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THE EFFECT OF DENSITY & THERMAL DIFFUSIVITY OF WOOD ON THE RATE OF BURNING OF WOOD CRIBS

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FOREST SERVICE - U. S. DEPARTMENT OF AGRICULTURE

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A program of research on free-burning wood fires is being conducted by the Forest Service[1] to build up experimental data on the properties of such fires, with the ultimate objective of describing the physical phenomena in terms of fundamental laws. Density was the first wood property investigated. This report gives data on the rate of burning of cribs of five species of wood, each of several density classes. Thermal diffusivity values of the wood were also estimated and correlated with the rate of burning.

The Fuel

The species of wood selected for this study were:

white fir	Abies concolor
southern magnolia	Magnolia grandiflora
sugar maple	Acer saccharum
basswood	Tilia americana
longleaf pine	Pinus palustris

These species included conifers (fir and pine) and broadleaved trees (maple, magnolia, and basswood), woods with little oleoresin (maple, magnolia, and white fir), and woods with considerable oil (basswood) and resin (longleaf pine). The wood of all species was a random mixture of heartwood and sapwood. All the lumber had been kiln-dried to a moisture content of 10 to 12 percent.

Each shipment of lumber was sawn into nominal 1.25-cm. square sticks 2.5 to 3.5 meters long. The sticks were culled of defective pieces and air conditioned to uniform moisture content. Each stick was weighed, measured, and marked with the value of its density. The sticks of each species were then segregated into density classes of .01 gm./cc.

1/ PROJECT FIRE MODEL, W. L. Fons, Project Leader, was begun in cooperation with Office of Civil Defense Mobilization and is now being continued with the National Bureau of Standards. The work presented in this paper was done at the Pacific Southwest Forest and Range Experiment Station at Berkeley, California. The project has since been transferred to the Southern Forest Fire Laboratory, Southeastern Forest Experiment Station, Macon, Georgia.

The heat value of the wood, in the form of pelletized sawdust cut from a large number of sticks, was measured in a bomb calorimeter. For white fir and longleaf pine, the heat values of several density classes were measured, but the values were found to bear no relation to the density. The averages of the heat-value measurements are given in table 1.

Table 1.--Heat values and oleoresin contents of the fuels

Wood species	High[1] heat value, measured	Low[2] heat value, estimated	Extractives soluble in benzene
	Cal./gram	Cal./gram	Percent
Basswood	4,634	4,340	3.97
Maple	4,746	4,450	0.25
Magnolia	4,756	4,470	0.29
White fir	4,811	4,520	0.34
Longleaf pine	4,873	4,580	2.23

1/ With the water condensed to liquid.
2/ Assuming all water to be in the form of vapor at 100°C.

The oleoresin content of the wood was determined by Soxhlet extraction of sawdust with benzene. The extraction was performed on five density classes of the longleaf pine, but the resin content was found not to vary regularly with the density of the wood. The results of the extraction measurements are given in table 1.

Crib Construction

The fuel beds for experimental fires were cribs built by laying sticks in tiers, with 3.17 cm. spacing between sticks in each tier, and the direction of the sticks in successive tiers alternating at right angles (fig. 1). At each junction the sticks in successive tiers were bonded by a small drop of resorcinol-formaldehyde resin glue.[2]

The density of the wood for each crib was controlled by selecting the sticks for each crib from a narrow density range. The range for the short (lateral) sticks was often wider than the range for the long (longitudinal) sticks (table 2) because the few longitudinal sticks could not be

2/ This resin carbonizes less readily than wood. Two blocks of wood, glued with resorcinol-formaldehyde resin, become, on firing, two layers of charcoal bonded together by the resin or its carbonized product.

