is revised to equal the distance from the front of the fire to the rear:

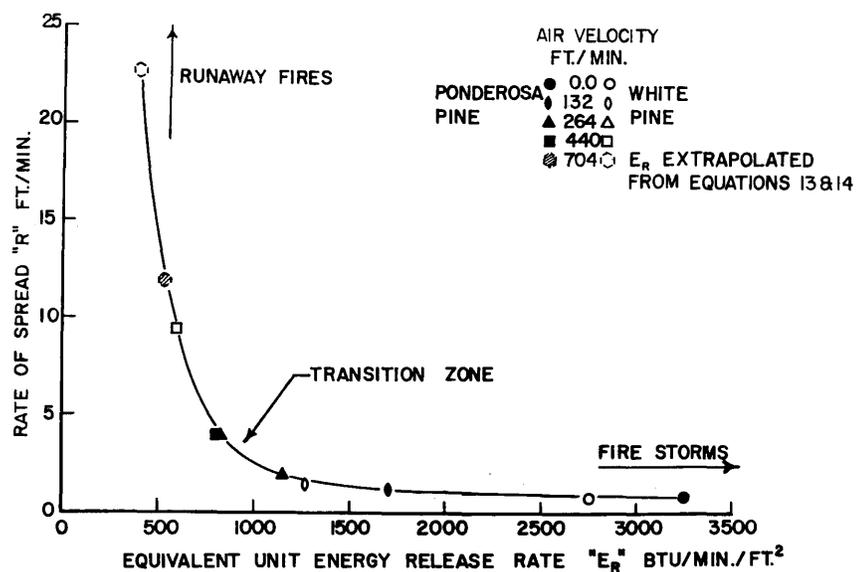


Figure 18.--Fire characteristic curve relating rate of spread and equivalent unit energy release rate.

$$\frac{L}{D} = K \left[ \frac{(m'')}{\rho (gD)^{1/2}} \right]^n \quad (15)$$

where:

L = flame length in feet (distance from base to tip of fire)

D = flame depth in feet

m'' = unit mass flow rate in lbs./min./ft.<sup>2</sup>

ρ = air density (8.1 × 10<sup>-2</sup> lbs./ft.<sup>3</sup>)

g = gravitational constant (1.152 × 10<sup>5</sup> ft./min.<sup>2</sup>).

To represent the orifice diameter, we used flame depth rather than some equivalent dimension based on the square root of flame depth multiplied by fuel bed width. The value of m'' (mass flow rate of combustion gases per unit area) was determined from the weight loss data in much the same manner as the equivalent unit energy release rate E<sub>R</sub> was computed. When results of this analysis were compared to the relation developed by Thomas' equation (16), they showed good correlation (fig. 19).

$$\frac{L}{D} = 42 \left[ \frac{(m'')}{\rho (gD)^{1/2}} \right]^{0.61} \quad (16)$$

The dimension of flame depth appears to be the correct measure to use, and radial symmetry is unnecessary. For our fuel beds the numerical values on both sides of the equation increased as moisture content increased.

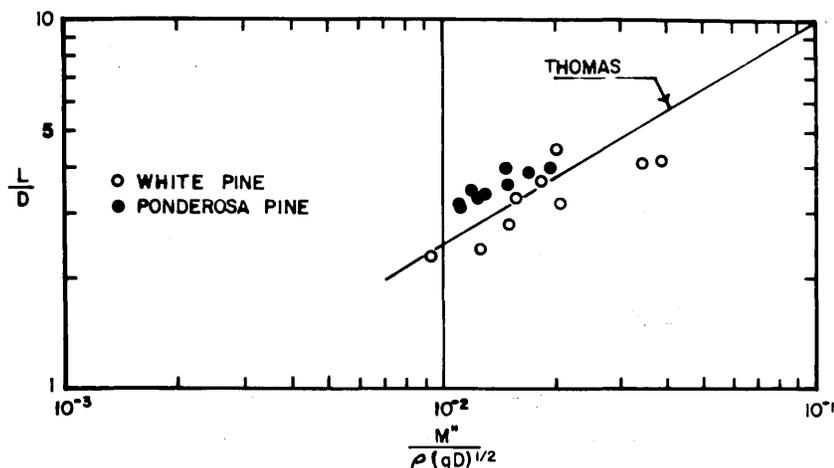


Figure 19. -- Diffusion flame characteristics of fires under no-wind conditions compared to values in Thomas' equation.

Thomas extended his work to include the influence of air velocity; we checked our data against his analysis. The values for each moisture level were averaged at each air velocity. The relations tested were of the form:

$$\frac{L}{D} \frac{(U^2)^{0.11}}{gD} = K \left[ \frac{(m'')}{\rho (gD)^{1/2}} \right]^n \quad (17)$$

These were compared to Thomas' results (fig. 20). A slight difference is evident between white pine and ponderosa pine fires, but a single line can approximate the relation for both fuels. The equation of this line, plotted from our data, is:

$$\frac{L}{D} \frac{(U^2)^{0.11}}{gD} = 164 \left[ \frac{(m'')}{\rho (gD)^{1/2}} \right]^{0.97} \quad (18)$$

whereas Thomas obtained this equation:

$$\frac{L}{D} \frac{(U^2)^{0.11}}{gD} = 70 \left[ \frac{(m'')}{\rho (gD)^{1/2}} \right]^{0.43} \quad (19)$$

The difference apparent between the two sets of data may be attributed to differences in measurement techniques, or possibly to variations in size of fuel particles.

A series of outdoor fires was studied in prepared fuel beds of logging slash during the summer of 1962 (2, p. 18). The fuel was lodgepole pine and Douglas-fir needles, and branch wood up to 2 inches in diameter. The fuel beds, 6 feet wide by 60 feet long, were ignited at one end. We recorded data similar to those recorded for the laboratory fires.

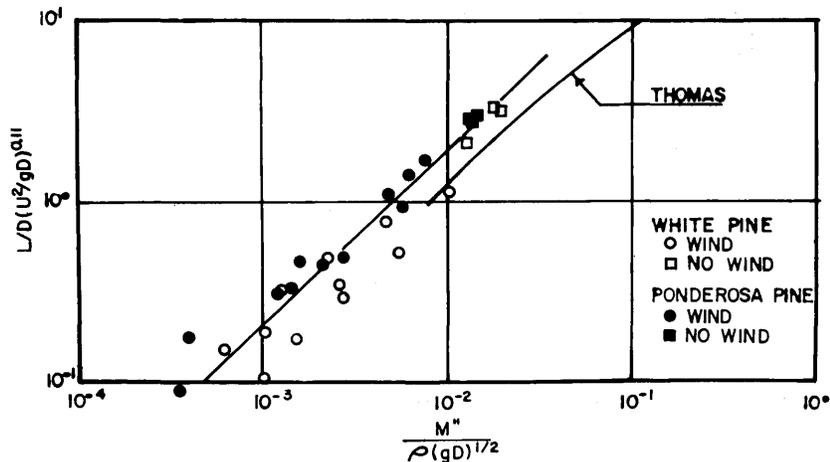


Figure 20. -- Diffusion flame characteristics for laboratory fires under the influence of wind.

The outdoor fires were checked by the diffusion flame analysis for wind to determine their correlation with laboratory fires. Since the actual rate of weight loss could not be measured, we used maximum burning rate to compute mass flow rate of the combustion gases. The mass flow rate was determined from the equation:

$$m'' = \frac{W_0 R}{D} \text{ lbs./ft.}^2/\text{min.} \quad (20)$$

where:

$W_0$  = loading in lbs./ft.<sup>2</sup>

$R$  = rate of spread in ft./min.

$D$  = flame depth in feet.

The relation given in equation (17) was applied and the data were plotted (fig. 21).

