U. S. FOREST SERVICE
RESEARCH PAPER INT-8
1964

MECHANISMS OF FIRE SPREAD
RESEARCH PROGRESS REPORT NO. 1

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By

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INTRODUCTION

An understanding of fire spread is important to the development of improved methods and systems for the control of free burning fires. Gaining knowledge about fire spread in forest fuels is complex because many variables are involved and because we still lack full understanding of the interaction of these variables. The research reported here involves studies of fire spread in natural forest fuels in which the characteristics of the fuel and the weather environment were controlled.

Several investigators have studied the spread of fires in forest fuels where burning was not started until the desired ambient conditions were obtained (Curry and Fons 1940; Fons 1946; Fahnestock 1960). Direct control of wind, air temperature, humidity, and fuel moisture content could not be accomplished although these items were measured during the studies and cross correlations were accomplished. Some uncertainties enter the relationships if the environmental conditions cannot be controlled, and the full importance of a given factor cannot be determined until control can be achieved. Other investigations have dealt with solid or liquid fuels in which fire environmental characteristics are of lesser importance. By conducting our research in a laboratory where ambient conditions could be controlled, the masking tendency of certain ambient conditions could be kept at a minimum.

The present research project on Mechanisms of Fire Spread involves experiments performed as follows:

1. Natural forest fuels were used in fuel beds artificially packed in a random manner.

2. Fuel beds were controlled with respect to type and species of material, moisture content, and compactness of fuel particles. Compactness was controlled to the degree constant loading was achieved.

3. Fires were burned in these fuel beds under controlled conditions of air temperature, relative humidity, and wind velocity.

4. Investigations were aimed at providing information about the influence of both fuel and environment parameters on the mechanisms of fire spread along a segment of the flame front.

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All experiments were performed in a specially equipped forest fire laboratory. The experimental facilities include: a 66-foot-high combustion laboratory where air temperature, relative humidity, and atmospheric pressure can be varied and controlled; a fuels laboratory for preparation of fuel materials; and conditioning cabinets for bringing fuels to required moisture content. Future experiments will include use of two wind tunnels. Results of laboratory experiments are checked by field experiments.

This progress report deals only with experiments measuring rate of fire spread in two forest fuels in the combustion laboratory.

SUMMARY OF RESEARCH RESULTS

To date, 32 experimental fires have been studied in two types of natural, light forest fuels to determine the effects of moisture content on the rate of fire spread and other fire characteristics. The two fuels are beds of ponderosa pine (*Pinus ponderosa* Laws.) and western white pine (*P. monticola* Dougl.) needles. The environmental conditions include: fuel moisture 3 to 16 percent; air temperature 90° to 95° F., and relative humidity 5 to 75 percent.

These 32 experimental fires were preceded by 21 preliminary test fires that were burned to determine the effects of fuel bed width and depth, use of fuel bed side strips, an exhaust system, and to test instrumentation and other experimental techniques.

Results of these experiments show that:

1. Reproducible fuel beds of forest fuels can be made.

2. Forest fuels can be employed in steady-state fire experiments using principles similar to those developed by Project Fire Model as reported in Publication 786, NAS-NRC (Fons et al. 1959).

3. Fire environmental factors can be varied and controlled to permit studies of the effect of moisture content on fire spread.

4. Rate of fire spread in ponderosa pine and white pine needles is a linear function of moisture content within the range of 5- to 15-percent fuel moisture.

5. Residence flame time and flame depth appear to reach a maximum when fuel moisture is between 8 and 10 percent.

6. The rates of fire spread in ponderosa pine and white pine needles are nearly identical for the specific loading and compactness, but ponderosa pine burns more intensely.

BACKGROUND

Forest fire researchers in the United States have developed empirical methods for evaluating and estimating fire spread. Analysis of nearly 3,000 wildfires has shown the importance of fuel, topography, and weather parameters on fire spread (Barrows 1951a, 1951b). More recently Project Fire Model has shown the finite importance of wood fuel characteristics to fire spread (Fons et al. 1962). Experiments to measure fire spread in logging slash have emphasized the importance of fuel species characteristics, fuel amount, and some aspects of weather environment on fire spread and intensity (Fahnestock 1960).

The Committee on Fire Research of the National Academy of Science-National Research Council has emphasized the importance of understanding fire spread in forest fuels. In outlining a proposed fire research program, the committee specifically detailed the following type of studies:

"D. Determination of the Model Laws for Fire Development and Spread

1. Measurements to be made include such items as:

   a. Fuel-system properties and air properties (including temperature, wind velocity, humidity, lapse rate)."

(The Committee on Fire Research 1958)

These backgrounds of research experience and recommendations for a national program of fire research led to the present project on Mechanisms of Fire Spread. The project became feasible with the creation of needed research facilities at the Northern Forest Fire Laboratory (Anonymous 1960).

In 1961 a coordinated research program was started by Washington State University and the Northern Forest Fire Laboratory with the assistance of National Science Foundation grants. Under NSF Grant No. G-16275, Washington State University is performing studies directed toward mathematical and physical modeling of single fuel elements. The Northern Forest Fire Laboratory with the assistance of NSF Grant No. G-16303 is studying the mechanisms of fire spread along a segment of the flame front in natural forest fuels. Both these interrelated studies are aimed at mathematical and physical descriptions of fire spread that can be the basis for future modeling and analysis of the several variables involved in free burning fires.

The initial approach at the Northern Forest Fire Laboratory is based upon a fuel bed model which can be subjected to rather strict environmental control. In this type of model two basic measurements can describe the rate of spread in a simplified equation where rate of spread equals the flame depth over the residence time or $R_s = D/T_r$. Measurement of these parameters will allow investigation of the independent variables and determination of the interrelations. This requires accurate control and/or measurement of such items as moisture content, air temperature and humidity, fuel loading, air velocity, convection column properties, flame temperature and shape, and radiant energy.

The studies are being conducted by Hal E. Anderson, physicist; Richard C. Rothermel, research aeronautical engineer; Erwin H. Breuer and Merlin L. Brown, electronic technicians; and Robert D. Schuette, physical science aid. Charles H. Kaehn, mechanical engineer, participated until October 1962.

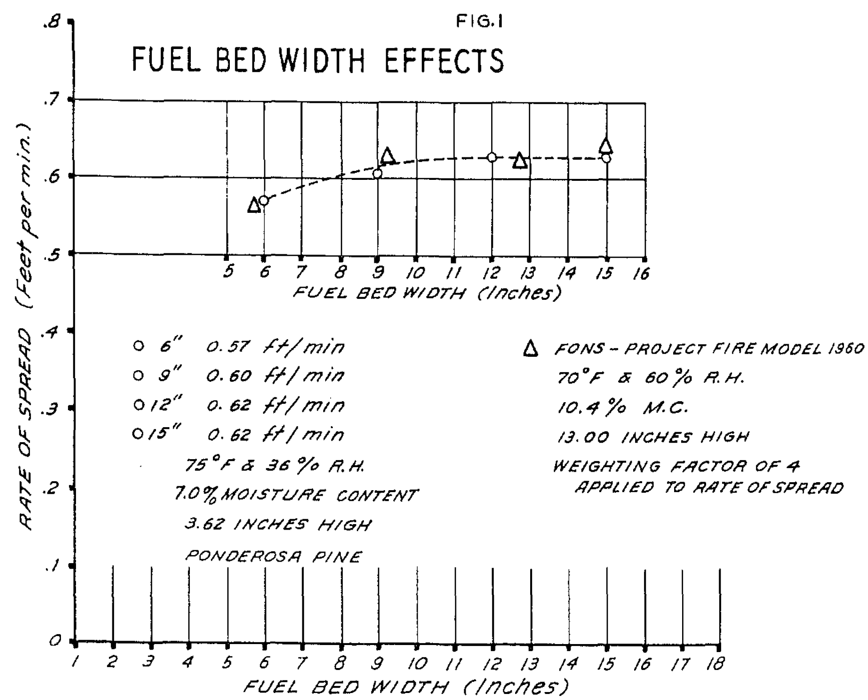
RESEARCH AREAS

FUEL BED CHARACTERISTICS

Initial studies were directed toward determining the most suitable fuel bed depth, width, and loading for building a fuel bed that would be reproducible. These investigations led to the conclusion that a fuel bed wider than 12 inches and 3 or more inches deep would provide a model in which width and depth do not materially affect characteristics of the rate of spread. The same dimensions have been used for ponderosa and white pine mat-type fuel beds; ponderosa pine beds were used as the test standard, since all preliminary investigations have been made using this fuel. Figure 1 shows the effects of varying fuel bed widths and compares the results of these investigations with ponderosa pine to those conducted by Project Fire Model. The rate of spread for the Fire Model studies was a factor of 4 less and the points shown weighted by this factor.