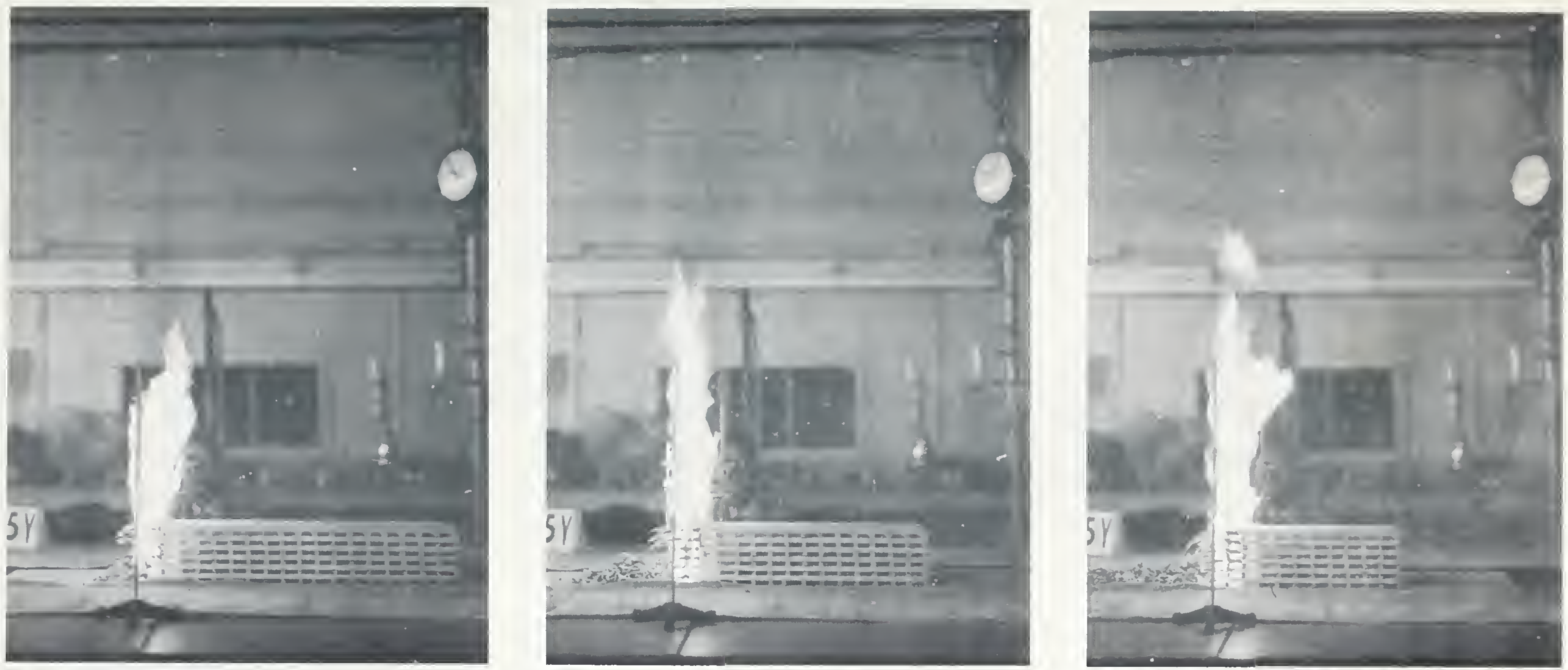

Figure 1.--Flame from a crib fire at different times during the test, illustrating the fixed position of the flame as the crib was moved.

Table 2.--Density of wood in cribs made from sticks of five different species of wood

Fire no. and crib no.	Wood species	Range of density used in cribs[2/]		Average density[2/]
		Long sticks	Short sticks	
		Gm./cc.	Gm./cc.	Gm./cc.
1	White fir	.422-.445	.422-.445	.434
2		.351-.375	.351-.375	.361
3		.486-.570	.486-.570	.511
4		.291-.314	.291-.314	.303
5		.447-.485	.447-.485	.465
6		.366-.412	.262-.570	.393
7		.366-.412	.262-.570	.396
8		.366-.412	.262-.570	.389
9		.366-.412	.262-.570	.390
1M	Magnolia	.432-.451	.418-.464	.445
2M		.465-.475	.446-.493	.472
3M		.503-.513	.484-.531	.511
4M		.532-.567	.513-.578	.548
5M		.446-.465	.408-.465	.453
1B	Basswood	.342-.371	.328-.376	.361
2B		.395-.405	.376-.424	.407
3B		.443-.453	.424-.472	.453
4B		.487-.496	.472-.511	.496
5B		.386-.414	.376-.424	.408
1S	Sugar maple	.687-.696	.677-.706	.687
2S		.725-.734	.715-.744	.724
3S		.772-.782	.753-.801	.771
4S		.725-.734	.715-.744	.724
1Y	Longleaf pine	.505-.513	.495-.522	.515
2Y		.561-.569	.551-578	.569
3Y		.617-.625	.607-.634	.629
4Y		.645-.672	.635-.681	.663
5Y		.729-.756	.719-.765	.752