The field data (fig. 21) fell to the right of the pine needle laboratory data and Thomas' 1/2-inch stick data. This was expected because all the fuel was assumed to be contributing to the mass flow rate  $m''$  in the fire front. In a heterogeneous fuel bed the fine fuels ignite first and therefore contribute most heavily to the fire front. If the fine fuels up to one-fourth inch in diameter are assumed to be supporting the initial flame size, then  $m''$  is reduced to a value that aligns the field data with the laboratory pine needle data. If all the fuel up to one-half inch in diameter is assumed to be contributing, then the field data align with Thomas' 1/2-inch crib data.

This demonstrates a possible use for the diffusion flame characteristic equation provided the size classification of the fuel is known. When this is known, the burning rate per unit area, or mass flow rate, can be determined. If forest fuel can be classified so that loading and size percentages are known, estimates of mass flow rate ( $m''$ ) and equivalent unit energy release rate ( $E_R$ ) can be made. If  $E_R$  can be so estimated for outdoor fires, it may be possible to relate fires of different sizes with the fire characteristic curve (fig. 18).

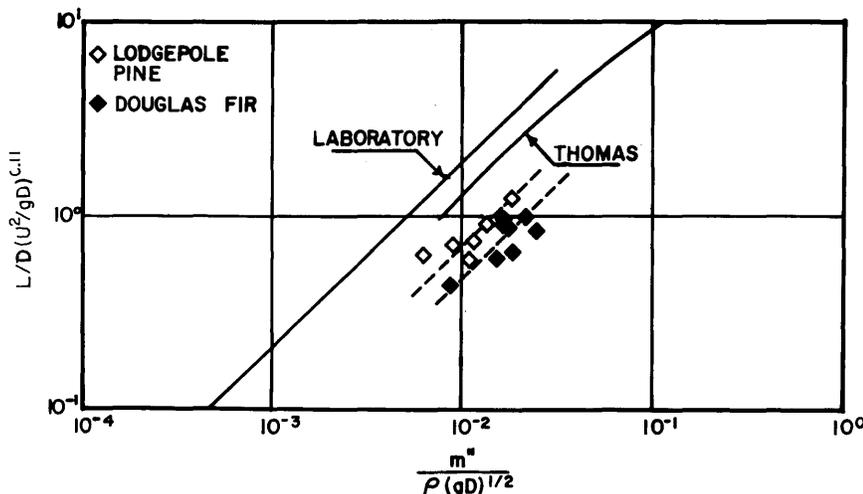


Figure 21. -- Diffusion flame characteristics for field fires under the influence of wind.

## SUMMARY AND CONCLUSIONS

Our studies of the effects of fuel moisture and wind upon the rate of fire spread in ponderosa pine and white pine needle fuel beds have shown the following:

1. As wind increased, the fire spread at an increasing rate.
2. The fire was carried in the surface fuel particles.
3. Flame depth increased and vertical depth of burn decreased as windspeed increased.
4. In the absence of wind, rate of spread decreased linearly as fuel moisture increased.

Additional experiments were conducted to aid in explaining how fire is propagated. For these, a thermocouple was placed inside a needle to register changes in temperature. These experiments showed the following:

1. The thermocouple began to show rise in temperature when the fire was still two flame lengths away.
2. Temperature inside the needle became higher than that for the boiling point of water before the fire reached it.
3. In the absence of wind, the initial rise in temperature must be due to radiation from the overhead flame because of the large distance from the fire and because air is flowing toward the fire, not away from it.
4. When the fire draws close to the needle, radiation from within the fuel bed may also contribute to the temperature rise.
5. In the presence of wind, the air temperature at the surface of the fuel bed was found to be hotter than the fuel; therefore, both convective heating and radiant heating can contribute to the rise in temperature of the fuel particles.
6. In the presence of wind, combustible gases may form on the surface of the fuel bed ahead of the main flame front. The exact source of these gases is not known. These gases seem to be ignited periodically by the fire and to sweep ahead of the main fire front along the surface of the fuel. They appear to play a major role in the mechanism of fire spread in the presence of wind.

Results of this study of the effect of wind upon rate of spread in fine fuels do not correspond to results of other studies that used cribs made of dimensioned sticks. Possibly this may be explained by differences in the fuel particle size,  $\sigma$ , and fuel bed porosity,  $\lambda$ . There was a correlation between rate of spread and the product of  $\sigma$  and  $\lambda$ .

These studies revealed the importance of the equivalent unit energy release rate. Rate of spread plotted against equivalent unit energy release rate produces a curve on which the average values of both fuel types fall. This curve clearly demonstrates the characteristics of a fire; therefore it is named the fire characteristic curve. Fires having low rates of spread and high rates of energy release are at one end of the curve and have many characteristics of a fire storm. Fires with rapid rates of spread and low, nearly constant, energy release values

are at the other end of the curve and have the characteristics of runaway fires. The knee of the curve represents a transition zone in which the mechanism of spread is changing from the no-wind to the wind model. Several important parameters reach minimum values at the transition zone.

Diffusion flame analysis that Thomas used on crib fires was applicable to mat-type fuel bed fires if flame depth was used in place of equivalent orifice diameter. The use of this analysis may enable us to predict burning rates of outdoor fires from their flame dimensions.

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APPENDIX A

<u>Symbol</u>	<u>Definition</u>	<u>Measure</u>
$A_c$	= area of combustion at surface of fuel	ft. <sup>2</sup>
B	= rate of weight loss (burning rate)	lbs./min.
D	= depth of flame zone from leading edge of fire to trailing edge of fire front	ft.
$E_R$	= equivalent unit area energy release rate	B.t.u./ft. <sup>2</sup> /min.
H	= low heat of combustion value of fuel	B.t.u./lb.
$I_{OH}$	= peak overhead irradiance	B.t.u./ft. <sup>2</sup> /HR
$I_T$	= total radiant heat received during passage of the flame	B.t.u./ft. <sup>2</sup>
$I_{18}$	= irradiance to a point 18 feet forward of the fire	B.t.u./ft. <sup>2</sup> /HR
J	= mechanical equivalent of heat	ft. lb./B.t.u.
L	= flame length from midpoint of flame depth to tip of flame	ft.
$L_v$	= vertical height of flame tip above fuel surface	ft.
$M_a$	= unit mass of air	lb./ft. <sup>3</sup>
$M_f$	= fuel moisture content	percent
$M_g$	= unit mass of convection column gases	lb./ft. <sup>3</sup>
Q	= total heat release rate	B.t.u./lb.
R	= rate of spread at any condition	ft./min.
RH	= relative humidity	percent
$R_0$	= rate of spread in absence of wind	ft./min.
$R_{pp}$	= rate of spread in ponderosa pine needles	ft./min.
$R_{wp}$	= rate of spread in white pine needles	ft./min.
$T_0$	= ambient temperature	°F.
tb	= burn thickness	ft.
U	= velocity of air	ft./min.
V	= velocity of convection column	ft./min.
$W_0$	= unit area loading of oven-dry fuel	lb./ft. <sup>2</sup>
g	= acceleration due to gravity	ft./min. <sup>2</sup>
$m''$	= mass flow rate of combustible gases per unit area	lb./ft. <sup>2</sup> /min.
q	= dynamic pressure of air stream	lb./ft. <sup>2</sup>
$\theta$	= residence time of flaming zone at any point in fuel bed	min.
$\lambda$	= void volume per unit of fuel surface area	ft. <sup>3</sup> /ft. <sup>2</sup>
$\rho$	= air density	lb./ft. <sup>3</sup>
$\sigma$	= fuel particle surface area per unit volume	ft. <sup>2</sup> /ft. <sup>3</sup>
$\phi$	= deflection angle of flame from vertical	degrees

## APPENDIX B

### INFLUENCE OF SURFACE FLOW OF WIND UPON RATE OF SPREAD

A series of preliminary fires in the wind tunnel was used to check instrumentation and experimental techniques. During these tests the fire spread four to seven times faster in the first half of the fuel bed. The flames were tipped considerably farther in the first 4 feet; this indicated a stronger influence of the wind upon this portion of the fire.