Figure 2 shows the effects of fuel bed depth upon rate of spread. It indicates that fuel depths greater than 3.0 inches do not influence rate of spread. A comparison with Project Fire Model shows the same characteristic. Fire spread studies show an essentially constant rate of spread for fuel bed depths greater than 3.0 inches. The differences are probably due to fuel size and shape, compactness, and the geometry of the fuel loading.

Fuel loading and distribution presented a problem since we had to maintain constant loading and compactness to have correlation between one set of fires and the next. Loading was maintained at 0.50 pound per square foot wet weight and compactness at 8.33 square inches/cubic inch for ponderosa pine and 9.95 square inches/cubic inch for white pine. Our first loading techniques resulted in an uneven distribution of residue. The method used was to load on



an equal unit volume loading by filling each 6- by 12-inch area with the proportioned weight to the proper fuel depth. Our present method applies a proportioned amount of fuel to one-third the fuel depth for the fuel bed length and making three layers of fuel. This improved the distribution of residue after burning and provided a more consistent measure of rate of spread.

FUEL CONDITIONING

All of the fires used for studies of rate of spread under the influence of varying moisture content have been burned at a stabilized moisture content. To provide fuel at the proper conditions, preconditioning cabinets were fabricated. Temperature is controlled by use of steam coils and/or refrigerant coils, and humidity is controlled by use of saturated salt solutions. Suitable salts provide relative humidities from 8 to 75 percent. Table 1 shows the various relative humidities and moisture contents that can be achieved at 90° to 95° F. Only freshly cast needles are collected for use in the fuel bed; these are cleaned to remove as much foreign material as possible.

The decided difference between moisture contents of ponderosa pine and white pine is shown in figure 3. Plotted with these data is the equilibrium moisture content curve for wood shown in the U.S. Department of Agriculture's "Wood Handbook." The moisture content curve for ponderosa pine needles is similar to that of wood, but white pine needles show a higher moisture content and a different response curve. This suggests that the light natural fuels have responses to relative humidity that can be quite different from that of wood. The fuels used for these studies were ovendried at 130° F. for 2 hours before being exposed to the test humidities, and were in the preconditioning cabinets for 2 weeks or longer before they were used in a test-fire fuel bed. Moisture contents were determined by the xylene distillation method (Buck and Hughes 1939).

FIG. 2

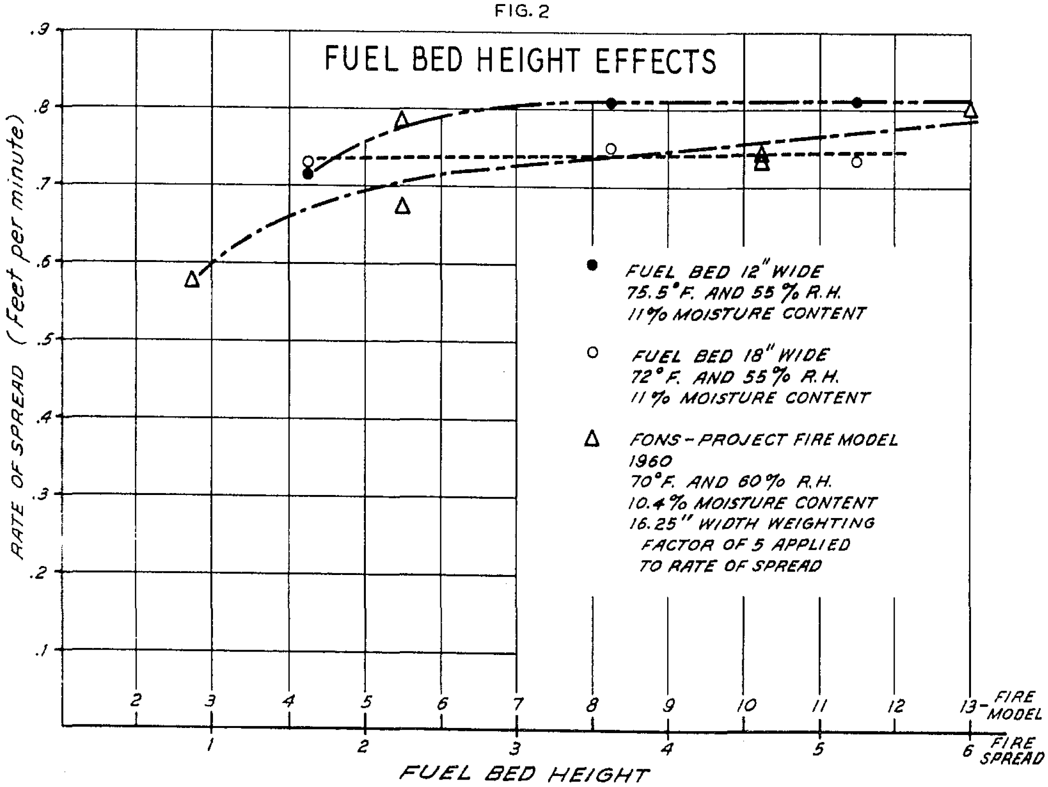


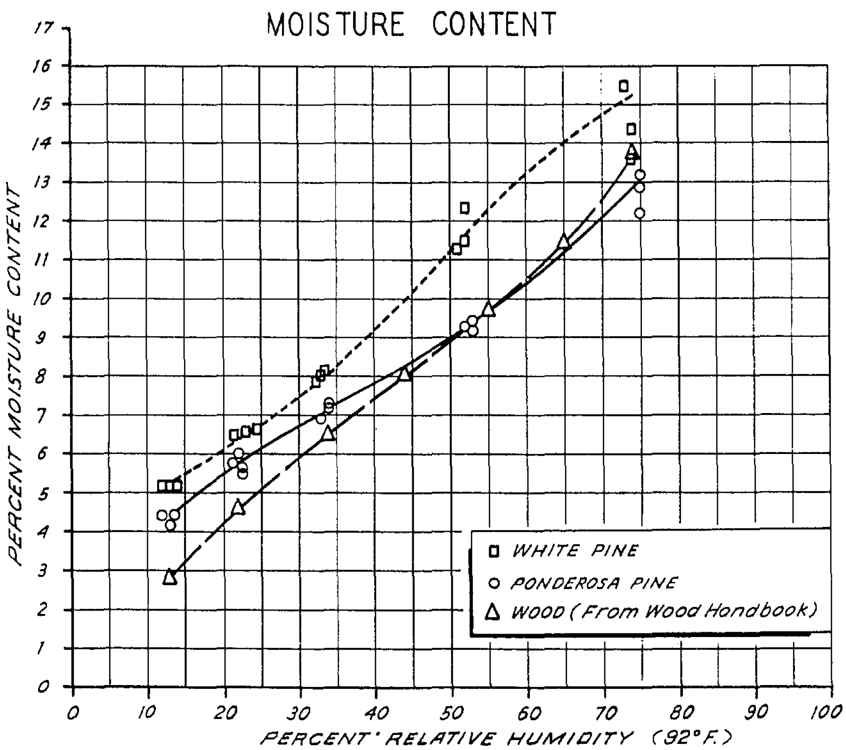
Table 1.--Saturated salt solutions for stabilized moisture contents

Chemical name	Formula	Relative humidity	Moisture content ponderosa pine	Moisture content white pine
		- - - - - - - - -	Percent - - - - - - - - -	- - - - - - - - - - - - -
Potassium hydroxide	KOH	8	3.8 estimated	5.2 estimated
Lithium chloride	LiCl	12.5	4.3 measured	5.6 measured
Potassium acetate	KA_c	22	5.7 "	6.6 "
Magnesium chloride	$MgCl_2 \cdot 6H_20$	32	7.0 "	7.9 "
Magnesium nitrate	$Mg(N0_3)_2 \cdot 6H_20$	52	9.4 "	11.7 "
Sodium chloride	NaCl	75	13.4 "	15.2 "

RATE OF SPREAD

The primary objective of this study is to determine the relations existing between rate of spread and moisture content, air velocity, and slope. The influence of moisture content was selected as the initial study so that techniques of measurement and analysis could be developed under conditions exhibiting slower rates of spread and a stable flame, and because of moisture's role in allowing a fire to grow.