1/ Each crib had 6 lateral and 6 longitudinal tiers, and was 13.97 cm. high and 23.50 cm. wide. Cribs Nos. 5, 8, and 9 were 121.29 cm. long; and the others were 90.17 cm. long. The nominal stick size was 1.25 cm. square, but the actual dimensions in centimeters were as follows: Cribs nos. 1, 2, 3, 4, 6, 7--1.135 x 1.168; Crib No. 5--1.138 x 1.163; Cribs Nos. 8, 9--1.146 x 1.163; Cribs Nos. 1M to 5M--1.146 x 1.161; Cribs Nos. 1B to 5B--1.146 x 1.158; Cribs Nos. 1S to 4S--1.151 x 1.161; Cribs Nos. 1Y to 5Y--1.153 x 1.181.

2/ Based on bone-dry weight and bone-dry volume as determined by shrinkage values. U.S. Forest Products Laboratory. Wood handbook. Agr. Handb. 72. 528 pp., illus. 1955. (Table 39, pp. 315-318.)

randomized as well as the many lateral sticks that went into each crib. In all cribs the average density of the lateral sticks was nearly the same as the average density of the longitudinal sticks.

After assembly, the cribs were conditioned for several weeks in a cabinet at constant temperature and humidity until they had reached moisture equilibrium as determined by weighing. An attempt was made to equalize all cribs to 10.5 percent moisture content. Sample blocks 2.5 cm. long were cut from sticks of each species of wood and kept in the cabinet with their corresponding crib as moisture samples. These were distilled with xylene (Buck and Hughes, 1939) to indicate the moisture content of each crib at the time each crib was burned (table 3).

Table 3.--Summary of experimental conditions at time of test

Fire no. and crib no.	Wood species	Room temperature 1/ Before fire		Relative humidity 1/ Before fire		Crib weight Air dry		Moisture content
		Before fire	After fire	Before fire	After fire	Air dry	Bone dry	
		°C.	°C.	Pct.	Pct.	Gms.	Gms.	Pct.
1	White fir	18.3	20.8	50.0	49.5	3753.5	3418.2	9.81
2		20.0	22.2	48.0	42.0	3129.0	2870.4	9.01
3		20.0	22.8	54.0	53.0	4384.5	3976.1	10.27
4		21.1	22.8	55.0	53.0	2664.0	2415.0	10.31
5		21.3	24.2	61.0	55.4	5413.5	4904.9	10.37
6		22.5	26.9	59.0	50.5	3410.5	3088.7	10.42
7		21.1	23.1	53.0	49.5	3476.0	3129.8	11.06
8		22.6	26.9	61.5	50.5	4612.0	4159.1	10.89
9		14.2	16.4	63.5	61.0	4623.0	4183.0	10.52
1M	Magnolia	18.1	18.9	68.0	66.0	3923.5	3524.8	11.31
2M		16.1	17.8	73.0	67.5	4164.5	3739.7	11.36
3M		17.2	18.3	63.2	61.0	4507.5	4049.9	11.30
4M		16.2	18.3	73.2	68.0	4834.5	4341.3	11.36
5M		15.7	17.8	78.0	72.0	3981.0	3588.4	10.94
1B	Basswood	16.9	18.2	59.9	52.0	3071.0	2836.2	8.28
2B		16.4	17.2	74.6	71.0	3543.5	3203.6	10.61
3B		17.2	18.4	71.5	69.2	3940.5	3561.6	10.64
4B		15.0	16.1	79.0	73.5	4317.0	3903.3	10.60
5B		16.7	18.2	76.5	70.8	3530.0	3209.1	10.00
1S	Sugar maple	19.9	22.2	52.3	43.6	6069.5	5486.8	10.62
2S		18.4	20.7	75.6	68.8	6378.0	5774.6	10.45
3S		20.7	22.5	68.8	63.0	6802.5	6155.6	10.51
4S		15.6	17.2	78.0	69.5	6344.5	5780.9	9.75
1Y	Longleaf pine	16.8	18.6	73.5	70.5	4574.0	4132.6	10.68
2Y		15.3	16.9	79.0	76.5	5058.0	4569.5	10.69
3Y		18.9	20.6	71.0	61.0	5565.0	5044.4	10.32
4Y		18.1	20.2	68.0	62.0	5893.0	5320.5	10.76
5Y		19.4	20.7	66.5	62.6	6656.0	6030.1	10.38