In a smoke test, a tight rolling vortex was observed over the first 2 feet of the fuel bed; its diameter gradually increased, and the vortex dissipated over the last 4 feet of the bed. The boundary layer was investigated with a constant-current hot wire anemometer. The hot wire confirmed the visual observations of the smoke and showed the vortex formation, breakup, and dissipation (fig. 22). The center of the vortex gradually rose from 1 inch at fuel bed station, 0.5 foot to 3 inches at station 1.0 foot, and to 5.0 inches at station 2.0 feet. During this time

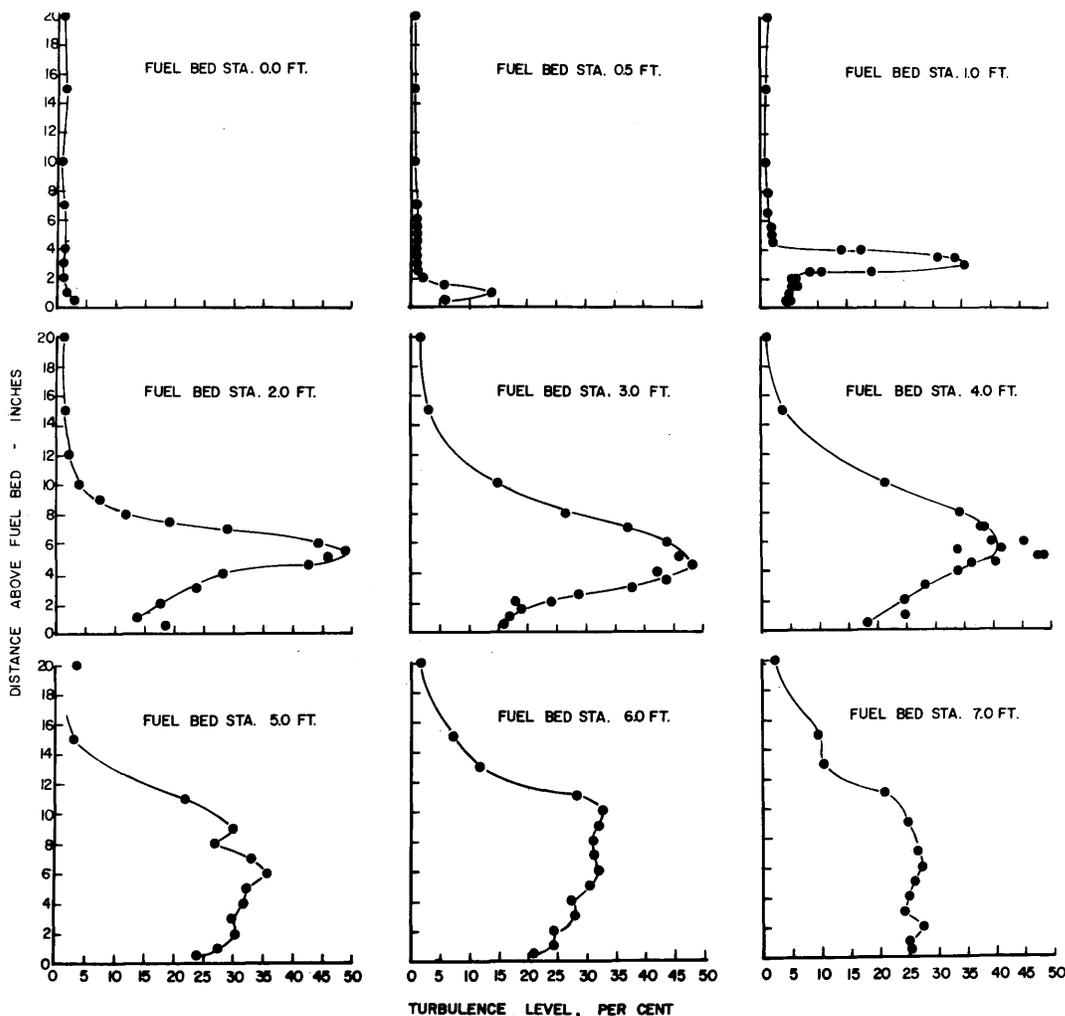


Figure 22.--Surface layer turbulence over ponderosa pine needle fuel bed at free-stream air velocity of 3 m.p.h.

the diameter of the vortex grew larger until at 4.0 feet it no longer held any well-defined shape and broke up. At 5, 6, and 7 feet the air motion appeared to be random; and the turbulence level, which had been as high as 50 percent, decreased to 25 to 30 percent at 7 feet.

These measurements were made over the fuel bed in the absence of any fire and, of course, the same turbulence pattern would not exist if the fuel bed were burning. The measurements do show, however, that when the fuel bed is ignited at station zero, the free-stream air velocity extends down to the surface of the fuel bed and can tip the weak flame almost 90° over the unburned fuel. The free-stream air velocity is then dominant over the flame until the energy output of the fire builds up and straightens the flame. This did not occur until the fire was well into the fuel.

The solution to the problem was to lift the free-stream air velocity above the surface of the fuel at station 0.0 by placing a trip fence or spoiler across the fuel bed 1 foot ahead of the fuel bed. The trip fence was 1-5/8 inches high and induced a turbulent boundary layer which was surprisingly uniform over the entire length of the fuel bed. Results of a hot wire turbulence survey with the spoiler in place (fig. 23) showed that beyond 2 feet the vortex appears to have dissipated and the maximum turbulence levels are about 30 percent.

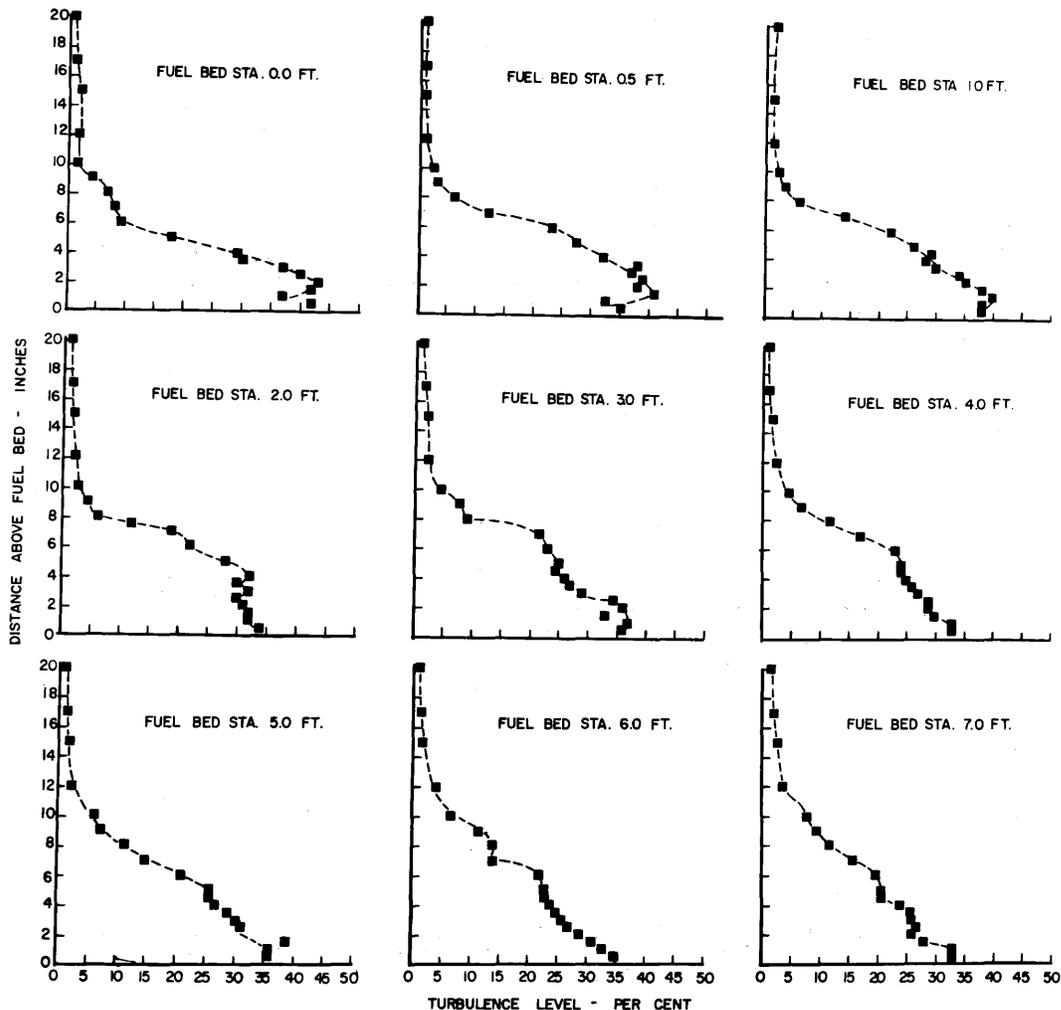


Figure 23. --Surface layer turbulence over ponderosa pine needle fuel bed with spoiler at free-stream air velocity of 3 m.p.h.