FIG. 3



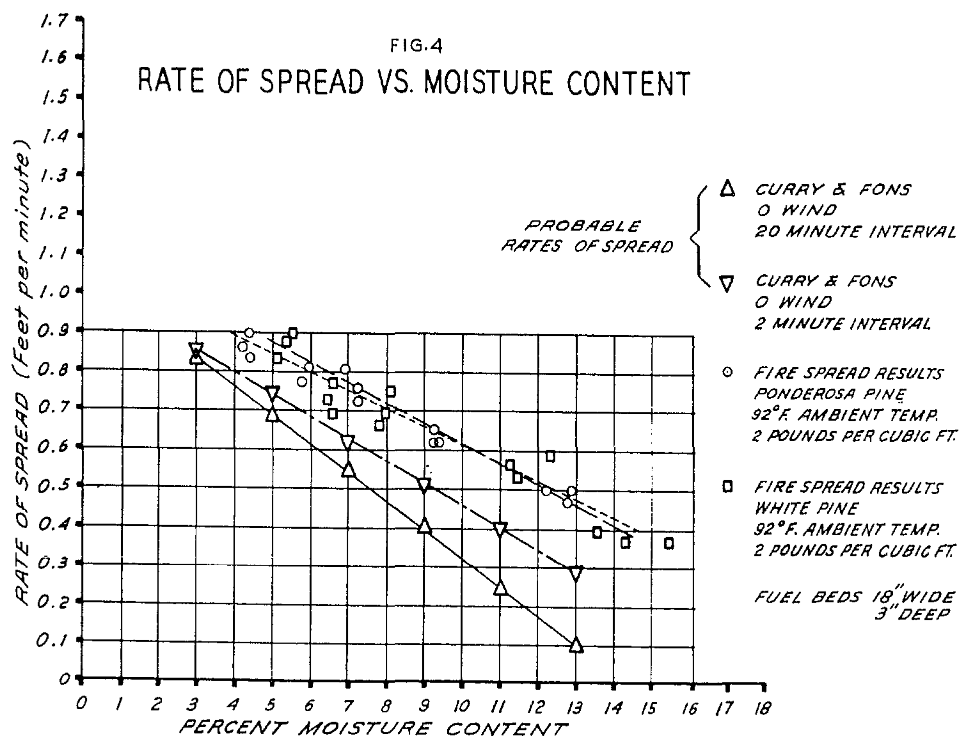
Measurements are made by visual methods and by thermocouples located in the fuel bed with their junctions just at the surface of the fuel. Six chromel-alumel thermocouples of 30-gage material are located on 9-inch centers in the center portion of the 8-foot fuel bed. The signals from these thermocouples drive light-beam galvanometers in continuous recording oscillographs. From the traces thus generated, the rate of spread can be calculated, and by further analysis the residence time[2] can be determined. These thermocouples also indicate the rate of temperature buildup in the fuel before the fire reaches it. The rate of spread values obtained are compared to the visual measurements. Three fires are burned in each fuel at each moisture content condition and checked for repeatability of rate of spread. The percent variation between the visual and thermocouple rate of spread is -4.2 to +3.6 percent for ponderosa pine and -11.5 to +5.5 percent for white pine. Rate of spread plotted against moisture content yields a linear curve (fig. 4).

The rate of spread in the two fuel types is not greatly different; however, other measurements and observations show considerable difference in their combustion characteristics. Figure 4 shows the results of field tests in ponderosa pine (Curry and Fons 1938). Their work shows a probable slower rate of spread over the entire moisture range but a greater change in rate of spread per unit change in moisture content. The plotted points indicate only the probable rate of spread--not measured values. The differences in results of the two studies may be caused by dissimilar loading, in-draft effects of center-firing used by Curry and Fons, and moisture content gradients within the fuel. Fire spread studies will be continued until a minimum moisture content is achieved to determine whether the curve remains linear or becomes nonlinear at low humidities.

[2] The duration of time a fuel particle or thermocouple is in the flaming zone.

FIG. 4

RATE OF SPREAD VS. MOISTURE CONTENT



By further analysis of the signals generated by the thermocouples at the surface of the fuel, residence time can be estimated. Analysis included time displacement of each thermocouple's signal when the flame front reached the thermocouples and copying the signal traces. From these grouped traces for each fire, the temperature profile of the base of the combustion zone could be analyzed. Figure 5 shows residence time plotted against moisture content. At moisture content levels between 8 and 10 percent, both fuels show a maximum residence time. By using the data obtained from the thermocouples, which provide both rate of spread and residence time, the flame width can be calculated from the equation $R_s = D/T_r$. Figures 6 and 7 show these values plotted against moisture content and show the visual measured values of flame width for ponderosa pine and white pine, respectively.

FIG. 5

RESIDENCE TIME VS. MOISTURE CONTENT

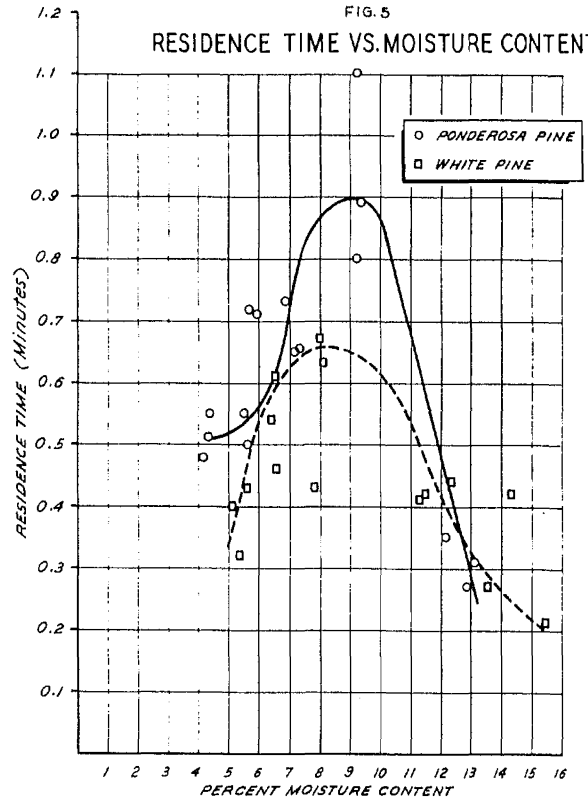
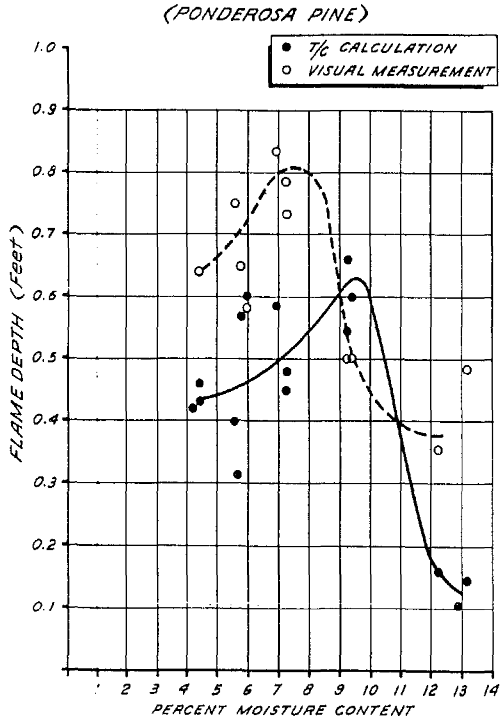


FIG. 6

FLAME DEPTH VS. MOISTURE CONTENT

(PONDEROSA PINE)



Flame width was measured by thermocouples and visual methods to compare the two techniques and determine whether measurements could be made in fires where visual assessment was not possible.