Fuel beds burned behind the spoiler produced a uniform rate of spread from 2 feet to 7.5 feet. Typical rate of spread data for fires burned with and without the spoiler are shown in figure 24. All wind tunnel data presented in this report were taken with the spoiler in place.

Figure 24.--Effect of surface layer turbulence on rate of spread with and without a spoiler.

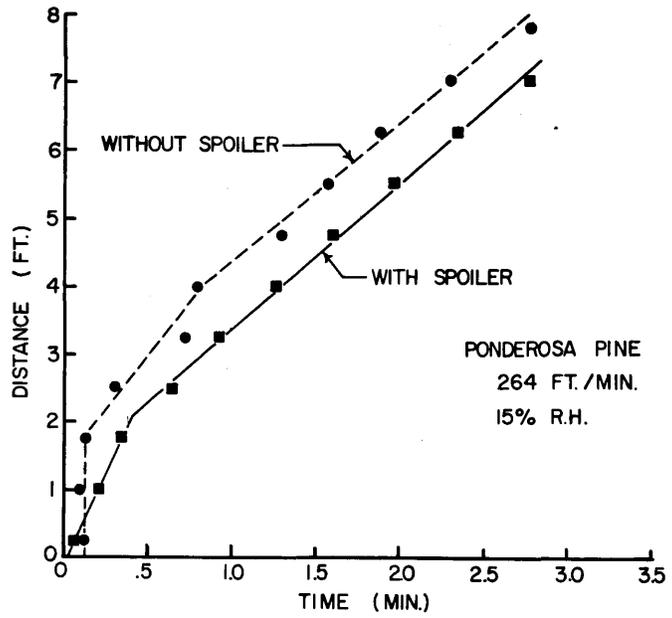


Table 2

Fire no.	Test area ambient conditions				Fuel and fuel bed parameters				Burning parameters				Heat variables			
	T <sub>0</sub> °F	RH %	M <sub>f</sub> %	W <sub>0</sub> lb/ft <sup>2</sup>	R	R <sub>0</sub> ft/min	B	A <sub>0</sub> ft <sup>2</sup>	t <sub>b</sub> ft	D	L	E	BR	I <sub>QR</sub>	I <sub>T</sub>	I <sub>1E</sub>
				R <sub>0</sub> ft <sup>2</sup> /lb						ft	Btu/min	Btu/ft <sup>2</sup> min	Btu/ft <sup>2</sup> hr	Btu/ft <sup>2</sup>	Btu/ft <sup>2</sup> hr	Btu/ft <sup>2</sup> hr
PP-1-C	93	13	4.20	0.48	8669	0.845	0.50	0.63	-	0.42	3.2	-	-	-	-	15.4
PP-2-C	92.5	13.5	4.41	0.48	8669	0.860	0.50	0.63	-	0.43	3.2	-	-	-	-	15.6
PP-3-C	92	12	4.36	0.48	8669	0.900	0.51	0.69	-	0.46	3.6	-	-	-	-	17.0
PP-17-C	91.8	15.4	4.97	0.48	8669	0.863	0.59	1.29	0.13	0.86	3.5	4769	-	-	-	45.4
PP-19-C	90.7	15.5	4.78	0.48	8669	0.805	0.66	0.550	1.14	0.76	3.5	4878	-	-	-	14.6
PP-26-C	91	15.6	5.26	0.47	8669	0.792	0.69	0.460	1.20	0.80	3.5	4080	-	-	-	11.55
PP-27-C	90.8	15.7	4.51	0.48	8840	0.840	1.09	0.601	1.37	0.85	3.55	5315	3680	79	5.31	11.55
PP-28-C	90.6	15.7	4.93	0.48	8840	0.800	1.27	0.548	1.53	1.02	3.51	4844	3865	79	5.98	11.55
PP-4-C	92	75	13.15	0.48	8669	0.470	0.31	0.23	-	0.15	3.2	-	-	-	-	6.1
PP-5-C	91	75	12.21	0.49	8669	0.495	0.32	0.24	-	0.16	3.2	-	-	-	-	6.6
PP-6-C	92	75	12.68	0.48	8669	0.495	0.21	0.17	-	0.11	3.3	-	-	-	-	7.8
PP-7-C	91	52	9.96	0.48	8669	0.60	1.10	0.99	-	0.66	4.0	-	-	-	-	10.2
PP-8-C	92	53	9.59	0.48	8669	0.63	0.95	0.90	-	0.60	4.0	-	-	-	-	9.8
PP-9-C	92	53	9.26	0.48	8669	0.625	0.87	0.83	-	0.55	4.0	-	-	-	-	11.7
PP-35-C	90.5	50	9.16	0.45	8640	0.532	1.35	0.491	1.06	0.708	2.85	4350	4000	53.81	5.72	6.83
PP-33-C	90.7	50.4	9.11	0.45	8640	0.566	1.37	0.433	1.98	0.27	0.918	3530	2780	52.22	5.02	7.15
PP-34-C	90.5	50.8	9.20	0.45	8640	0.603	1.39	0.394	1.25	0.25	0.836	3530	2660	44.35	4.15	6.74
PP-10-C	92	33	6.92	0.48	8669	0.604	0.73	0.98	-	0.65	3.4	-	-	-	-	-
PP-11-C	92	34	7.28	0.48	8669	0.735	0.58	0.97	-	0.64	4.0	-	-	-	-	13.2
PP-12-C	91	34	7.25	0.48	8669	0.690	0.65	1.05	-	0.70	3.8	-	-	-	-	12.3
PP-29-C	90.5	30.2	6.48	0.47	8840	0.674	1.176	0.44	1.19	0.23	3.16	4420	3715	55.85	4.51	8.09
PP-30-C	91	30.6	6.52	0.47	8840	0.718	1.318	0.418	1.42	0.20	3.28	3980	2800	71.21	5.60	9.63
PP-31-C	90.8	30.1	6.53	0.47	8840	0.740	1.313	0.438	1.46	0.21	3.04	3662	2650	63.55	4.84	8.66
PP-13-C	91	22	5.96	0.47	8669	0.830	0.720	0.90	-	0.60	3.58	-	-	-	-	14.18
PP-14-C	91.2	22.5	5.84	0.47	8669	0.719	0.550	0.60	-	0.40	3.17	-	-	-	-	13.08
PP-15-C	92	22.5	5.84	0.47	8669	0.649	0.500	0.50	-	0.33	3.16	-	-	-	-	11.18
PP-16-C	92	21.5	5.76	0.47	8669	0.761	0.730	0.86	-	0.57	3.44	-	-	-	-	13.72
PP-20-C	90.9	9.8	3.81	0.48	8669	0.88	0.59	0.61	1.25	0.83	2.83	5410	4388	-	-	15.81
PP-21-C	92.0	8.1	3.83	0.48	8669	0.91	0.65	0.55	1.22	0.81	2.79	4878	3998	-	-	16.20
PP-22-C	91.8	9.2	3.77	0.48	8669	0.82	0.60	0.63	1.19	0.79	2.74	5867	4695	-	-	17.43
PP-23-C	99	6.6	2.24	0.49	8669	0.92	0.58	-	1.35	0.90	3.30	-	-	-	-	17.22