Since flame depth is calculated by multiplying rate of spread by residence time, it is expected that flame depth will have a relation to moisture content similar to that of residence time. This is shown by the above curves and verified by the visual measurements also plotted. It is apparent that the human eye sees a wider reaction zone than the thermocouples (fig. 6) since the visual curve encloses greater flame depths. The offset in the peak of the curve may be caused by error in selection of the point where active combustion is considered complete.

RADIANT HEAT

A Gier and Dunkle directional radiometer is used to measure the radiant heat flux at a point in front of the fire. It is placed 18 feet from the fire and vertically positioned to see all of the flame. Shape factor, flame emissivity, and other factors influencing the complete description of the emitted radiant heat were not included in the analysis since only a general indication was desired during these studies. The radiant flux was plotted (fig. 8) against moisture content after correction for ambient conditions. Measurements of radiant flux on both fuel types show a break at 11-percent moisture content, but white pine shows an increasing rate below 8 percent. The radiant flux measurement shows the difference in the amount of energy released by each fuel type, although the rates of spread are nearly the same.

FIG. 7

FLAME DEPTH VS. MOISTURE CONTENT

(WHITE PINE)

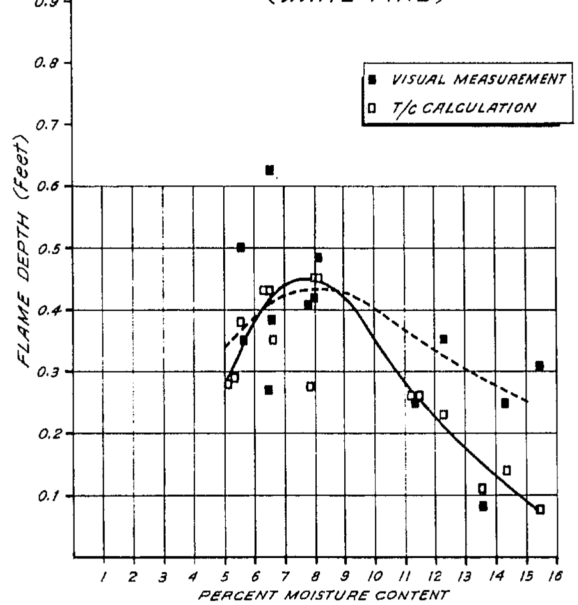
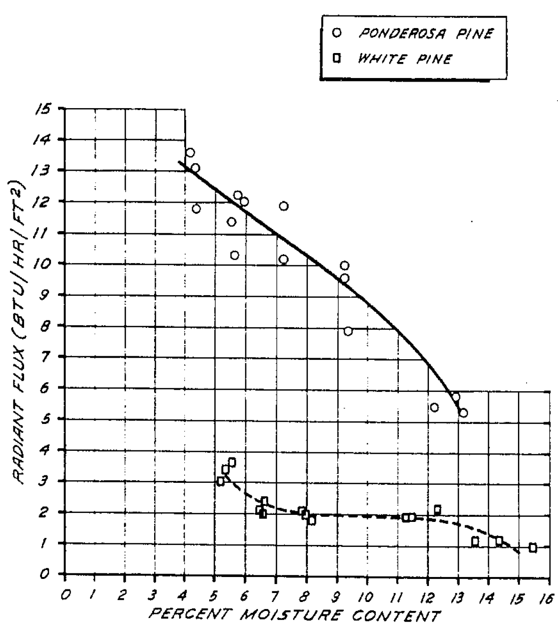


FIG. 8

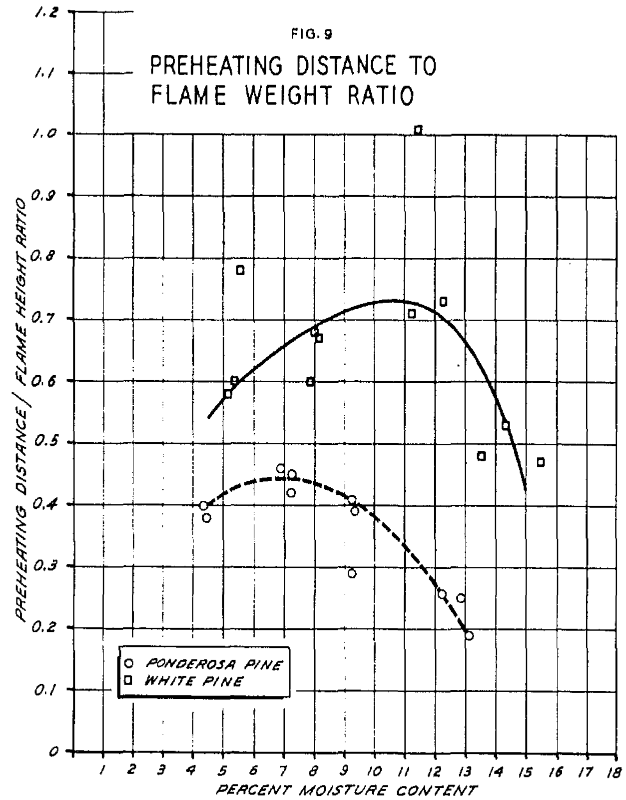
RADIANT FLUX AT 18 FEET VS. MOISTURE CONTENT

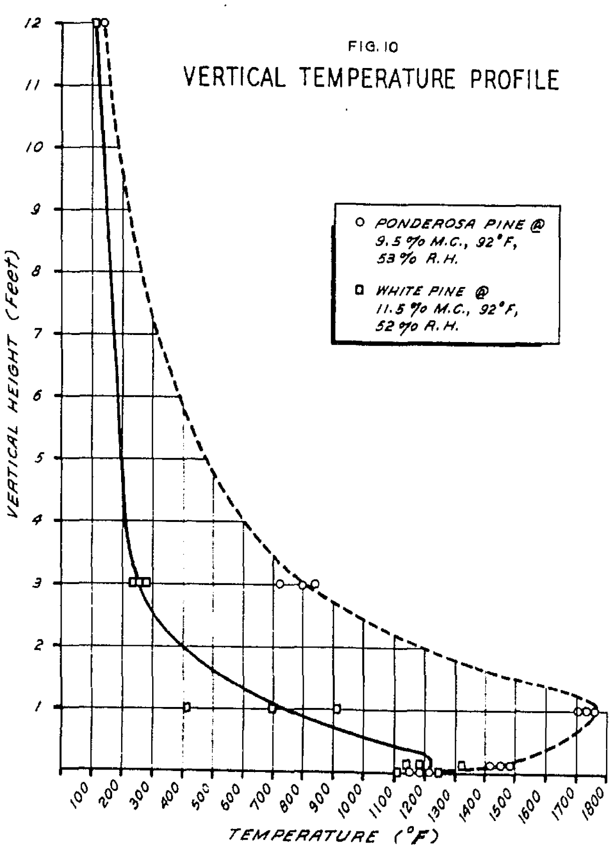


Use of the resident thermocouples made possible an initial study of the effective preheating distance for each type of fire. The continuous traces provided an indication of when the first sensible heating occurred; then, by using the average rate of spread, the distance in front of the flame for effective heating could be calculated. These values were calculated and a ratio of preheating distance to average flame height was determined. Figure 9 shows this ratio plotted against moisture content of the fuel. The distribution of points indicates that the most effective conditions for preheating may not be the driest moisture conditions. This may be due to the types of emitting constituents of the combustion products, absorbing elements between the flame and fuel, and variation of flame depth. The instrumentation used for this initial study was not designed for this purpose, and other means of measuring the radiation preheating effects are being investigated.

FLAME AND CONVECTION TEMPERATURES

Five levels of thermocouple networks were used to measure the vertical temperature gradients in the flame and convection column. The residence time thermocouples measured temperatures at the initial fuel surface height. An array of six thermocouples at $1\frac{1}{4}$ inches above the fuel indicated the temperature and profile of the flame at this height. At the 1- and 3-foot levels, three thermocouples on 3-inch centers provided temperature information. Five thermocouples in parallel at 12 feet above the fuel measured the average temperature at this point. Figure 10 shows the temperature profile of both fuels tested. Even though the rates of spread were approximately the same in the two fuel types, the temperature distribution was considerably different. The reason for this difference is shown by the combustion utilization of available fuel.





The amount of residue remaining after a ponderosa pine fire ranges from 5 to about 20 percent, but the white pine fires left a residue ranging from 60 to 90 percent of the total fuel load. The physical character of each fuel undoubtedly plays a major role through the volume/area ratio, needle length and thickness, needle warp, and compactness of the fuel. Chemical composition may also be important.

Measurements were taken at the $1\frac{1}{4}$-inch height above the fuel bed in an attempt to measure the flame depth. The results of these measurements to date (fig. 11) are compared to the flame depths calculated from the residence thermocouples. These curves show a considerable difference takes place within the first inch of height above the fuel bed. This behavior may influence visual and photographic techniques of determining flame depth.

OTHER MEASUREMENTS

Convective column velocities have been measured by a Kiel probe and an ionization pressure transducer that can measure 0.0002 inch of water. These measurements are only preliminary, and not enough data have been collected and analyzed to be useful.

The temperature profile of the combustion process could be depicted from the traces of the residence thermocouples. Distinctive flame charactertistics are displayed by each type of fuel. Three zones of combustion are displayed: the flame front; the transitive combustion zone; and the residual burning zone. The flame front, as it encompasses the residence thermocouple, generally is the zone of highest temperature. In a fuel bed of ponderosa pine, the more volatile fuel, the flame front is followed by a zone of lower temperature (transitive combustion zone) that shows little variation. This zone, in turn, is

FIG. 11

FLAME DEPTH MEASUREMENTS

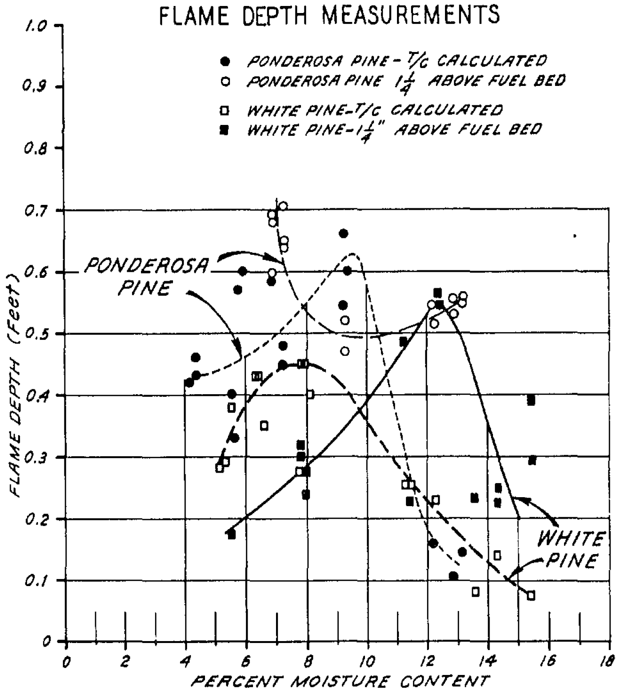
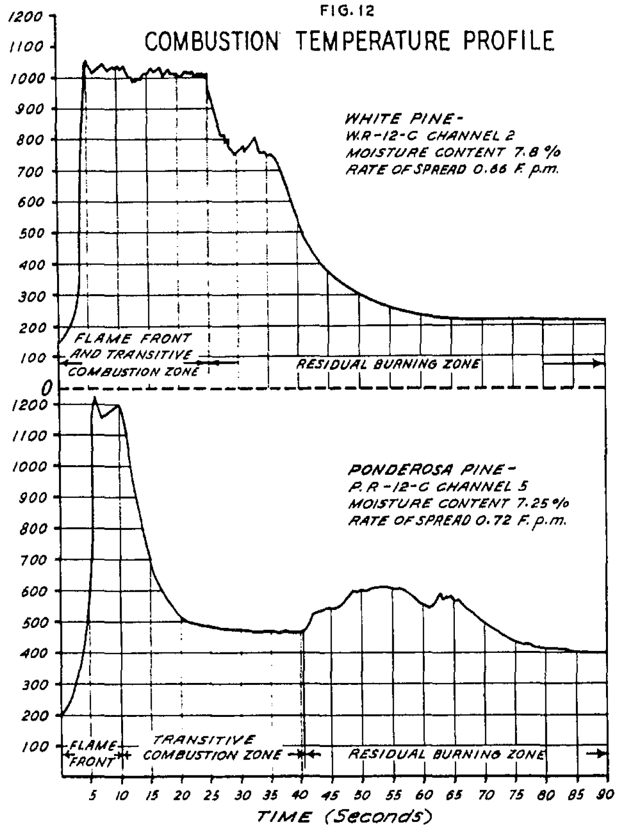


FIG. 12

COMBUSTION TEMPERATURE PROFILE



followed by the residual burning zone, characterized by an increase in temperature and perturbation that builds to a maximum and then declines as the heat generation diminishes within the fuel bed.

The white pine fires exhibit a different profile. The rise in temperature induced by the advancing flame front is sustained but rather erratic; then comes a sharp drop in temperature, followed by slowly diminishing temperatures. In these burnings of white pine needles, the flame front and transitive combustion zone have merged, and the sharp drop in temperature represents passing from the transitive combustion zone to the residual burning zone. The residence time in these studies has been the duration of time the thermocouple was in the flame front and transitive combustion zone. Figure 12 shows the general profile displayed by each type of fuel. Temperatures in the gas evolution zone may vary from 450° to 750° F. in the ponderosa pine fires.

Continued study of the characteristics exhibited by the fuels already tested and of additional fuels, plus study of the influence of wind and slope, should provide information leading to better understanding of characteristics of free burning fire and to more accurate evaluation of fire-danger potentials.

CONCLUSIONS

1. Steady rates of spread are obtained in mat-type beds of light forest fuels.

2. Rate of spread may be nearly identical for different types of forest fuels, but the fire intensity may differ greatly.

3. Rate of spread is a linear function of moisture content between 5- and 15-percent equilibrium moisture content.

4. Residence time and flame depth are not linear functions of moisture content but appear to be complex variables.

5. Stabilized moisture contents for various natural light forest fuels may deviate several percent from the equilibrium moisture content curve for wood at the same conditions.

6. Radiant flux at a point forward of the fire front is nearly linear with moisture content, but a slight rolloff occurs at about 11-percent moisture content.

7. Preheating of the fuel can be observed. Further refinement of instrumentation will make possible a description of this process.

8. Chemical properties and physical characteristics of fuel affect the intensity of the fire but appear to have little effect upon rate of spread.

9. Rate of spread is sensitive to the loading and compactness of the fuel; but by proper procedures, reproducible fuel beds can be made.

10. Application of techniques developed by Project Fire Model studies allows the investigation of fire spread in natural fuels as well as wood cribs.

11. Vertical temperature gradients indicate fire intensity and also indicate the flame boundary temperature to be approximately 700° F.

12. Proper use of thermocouples may enable a detailed analysis of combustion zone characteristics.

PROJECTED STUDIES

The studies of moisture content relations will be continued to a minimum moisture content, expected to be 3 percent. Remaining points to be checked include a rerun at 14-percent relative humidity, 8-percent relative humidity, and 5-percent relative humidity or less. No salt has been found for less than 5-percent relative humidity, but silica gel as a dry desiccant will be used. A method of weighing the fuel bed during the fire is being developed to provide a measure of the combustion rate. This is considered essential to basic understanding of the processes involved.