Table 3

Fire no.	Test area ambient conditions				Fuel and fuel bed parameters				Pinning parameters				Flame dimensions				Heat variables			
	T <sub>o</sub>	RH	W	H	M <sub>t</sub>	W <sub>o</sub>	H	R	Θ	B	A <sub>o</sub>	t <sub>b</sub>	D	L	I	E	F <sub>a</sub>	IGW	IR	I <sub>18</sub>
°F	%	lb/ft <sup>2</sup>	ft	ft <sup>2</sup> /min	lb/min	ft <sup>2</sup> /min	ft/min	min	lb/min	ft <sup>2</sup>	ft	ft	ft	ft	ft	ft <sup>2</sup> /min	ft <sup>2</sup> /min	ft <sup>2</sup> /min	ft <sup>2</sup> /min	ft <sup>2</sup> /hr
WP-1-C	93	14	5.16	0.47	8476	0.855	0.54	0.86	0.92	0.87	0.58	0.9	0.57	1.1	-	-	-	-	-	5.8
WP-2-C	92	13	5.55	0.47	8476	0.942	0.40	-	0.865	0.34	-	-	0.58	1.1	-	-	-	-	-	3.7
WP-3-C	93	12	5.37	0.47	8476	0.865	0.34	-	0.865	0.34	-	-	0.58	1.1	-	-	-	-	-	3.60
WP-4-C	92	12	5.50	0.47	8476	0.865	0.34	-	0.865	0.34	-	-	0.58	1.1	-	-	-	-	-	2.89
WP-10-C	90.5	12.5	5.50	0.47	8476	0.785	0.38	0.35	0.35	0.31	0.14	1.07	0.34	1.07	2947	5818	-	-	-	1.80
WP-19-C	91.5	12.5	6.04	0.47	8476	0.811	0.42	0.50	0.42	0.35	0.19	0.94	0.24	0.94	2543	7054	-	-	-	1.80
WP-26-C	91	15.7	5.25	0.47	8422	0.93	0.67	0.185	0.94	0.07	0.07	1.42	0.684	1.42	1557	1656	19.0	1.16	1.16	3.08
WP-27-C	90	15.7	5.52	0.47	8422	0.91	0.63	0.222	0.86	0.09	0.09	1.56	0.574	1.56	1870	2174	12.68	0.78	0.78	3.27
WP-28-C	90.7	15.8	5.42	0.47	8422	0.823	0.46	0.140	0.97	0.06	0.06	1.05	0.380	1.05	1173	2068	11.08	0.74	0.74	2.31
WP-4-C	91	74	14.35	0.48	8476	0.356	0.36	-	0.21	-	-	0.75	0.14	0.75	-	-	-	-	-	2.4
WP-5-C	92	74	14.52	0.48	8476	0.405	0.28	-	0.17	-	-	0.75	0.11	0.75	-	-	-	-	-	1.1
WP-6-C	92	74	15.25	0.48	8476	0.405	0.28	-	0.17	-	-	0.75	0.11	0.75	-	-	-	-	-	1.9
WP-7-C	93	73	15.47	0.47	8476	0.344	0.21	-	0.11	-	-	0.88	0.07	0.88	-	-	-	-	-	1.8
WP-8-C	92	52	11.48	0.47	8476	0.55	0.48	-	0.39	-	-	0.86	0.26	0.86	-	-	-	-	-	2.4
WP-9-C	92	51	11.28	0.47	8476	0.54	0.48	-	0.39	-	-	0.86	0.26	0.86	-	-	-	-	-	2.6
WP-10-C	92	52	12.32	0.47	8476	0.55	0.45	-	0.35	-	-	1.17	0.25	1.17	-	-	-	-	-	2.5
WP-22-C	90.7	50.2	10.30	0.45	8422	0.638	0.582	0.185	0.54	0.11	0.11	1.14	0.359	1.14	1540	2860	13.46	1.17	1.17	1.54
WP-33-C	90.9	50.1	10.89	0.45	8422	0.688	0.52	0.198	0.59	0.10	0.10	1.25	0.423	1.25	1375	4446	4.75	0.46	0.46	1.54
WP-34-C	90.4	50.8	10.89	0.45	8422	0.685	0.542	0.135	0.54	0.10	0.10	1.25	0.427	1.25	1335	4447	4.75	0.41	0.41	1.46
WP-11-C	92	35.5	8.13	0.47	8476	0.758	0.60	-	0.60	-	-	1.3	0.40	1.3	-	-	-	-	-	2.5
WP-12-C	92	35.5	7.84	0.48	8476	0.585	0.45	-	0.47	-	-	1.1	0.31	1.1	-	-	-	-	-	2.4
WP-13-C	92.5	35	8.00	0.47	8476	0.684	0.64	-	0.38	-	-	1.1	0.25	1.1	-	-	-	-	-	2.7
WP-23-C	90.0	30.1	7.47	0.48	8422	0.755	0.417	0.140	0.47	0.07	0.07	1.4	0.315	1.4	1179	2495	15.85	1.16	1.16	2.31
WP-24-C	91	25.8	7.95	0.46	8422	0.804	0.50	0.164	0.60	0.07	0.07	1.31	0.402	1.31	1363	2294	15.85	1.09	1.09	2.31
WP-31-C	90.8	30.9	7.73	0.46	8422	0.698	0.43	0.176	0.57	0.07	0.07	1.4	0.378	1.4	1462	2515	14.25	0.92	0.92	2.5
WP-14-C	91.5	21.5	6.46	0.47	8476	0.804	0.54	-	0.65	-	-	0.745	0.43	0.745	-	-	-	-	-	2.62
WP-15-C	91.5	23.0	6.35	0.47	8476	0.714	0.61	-	0.65	-	-	0.980	0.43	0.980	-	-	-	-	-	2.50
WP-16-C	92.0	24.8	6.61	0.47	8476	0.733	0.46	-	0.53	-	-	0.745	0.35	0.745	-	-	-	-	-	3.10
WP-20-C	91.3	6.2	4.47	0.48	8476	1.02	0.63	-	0.72	-	-	0.68	0.48	0.68	-	-	-	-	-	4.44
WP-31-C	91.3	7.8	4.37	0.48	8476	0.85	0.47	0.14	0.45	0.08	0.08	0.71	0.30	0.71	1167	2638	-	-	-	3.62
WP-25-C	92	10.8	4.66	0.46	8476	0.85	0.53	0.31	0.51	0.17	0.17	0.34	0.34	0.34	2628	5153	-	-	-	3.54
WP-25-C	100	6.4	2.89	0.49	8476	1.10	0.66	0.285	1.19	0.06	0.06	0.79	0.79	1.15	1907	3603	-	-	-	6.54

1/ Ponderosa pine (P. ponderosa Lm)  
 2/ Western white pine (P. monticola Dougl.)  
 3/ Other parameter held constant throughout the study:  
 Ponderosa pine:  
 $\rho = 31.6 \text{ lb/ft}^3$   
 $G = 1858 \text{ ft}^2/\text{ft}^3$   
 $\lambda = 0.030 \text{ ft}^2/\text{ft}^2$   
 Western white pine:  
 $\rho = 24.8 \text{ lb/ft}^3$   
 $G = 1800 \text{ ft}^2/\text{ft}^3$   
 $\lambda = 0.024 \text{ ft}^2/\text{ft}^2$