After we complete the moisture content study, we expect to incorporate wind variations into the tests using the low-speed wind tunnel. Tests will be run at three or more windspeeds between 1 and 5 miles per hour with at least three different moisture content levels.

Experiments with variation of slope will be started after completion of studies of moisture and wind. We shall first run a series under no-wind conditions; later we shall add changes in moisture content and then changes in wind condition.

As these studies progress and we develop an understanding of the phenomena involved, we expect to formulate equations that describe the reactions and interrelations that link fire characteristics to fire propagation.

Table 2.--Summary of test data

Fire identification		Fuel information					Laboratory conditions		Radiant flux B.t.u./hr./ft.^{2}		Flame and convection column temperatures °F									Flame height	Flame depth F_D (ft.)		Residence time t_r (min.)		Rate of spread (ft./min.)	
Fire No.	Run No.	Fuel wt.	M.C. %	Dry wt.	Heat content per lb.	Total B.t.u. content	T_D °F	% R.H.	Max.	Ave.	Fuel level	1½"	4"	1'	2'	3'	4'	8'	12'	Visual[4/] ft.	Visual	$F_D=(R_s)(t_r)$ T/C	Visual	T/C	Fuel T/C	Obs.
pp-1-C[1/]	1	6.00	4.20	5.75	8869	51,000	93	13	15.4	13.6	1162	1645	675	122	1600	495	123	156	144	3.2	0.7[5/]	0.42	0.01[5/]	0.50	0.845	0.857
pp-2-C	1	6.00	4.41	5.73	8869	50,800	92.5	13.5	15.6	11.8	860	----	1046	567	1016	646	327	208	143	3.2	0.7[5/]	0.43	0.01[5/]	0.50	0.860	0.830
pp-3-C	2	6.00	4.38	5.74	8869	50,900	92	12	15.6	13.1	1057	1394	1587	434	249	761	123	208	143	3.8	0.64	0.46	0.77	0.51	0.900	0.893
wp-1-C[2/]	1	6.00	5.16	5.69	8476	48,300	93	14	5.8	3.0	1048	----	1050	122	156	264	101	125	116	0.9	0.4[5/]	0.57	0.66	0.34	0.855	0.830
wp-2-C	2	6.00	5.55	5.67	8476	48,000	92	13	4.2	3.6	1064	1503	1371	122	106	317	95	126	115	1.1	0.50	0.58	0.62	0.40	0.942	0.893
wp-3-C	2	6.00	5.37	5.68	8476	48,100	93	12	3.7	3.4	721	1420	868	151	156	250	93	112	112	1.0	0.35	0.55	0.64	0.34	0.865	0.876
pp-4-C	3	6.625	13.15	5.75	8869	51,000	92	75	6.1	5.3	1020/697[3/]	1417/1217		1801/1350		722/682			133/127	3.2	0.48	0.15	0.93	0.31	0.470	0.461
pp-5-C	4	6.625	12.21	5.82	8869	51,600	91	75	6.6	5.5	911/729	1520/1233		1612/1209		599/543			124/118	3.2	0.36	0.16	0.63	0.32	0.495	0.494
pp-6-C	6	6.625	12.88	5.77	8869	51,200	92	75	7.8	5.8	1025/779	1468/1300		1619/1333		614/553			135/122	3.3	0.06[5/]	0.11	0.35	0.21	0.495	0.493
wp-4-C	4	6.625	14.33	5.73	8476	48,500	91	74	2.4	1.2	968/683	1372/1002		437/405		252/202			106/97	0.75	0.25	0.14	0.77	0.36	0.386	0.365
wp-5-C	5	2.208	17.62	1.82	8476	15,400	92	74	1.1	0.8	553/399	1046/		298/246		160/132			102/100	0.50	0.12					0.421
wp-6-C	5	6.625	13.59	5.72	8476	48,500	92	74	1.9	1.2	985/686	1256/1031		526/424		179/177			105/102	0.79	0.08[5/]	0.11	0.28	0.28	0.405	0.388
wp-7-C	6	6.625	15.47	5.60	8476	47,400	93	73	1.8	1.0	965/671	1336/1070		630/511		260/226			108/105	0.88	0.32	0.07	0.85	0.21	0.344	0.362
pp-7-C	7	6.375	9.26	5.76	8869	51,100	91	52	10.2	9.6	1180/930	1452/1329		1714/1253		798/690			141/128	4.0	0.50	0.66	0.81[6/]	1.1	0.60	0.616
pp-8-C	8	6.375	9.39	5.78	8869	51,300	92	53	9.8	7.9	1150/1034	1419/1331		1733/1380		724/661			141/128	4.0	0.50	0.60	0.81[6/]	0.95	0.63	0.616
pp-9-C	9	6.375	9.26	5.76	8869	51,100	92	53	11.7	10.0	1215/919	1481/1333		1755/1372		839/715			141/132	4.0	0.50	0.55	0.93	0.87	0.625	0.648
wp-8-C	7	6.375	11.48	5.64	8476	47,800	92	52	2.4	1.9	1111/954	1144/782		412/362		239/234			111/103	0.86	0.08[5/]	0.26	0.15[6/]	0.48	0.55	0.525
wp-9-C	8	6.375	11.28	5.66	8476	47,950	92	51	2.6	1.9	1155/1042	1189/815		701/618		259/243			118/105	1.20	0.25	0.26	0.43[6/]	0.48	0.54	0.569
wp-10-C	9	6.375	12.32	5.59	8476	47,300	92	52	2.5	2.2	1250/923	1324/1102		911/655		285/261			114/108	1.17	0.35	0.23	0.85	0.43	0.55	0.584
pp-10-C	10	6.187	6.92	5.76	8869	51,100	92	33	---	---	1042/848	1399/1299		1721/1480		717/501			142/129	3.4	0.83	0.65	0.90	0.73	0.804	0.803
pp-11-C	11	6.187	7.28	5.74	8869	50,900	92	34	13.2	11.9	1259/890	1371/1269		1636/1311		780/660			144/133	4.0	0.73	0.64	1.00	0.58	0.735	0.756
pp-12-C	12	6.187	7.25	5.74	8869	50,900	91	34	12.3	10.2	1221/993	1496/1291		1680/1406		893/708			147/134	3.8	0.78	0.70	1.07	0.65	0.690	0.720
wp-11-C	10	6.187	8.13	5.68	8476	48,100	92	33.5	2.5	1.8	1151/862	1356/1101		764/656		284/227			123/109	1.3	0.48	0.40	0.67	0.60	0.758	0.746
wp-12-C	11	6.187	7.84	5.70	8476	48,500	92	32.5	2.4	2.1	1209/900	1151/939		561/468		528/329			114/106	1.1	0.41	0.31	0.63	0.43	0.585	0.661
wp-13-C	12	6.187	8.00	5.69	8476	48,300	92.5	33	2.7	2.0	999/729	1173/923		814/543		244/192			115/109	1.1	0.42	0.25	0.58	0.64	0.684	0.691
pp-13-C	13	6.00	5.96	5.64	8869	50,000	91	22	14.18	12.04	1189/894	1445/1306		1497/1222		712/456			147/128	3.58	0.579	0.60	0.824	0.720	0.830	0.809
pp-14-C	14	6.00	5.54	5.67	8869	50,300	91.2	22.5	13.08	11.40	1078/901	1603/1339		1515/1146		818/657			140/127	3.17	0.750	0.40	0.803	0.550	0.719	0.723
pp-15-C	15	6.00	5.64	5.66	8869	50,200	92	22.5	11.18	10.32	1135/829	1348/1253		1578/1144		821/605			141/127	3.16	0.750	0.33	0.898	0.500	0.669	0.673
wp-14-C	13	6.00	6.46	5.61	8476	47,510	91.5	21.5	2.62	2.10	1115/988	1259/1072		551/454		241/190			112/107	0.745	0.270	0.43	0.570	0.540	0.804	0.724
wp-15-C	14	6.00	6.53	5.61	8476	47,510	91.5	23.0	2.50	2.00	1142/979	1352/1130		500/478		253/199			115/106	0.980	0.625	0.43	0.470	0.610	0.714	0.687
wp-16-C	15	6.00	6.61	5.60	8476	47,450	92.0	24.5	3.10	2.40	1236/865	1339/1138		771/543		408/357			114/108	0.892	0.383	0.35	0.556	0.460	0.753	0.767
pp-16-C	16	6.00	5.76	5.65	8869	50,110	92	21.5	13.72	12.20	1268/1045	1367/1183		1553/1364		824/597			150/130	3.44	0.650	0.57	0.846	0.730	0.781	0.769

1/ pp = ponderosa pine
2/ wp = white pine
3/ Peak temperature/average maximum: used for all positions above fuel bed.
4/ Visual measurements made by observer at time of fire. Time lapse movies also made but not included at present.
5/ Observations made of narrow flame front preceding transitive combustion zone.
6/ Calculated from observed rate of spread and flame depth.