Table 4

Fire No.	Test area ambient conditions $\bar{z}$				Fuel and fuel bed parameters				Burning parameters				Flame dimensions				Heat variables							
	U	T <sub>0</sub>	RH	$\bar{z}$	M <sub>1</sub>	M <sub>2</sub>	W <sub>0</sub>	H	R	R	⊙	B	A <sub>0</sub>	T <sub>b</sub>	D	L	H	⊙	⊙	⊙	Z	Z <sub>R</sub>	I <sub>GR</sub>	I <sub>T</sub>
	ft/min	°F	%	ft	kg	kg	lb/ft <sup>2</sup>	ft	ft/min	min	lb/min	ft <sup>2</sup>	ft	ft	ft	ft	ft	deg	deg	Rm/ft <sup>2</sup>	Rm/min	Rm/ft <sup>2</sup>	hr	Rm/ft <sup>2</sup>
FP-1-WL	132	95.5	16.3	4.53	0.48	0.48	8869	1.52	0.96	0.65	2.19	0.15	1.45	2.39	2.13	28.6	28.6	56.0	5.760	2.617	56.0	56.0	2.06	
FP-2-WL	132	97.0	15.5	4.56	0.48	0.48	8869	1.68	1.33	0.652	2.48	0.12	1.32	2.31	2.38	28.7	28.7	68.0	4.490	1.423	68.0	68.0	2.27	
FP-3-WL	132	91.8	15	4.22	0.48	0.48	8869	1.87	1.13	0.607	2.62	0.12	1.86	2.13	1.99	30.6	30.6	68.7	5.580	1.892	68.7	68.7	2.24	
FP-4-WL	264	96	13.5	3.74	0.48	0.48	8869	2.40	1.83	0.791	2.69	0.12	4.46	2.12	1.91	43	43	73.9	7.080	1.043	73.9	73.9	1.68	
FP-5-WL	264	97	13	3.78	0.48	0.48	8869	2.84	1.60	0.81	2.81	0.13	4.54	2.28	1.94	43	43	73.0	9.140	1.244	73.0	73.0	1.44	
FP-6-WL	264	92.3	15.9	5.10	0.47	0.47	8877	1.89	1.47	0.49	4.17	0.13	2.78	2.02	1.74	33	33	55.2	4.265	1.017	55.2	55.2	1.63	
FP-7-WL	264	90.3	15.1	4.63	0.48	0.48	8812	2.12	1.62	0.58	5.15	0.09	3.43	2.12	1.74	33	33	57.4	4.870	1.989	57.4	57.4	1.63	
FP-8-WL	264	90.6	15.7	4.63	0.48	0.48	8812	2.01	1.40	0.593	4.23	0.10	3.41	2.28	1.72	39	39	57.4	5.000	1.238	57.4	57.4	1.46	
FP-9-WL	264	90.7	15.5	4.52	0.48	0.48	8812	2.06	1.70	0.624	5.24	0.06	3.49	2.32	1.99	30	30	63.8	5.900	1.043	63.8	63.8	1.74	
FP-10-WL	440	95	12.7	4.14	0.48	0.48	8869	3.71	1.72	1.12	9.87	0.11	6.38	2.85	1.75	53.2	53.2	85.0	10.630	1.034	85.0	85.0	1.31	
FP-11-WL	440	94.5	15.4	4.55	0.48	0.48	8877	3.52	1.88	1.02	9.30	0.10	6.60	2.68	1.75	46.6	46.6	81.4	9.020	1.911	81.4	81.4	1.31	
FP-12-WL	440	90.0	15.5	5.01	0.48	0.48	8869	3.95	1.74	0.97	9.24	0.09	6.16	2.94	1.92	47.8	47.8	92.4	8.600	928	92.4	92.4	1.32	
FP-13-WL	440	91.0	15.6	4.96	0.48	0.48	8812	4.88	1.64	1.22	12.0	0.09	8.00	---	---	---	---	70.2	10.750	840	70.2	70.2	0.81	
FP-14-WL	440	91.5	15.5	4.80	0.48	0.48	8812	5.34	2.03	0.80	16.2	0.06	10.8	---	---	---	---	77.2	7.060	436	77.2	77.2	0.81	
FP-15-WL	440	91.6	15.0	4.72	0.48	0.48	8812	5.48	1.42	0.87	11.7	0.05	7.78	---	---	---	---	76.5	7.650	656	76.5	76.5	0.79	
FP-16-WL	704	90	15	4.78	0.48	0.48	8812	16.7	2.04	1.93	51.2	0.04	34.1	---	---	---	---	104	17.000	332	104	104	0.35	
FP-17-WL	704	90	15	4.75	0.48	0.48	8812	12.7	1.99	---	36.0	---	25.3	3.66	1.82	56	56	107	19.700	442	107	107	0.48	
FP-18-WL	704	90	15	4.97	0.48	0.48	8812	13.8	2.15	2.24	44.6	0.06	29.7	3.37	1.53	61	61	112	18.500	585	112	112	0.45	
FP-19-WL	704	90	15	5.05	0.48	0.48	8812	11.6	1.84	2.10	32.0	0.07	21.3	3.53	1.63	57	57	115	18.500	585	115	115	0.56	
FP-20-WL	132	91	30.8	7.46	0.46	0.46	8877	1.17	1.02	0.25	1.79	0.08	1.19	1.84	1.73	21	21	45.4	2.219	1.238	45.4	45.4	2.08	
FP-21-WL	132	91.3	31.8	7.60	0.46	0.46	8877	1.24	1.12	0.31	2.09	0.09	1.39	1.65	1.73	21	21	49.6	2.729	1.236	49.6	49.6	2.27	
FP-22-WL	132	92.5	30.0	7.50	0.46	0.46	8877	1.17	0.98	0.33	1.71	0.10	1.14	1.87	1.53	23	23	40.8	2.729	1.724	40.8	40.8	1.97	
FP-23-WL	132	89.9	30.6	6.93	0.47	0.47	8812	1.11	0.94	0.321	1.56	0.11	1.04	2.85	2.49	28	28	36.2	2.530	2.502	36.2	36.2	1.64	
FP-24-WL	264	92.2	31.4	7.54	0.46	0.46	8877	1.33	0.76	0.393	1.52	0.11	1.01	2.32	1.93	34	34	42.7	3.460	2.502	42.7	42.7	1.40	
FP-25-WL	264	91.8	30.7	7.50	0.46	0.46	8877	1.96	1.66	0.50	4.28	0.11	2.85	1.61	1.36	31	31	42.7	4.439	1.034	42.7	42.7	1.40	
FP-26-WL	264	91.6	30.5	7.27	0.46	0.46	8877	1.85	1.53	0.48	4.49	0.09	2.99	1.48	1.28	30	30	44.6	4.261	946	44.6	44.6	1.27	
FP-27-WL	440	91.5	31.8	7.87	0.46	0.46	8812	3.76	1.56	0.35	4.32	0.07	2.88	1.55	1.38	32	32	48.2	3.107	716	48.2	48.2	1.46	
FP-28-WL	440	92.0	30.5	7.72	0.46	0.46	8812	4.10	1.50	0.84	8.45	0.08	5.63	1.72	1.29	46	46	49.7	7.402	875	49.7	49.7	0.75	
FP-29-WL	440	91.5	31.2	7.77	0.46	0.46	8812	4.95	2.25	0.70	16.68	0.05	11.12	2.04	1.54	40	40	68.2	7.314	592	68.2	68.2	0.93	
FP-30-WL	440	90.4	30.0	8.06	0.46	0.46	8812	3.57	1.52	0.85	8.15	0.08	5.45	2.71	1.90	44	44	58.6	6.168	371	58.6	58.6	0.67	
FP-31-WL	704	90.8	30.0	8.20	0.46	0.46	8812	3.60	1.69	0.74	9.12	0.07	6.08	2.84	2.10	41	41	56.7	7.500	919	56.7	56.7	0.80	
FP-32-WL	704	90	30	7.32	0.46	0.46	8812	9.81	2.02	1.19	29.7	0.04	19.8	3.32	1.59	56	56	63.8	6.550	716	63.8	63.8	0.88	
FP-33-WL	704	90	30	7.32	0.46	0.46	8812	10.5	1.74	1.26	27.5	0.05	18.3	3.68	1.63	61	61	68.9	10.490	354	68.9	68.9	0.36	
FP-34-WL	704	90	30	6.12	0.47	0.47	8812	9.3	1.87	1.45	26.1	0.06	17.4	4.19	1.71	61	61	91.9	12.600	486	91.9	91.9	0.37	
FP-35-WL	132	90	50.9	9.49	0.45	0.45	8812	0.794	0.78	0.20	0.93	0.10	0.62	1.73	1.51	26	26	26.8	1.763	1.901	26.8	26.8	1.92	
FP-36-WL	132	90.2	50.5	9.50	0.45	0.45	8812	0.874	0.86	0.206	1.13	0.09	0.75	1.35	1.24	19	19	26.8	1.618	1.653	26.8	26.8	1.74	
FP-37-WL	132	90.1	50.2	9.45	0.45	0.45	8812	0.921	0.93	0.21	1.29	0.08	0.66	1.47	1.52	20	20	30.4	1.653	1.441	30.4	30.4	1.25	
FP-38-WL	264	90.5	50.8	9.82	0.45	0.45	8812	1.543	0.91	0.352	2.10	0.09	1.40	1.65	1.45	26	26	26.1	2.105	1.476	26.1	26.1	0.96	
FP-39-WL	264	90.9	50.9	9.94	0.45	0.45	8812	1.568	1.03	0.358	2.43	0.09	1.62	1.78	1.49	31	31	34.4	3.160	1.508	34.4	34.4	1.23	
FP-40-WL	264	90.1	50.5	10.05	0.45	0.45	8812	1.456	0.98	0.366	2.16	0.09	1.41	1.89	1.49	30	30	30.6	3.250	1.587	30.6	30.6	1.20	
FP-41-WL	440	90.8	48.5	9.51	0.45	0.45	8812	3.54	1.31	0.638	6.96	0.07	5.24	2.59	1.72	46	46	44.6	5.680	813	44.6	44.6	0.70	
FP-42-WL	440	90.5	49.6	9.80	0.45	0.45	8812	3.65	1.43	0.689	7.83	0.07	5.22	2.69	1.78	48	48	44.0	5.368	778	44.0	44.0	0.68	
FP-43-WL	440	90.7	50.5	10.07	0.45	0.45	8812	3.25	1.38	0.700	6.69	0.08	4.46	2.31	1.56	46	46	37.0	6.165	519	37.0	37.0	0.65	