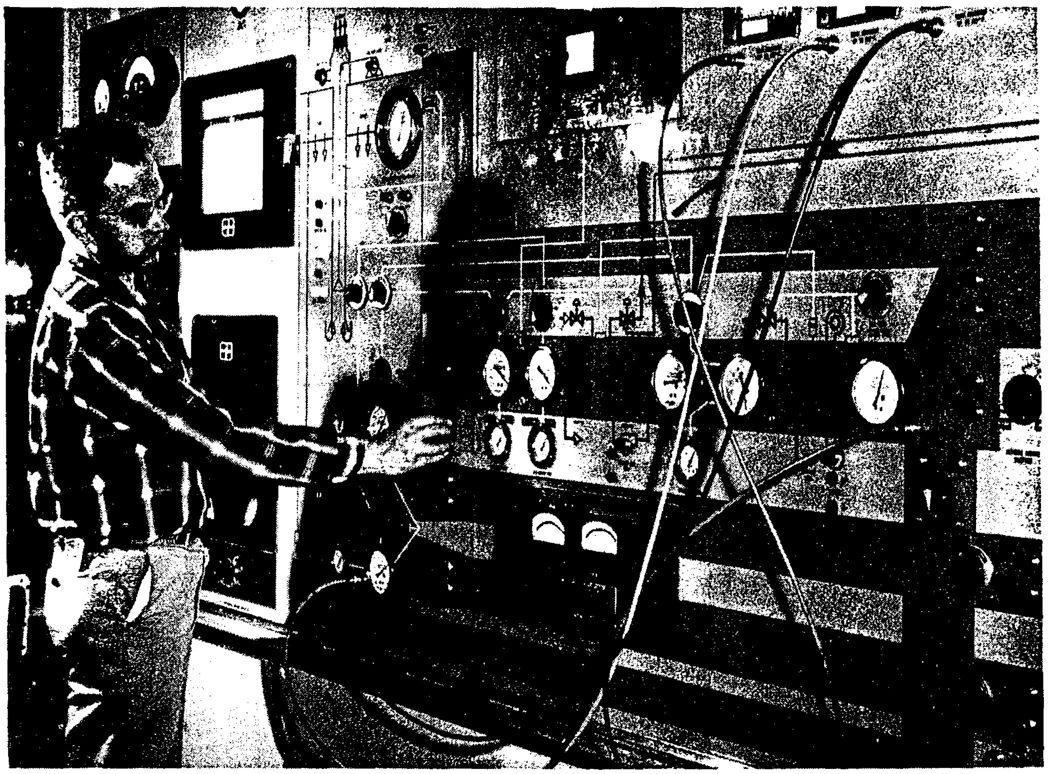


Figure 13.--Control panel for maintaining test conditions in the combustion laboratory and wind tunnels.

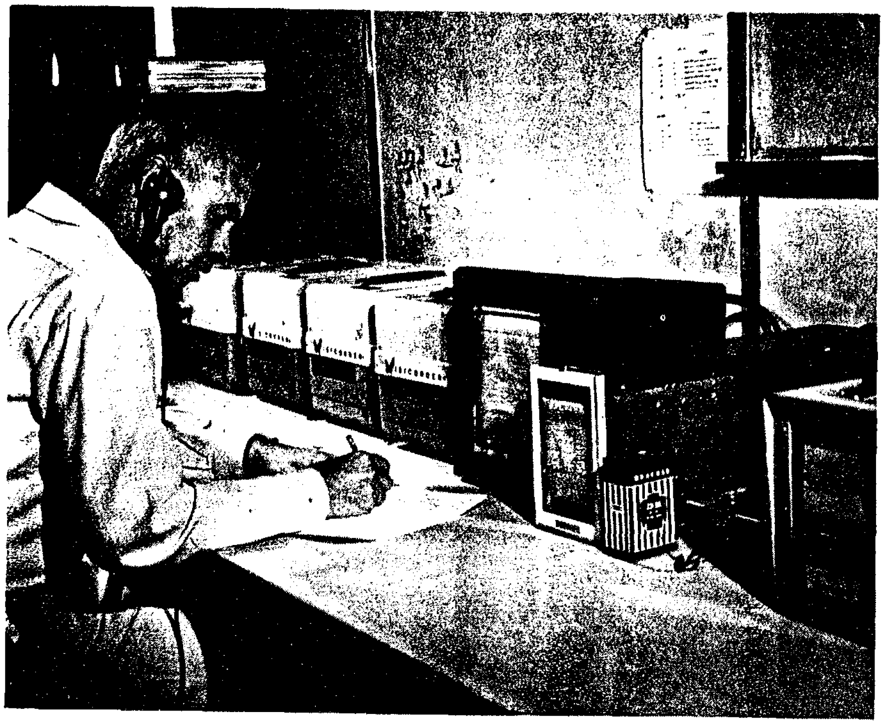


Figure 14.--Recorders used in measuring temperature, air velocity, radiation, and humidity.

Figure 15.--Environmental chambers used to precondition fuels prior to a test series.

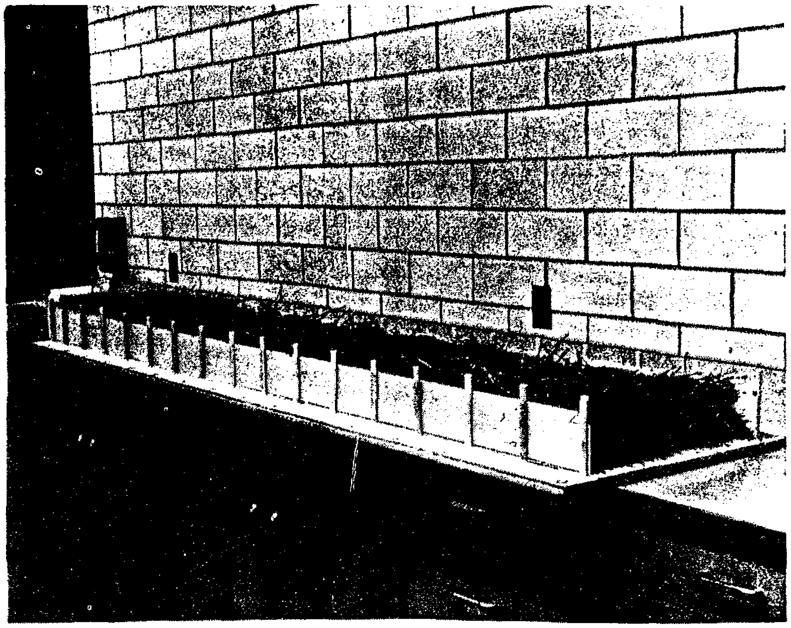


Figure 16.--Prototype fuel bed similar to those used during these studies.