Table 5

Fire No.	Test area ambient conditions <sup>2</sup>				Fuel and fuel bed parameters				Burning parameters				Flame dimensions				Heat variables			
	U ft/min	T <sub>0</sub> °F	RH %	W <sub>f</sub> %	W <sub>f</sub> %	W <sub>0</sub> lb/ft <sup>2</sup>	H ft	R ft/min	Θ min	B lb/min	A <sub>0</sub> ft <sup>2</sup>	τ <sub>0</sub> ft	D ft	L ft	H ft	φ deg.	K ft <sup>2</sup> /min	τ <sub>p</sub> ft <sup>2</sup> /min	I <sub>cv</sub> ft <sup>2</sup> /hr	I <sub>p</sub> ft <sup>2</sup>
WP-1-WL	132	94	15.5	5.25	0.47	8476	1.76	0.42	0.135	1.11	0.05	0.74	0.59	0.54	25	1.143	1.027	17.9	0.58	
WP-2-WL	132	93	16	5.31	0.47	8476	2.22	0.669	0.162	1.54	--	0.89	0.85	0.71	34.2	--	--	16.6	0.45	
WP-3-WL	132	96	14	5.76	0.33	8476	1.78	0.669	0.162	1.79	0.05	1.19	0.85	0.71	25	1.372	766	23.0	0.72	
WP-4-WL	132	91	14.9	5.51	0.32	8422	1.91	0.298	0.142	1.68	0.02	1.12	1.00	0.82	32	1.230	1.406	19.5	0.57	
WP-4-WL	264	92.5	16.1	5.17	0.32	8476	5.00	0.36	--	2.70	--	1.80	0.61	0.45	38	--	--	19.5	0.72	
WP-5-WL	264	94	13.4	4.40	0.32	8476	4.16	0.62	0.41	3.81	0.05	2.58	0.61	0.45	37.5	3.475	893	30.0	0.77	
WP-6-WL	264	94	13.5	4.40	0.32	8476	4.81	0.57	--	4.11	--	2.74	0.81	0.61	37.5	--	--	25.9	0.50	
WP-41-WL	264	89.5	13.4	5.40	0.32	8422	5.34	0.35	0.40	2.81	0.04	1.87	1.28	0.87	44	3.370	1.204	21.85	0.23	
WP-42-WL	264	93	13.2	5.19	0.32	8422	5.64	0.36	0.38	3.05	0.04	2.03	1.15	0.88	39	3.300	1.086	26.1	0.26	
WP-5-WL	440	91	16.1	6.02	0.31	8476	10.64	0.58	0.79	10.86	0.04	7.24	0.95	0.87	44	6.696	615	30.8	0.16	
WP-5-WL	440	94.5	14.4	6.01	0.31	8476	12.83	0.38	0.844	7.31	0.04	4.87	0.94	0.65	47	7.150	977	27.4	0.12	
WP-5-WL	440	94	13.6	6.50	0.31	8476	10.20	0.48	--	7.35	--	4.90	0.81	0.72	45	--	--	29.3	0.16	
WP-43-WL	440	90.4	13.1	5.60	0.32	8422	10.65	0.40	0.678	6.38	0.03	4.25	1.18	0.72	43	5.710	893	26.2	0.14	
WP-44-WL	440	90.5	13.3	5.20	0.32	8422	13.30	0.38	0.673	7.58	0.03	5.05	1.23	0.82	42	5.660	780	28.2	0.14	
WP-46-WL	704	91.2	14.8	5.37	0.32	8422	32	0.80	1.80	19.20	0.03	12.90	1.18	0.87	52	15.200	792	33.2	0.06	
WP-47-WL	704	91.6	14.8	5.41	0.32	8422	28.9	0.56	1.37	22.80	0.03	15.06	1.72	0.87	58	11.500	514	33.2	0.06	
WP-48-WL	704	90	15	5.70	0.31	8422	20.9	0.44	1.55	13.60	0.04	8.20	1.53	0.64	58	13.100	943	37.0	0.06	
WP-49-WL	704	90	15	5.88	0.31	8422	21.2	0.40	1.67	12.72	0.04	8.46	1.12	0.66	51	14.060	1,112	35.7	0.10	
WP-10-WL	132	92.2	31.1	8.70	0.30	8422	1.40	0.45	0.122	0.95	0.05	0.63	0.45	0.45	30	1.027	1,095	12.75	0.51	
WP-11-WL	132	92.7	30.8	8.61	0.31	8422	1.34	0.66	0.117	1.32	0.05	0.88	0.45	0.40	30	1.985	750	12.75	0.50	
WP-12-WL	132	91.5	31.5	8.94	0.30	8422	1.40	0.54	0.22	1.14	0.09	0.76	0.52	0.48	24	1.853	1,625	14.02	0.50	
WP-13-WL	264	92.1	31.2	8.19	0.31	8422	3.91	0.74	0.35	4.34	0.05	2.89	0.48	0.45	30	1.027	682	17.85	0.26	
WP-14-WL	264	92.1	30.4	8.57	0.31	8422	4.72	0.61	0.36	6.11	0.05	4.07	0.45	0.40	30	9.885	497	16.6	0.27	
WP-20-WL	264	91.6	31.0	8.31	0.31	8422	4.72	0.621	0.30	4.40	0.04	2.93	0.52	0.48	24	1.853	573	22.9	0.16	
WP-15-WL	264	91.5	31.3	8.19	0.31	8422	5.00	0.67	0.36	5.03	0.04	3.35	0.52	0.40	43	3.032	606	14.02	0.16	
WP-32-WL	264	90.9	30.5	8.30	0.31	8422	4.14	0.36	0.325	2.24	0.04	1.49	1.00	0.75	39	2,740	1,221	15.7	0.21	
WP-33-WL	264	90.9	30.5	8.55	0.31	8422	4.16	0.26	0.356	1.62	0.05	1.09	1.00	0.75	39	3,000	1,853	14.0	0.19	
WP-16-WL	440	91.6	31.4	8.51	0.31	8422	10.63	0.51	0.38	8.13	0.02	5.42	0.72	0.46	53	3,200	3,96	21.3	0.12	
WP-17-WL	440	92.2	30.9	9.31	0.30	8422	9.43	0.504	--	7.13	--	4.75	0.80	0.49	57	--	--	21.0	0.13	
WP-18-WL	440	92.5	30.5	9.43	0.30	8422	11.11	0.709	0.60	11.82	0.03	7.88	0.79	0.48	55	5.011	450	17.8	0.09	
WP-19-WL	440	92.1	30.9	9.39	0.30	8422	11.11	0.45	0.312	7.90	0.01	5.00	0.72	0.48	51	2,630	707	20.4	0.10	
WP-34-WL	440	90.6	30.1	8.26	0.31	8422	8.42	0.46	0.361	5.82	0.02	3.88	1.62	0.86	45	3,040	522	22.96	0.15	
WP-35-WL	440	90.8	29.9	8.51	0.31	8422	7.47	0.47	0.356	5.28	0.02	3.52	1.29	0.79	51	2,780	522	23.27	0.12	
WP-37-WL	704	90	30	9.42	0.30	8422	22.2	0.478	0.754	15.45	0.02	10.3	1.55	0.70	60	6,180	3,96	28.0	0.07	
WP-38-WL	704	90	30	9.70	0.30	8422	25.8	0.44	0.455	17.03	0.01	11.35	1.49	0.72	57	3,830	227	28.0	0.06	
WP-39-WL	704	90	30	9.70	0.30	8422	17.5	0.426	0.755	11.18	0.02	7.45	1.54	0.85	55	6,360	573	30.6	0.10	
WP-40-WL	704	90	30	8.50	0.31	8422	17.5	0.415	0.926	10.89	0.03	7.26	1.59	0.85	57	7,800	716	28.7	0.09	
WP-25-WL	132	90.2	50.5	11.15	0.30	8422	0.781	0.69	0.124	0.81	0.09	0.54	0.68	0.59	25	1,045	1,289	6.38	0.48	
WP-26-WL	132	90.5	50.5	11.50	0.30	8422	--	0.46	--	0.50	--	0.33	0.68	0.61	25	--	--	7.33	--	
WP-27-WL	132	91	50.0	11.09	0.30	8422	1.12	0.61	0.218	1.02	0.11	0.68	0.61	0.69	28	1,819	1,819	8.92	0.45	
WP-28-WL	264	90.1	50.0	11.23	0.30	8422	1.01	0.55	0.138	0.84	0.07	0.56	0.72	0.62	31	1,162	1,381	9.30	0.54	
WP-29-WL	264	90.1	50.1	11.81	0.29	8422	2.17	0.72	0.20	2.34	0.06	1.56	0.85	0.62	40	1,684	716	12.75	0.33	
WP-23-WL	264	90.1	50.3	12.19	0.29	8422	2.44	0.62	--	2.27	--	1.51	0.72	0.53	42	--	--	12.45	0.29	
WP-24-WL	264	90.8	50.3	11.79	0.29	8422	2.70	0.50	0.144	2.03	0.03	1.35	0.87	0.63	42	1,213	598	12.00	0.25	
WP-24-WL	264	91	50.0	11.68	0.29	8422	2.88	0.52	0.171	2.25	0.04	1.50	0.82	0.57	43	1,440	640	15.3	0.30	
WP-29-WL	440	90.6	50.2	11.80	0.30	8422	6.41	0.48	0.243	4.65	0.02	3.1	1.15	0.78	46	2,047	438	15.6	0.14	
WP-30-WL	440	90	50.0	11.87	0.29	8422	7.48	0.46	0.37	5.16	0.04	3.44	1.15	0.71	50	3,117	608	15.6	0.12	
WP-31-WL	440	90.3	50.3	11.76	0.29	8422	7.04	0.58	0.383	6.08	0.05	4.05	1.19	0.76	50	2,720	448	17.85	0.14	