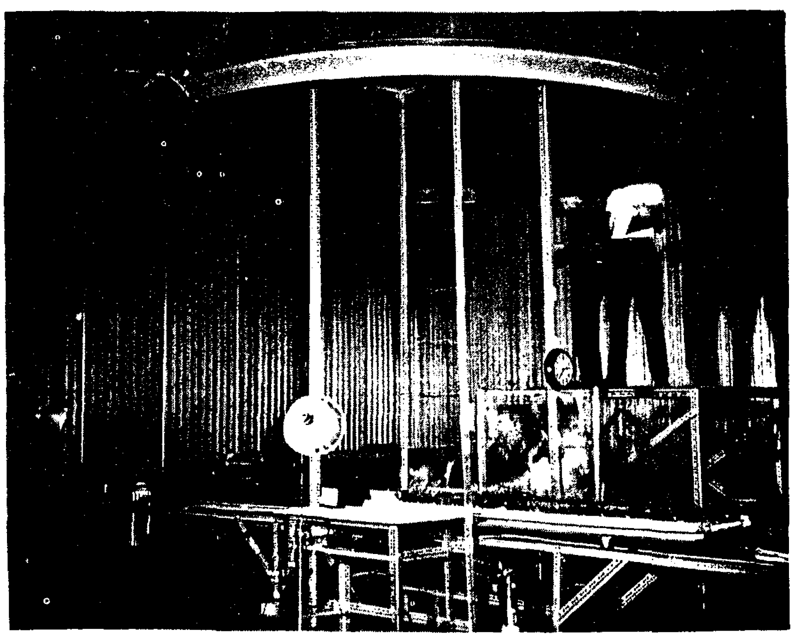


Figure 17.--General view of combustion laboratory during an experimental fire.

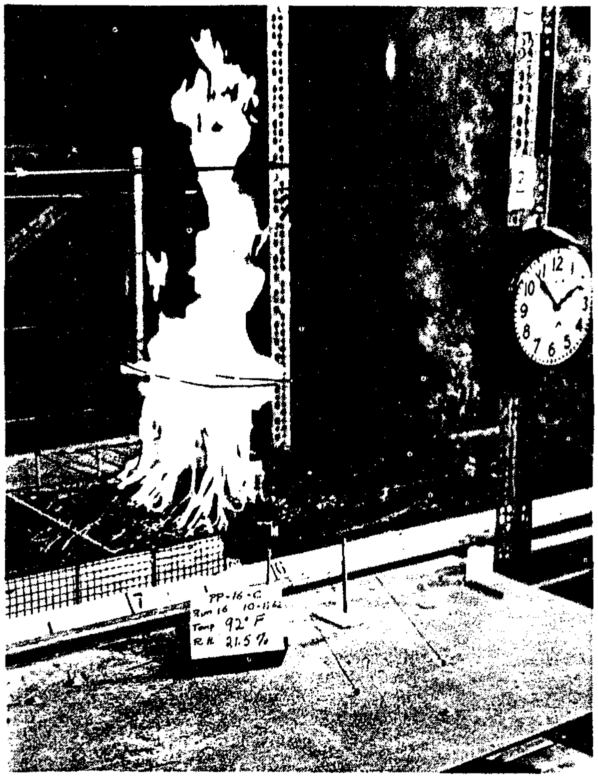


Figure 18.--Rear view of fire front showing dark zone directly behind flame front of ponderosa pine fire.

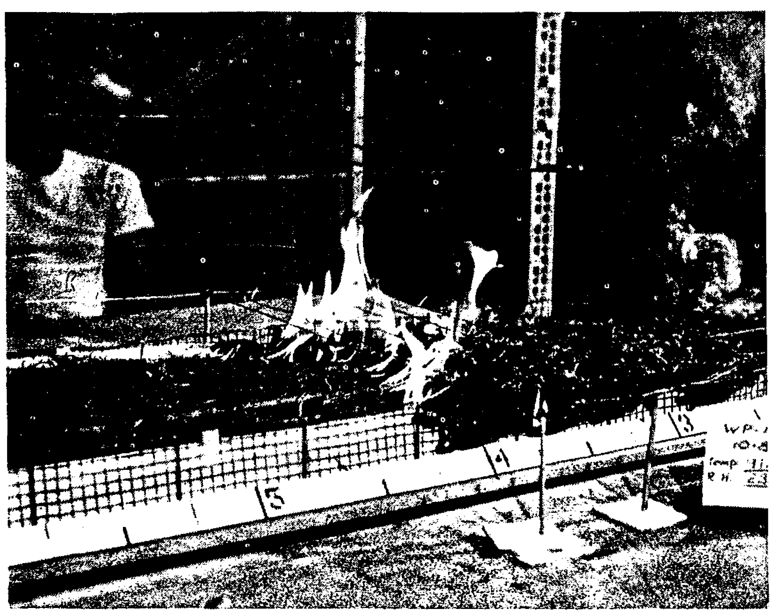
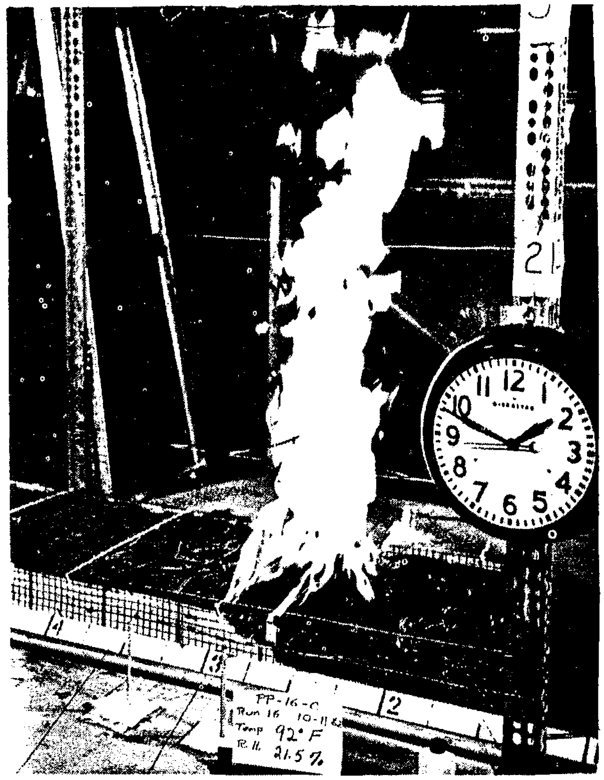


Figure 19.--Rear view of fire front in white pine needles. Comparison with figure 18 shows differences between ponderosa pine and white pine fires.

Figure 20.--Front view of ponderosa pine flame front.



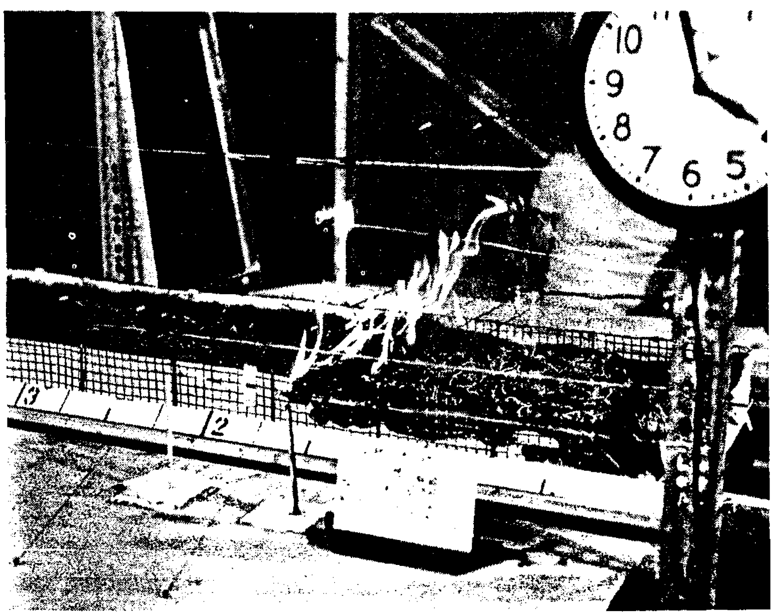


Figure 21.--Front view of white pine flame front.

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