Table 6

Fire No.	Species	Loading tons/acre	Test area ambient conditions			Fuel and fuel bed parameters			Burning parameters			Flame dimensions			Heat variables		
			T <sub>0</sub> °F	U ft/min	EH %	M <sub>f</sub> %	W <sub>0</sub> lbs/ft <sup>2</sup>	H ft	R ft/min	R min	B lb/min	D ft	L ft	Q Btu/min	Q Btu/ft <sup>2</sup> min	H <sub>R</sub>	
1	D.F.	32.5	87	4.0	28	8.4	1.35	8332	5.15	1.85	41.64	9.51	5.98	346,944	6,082		
2	D.F.	20.0	87	4.5	28	7.9	0.74	8332	5.05	0.75	22.32	3.80	4.07	185,970	8,165		
3	D.F.	7.5	90	3.0	24	7.3	0.50	8332	2.59	0.78	1.01	2.03	2.64	8,415	5,332		
4	L.P.P.	32.5	93	5.0	20	8.1	1.45	8709	9.10	---	6.28	---	8.46	54,695	7,141		
5	L.P.P.	20.0	92	7.0	21	7.7	0.93	8709	5.90	0.94	1.49	4.43	3.48	12,976	3,135		
6	L.P.P.	7.5	92	7.0	22	7.4	0.34	8709	4.70	0.82	7.99	5.90	6.40	66,573	13,748		
7	D.F.	32.5	81	3.0	32	7.0	1.35	8332	7.20	0.80	2.81	3.84	4.14	23,413	7,749		
8	D.F.	20.0	85	7.5	27	6.7	0.74	8332	4.82	0.65	1.72	3.45	2.59	14,331	6,416		
9	D.F.	7.5	89	4.5	23	6.3	0.50	8332	5.30	0.65	1.72	3.45	2.59	14,331	6,416		
10	L.P.P.	32.5	93	3.5	18	5.3	1.45	8709	3.40	1.94	9.58	6.58	7.17	85,432	6,532		
11	L.P.P.	20.0	93	3.5	18	6.3	0.93	8709	2.70	1.33	3.34	3.58	5.83	29,088	6,096		
12	L.P.P.	7.5	94	5.0	16	6.3	0.34	8709	5.22	0.72	1.27	3.77	3.77	11,060	4,093		
13	D.F.	32.5	91	2.0	22	5.8	1.35	8332	5.40	1.00	7.26	5.38	7.09	60,490	11,248		
14	D.F.	20.0	92	4.0	21	5.8	0.74	8332	3.39	0.91	2.28	3.10	3.88	18,997	6,749		
15	D.F.	7.5	92	2.0	21	5.7	0.50	8332	---	---	---	---	2.50	---	---		
16	L.S.P.	32.5	71	2.5	61	8.1	1.45	8709	4.80	1.21	8.47	5.83	9.52	73,765	10,451		
17	L.P.P.	20.0	70	0.5	61	7.7	0.93	8709	1.79	2.76	4.64	4.94	3.93	40,410	2,961		
18	L.P.P.	7.5	70	0.5	61	7.4	0.34	8709	1.80	---	---	---	3.82	---	---		

Rothermel, Richard C., and Hal E. Anderson.

1966. Fire spread characteristics determined in the laboratory. U.S. Dep. Agr., Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah. 34 pp., illus. (U.S. Forest Serv. Res. Pap. INT-30)

Fuel beds of ponderosa pine needles and white pine needles were burned under controlled environmental conditions to determine the effects of fuel moisture and windspeed upon the rate of fire spread. Empirical formulas are presented to show the effect of these parameters. A discussion of rate of spread and some simple experiments show how fuel may be preheated before the fire reaches the fuel. The interrelationship between unit energy release rate and rate of spread produces a fire characteristics curve. Diffusion flame analysis shows good agreement when working with  $\frac{1}{2}$ -inch stick fires.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Project headquarters are also at:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Provo, Utah (in cooperation with Brigham Young University)



*“The Forest Service of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation’s forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives – as directed by Congress – to provide increasingly greater service to a growing Nation.”*