1/ Taken 4 feet above floor level.

Equipment and Procedure

The tests were made in a laboratory of 40- by 40-foot floor area and 28-foot ceiling. The building is well insulated, and little heat flows to or from the outside through the walls and ceiling. In each of the four walls of the building is a 10-square foot window, covered on the inside with a glass-wool air filter and on the outside with adjustable louvers. The louvers were used to control the incoming air so that the flow measured by vane anemometers was nearly the same through each window.

Combustion gases were expelled from the laboratory by an exhaust system consisting of a hood 11 feet square, a stack 22 inches in diameter, and a motor-driven exhauster. The flow rate up the stack was about 153 cubic meters per minute.

The cribs were burned on a specially built table (fig. 1), which was provided with a chain belt on which a row of concrete slabs were placed as a base for the crib fires. The slabs measured 45.7 cm. wide, 30.5 cm. long, and 7.6 cm. thick and had a density of 1.44 grams per cubic centimeter. The concrete-slab base and chain belt were moved by means of a hand crank and worm-gear drive. The mechanism also drew two heavy asbestos sheets, one on each side of the concrete base, in synchronism with the movement of the base to simulate the relative movement of fire and surroundings in a progressing fire. The chain belt was moved 0.503 centimeters with each revolution of the hand crank.

Test procedures have been described elsewhere in detail (Fons, Bruce, and Pong, 1961). Briefly, the crib to be tested (equalized to approximately 10.5 percent moisture content) was removed from the conditioning cabinet, weighed, placed on the combustion table, and centered on the concrete base. A shallow metal trough containing an asbestos wick was placed under one end of the crib. Ten cubic centimeters of n-hexane was poured into the trough and ignited. The fire gradually spread from the ignited end along the crib, reducing the wood to a residue of charcoal. As the fire spread, the concrete base on which the burning crib rested was moved by the chain belt to feed the unburned portion of the crib into the fire and keep the column of flame stationary in space. A pinhole sight with a vertical rod was employed as the reference in maintaining the constant position of the flame (fig. 1). The time was recorded by the operator of the combustion table every 10 revolutions of the hand crank. Wet and dry bulb temperatures were taken before and after each test (table 3).

Experimental Results

Typical plots of experimental data are shown in figure 2. After the initial period of buildup, the fires came to a steady state and the progression was linear. The rate of fire spread was determined by measuring the slope of the graph formed by plotting distance traveled against time. The rates of spread and the calculated rates of combustion are given in table 4 for the 28 fires reported.

Table 4.--Rate of burning results of cribs of five species of wood varying in density and diffusivity

Fire no.	Wood species	Density	Reciprocal of density	Thermal diffusivity[1]	Rate of-- Spread	Rate of-- Combustion[2]
		Gram/cc.	cc./gram	cm.^{2}/min.	cm./min.	cal./min.
1	White fir	.434	2.30	.112	3.83	658,000
2		.361	2.77	.117	4.85	698,000
3		.511	1.96	.108	3.12	623,000
4		.303	3.30	.122	6.05	732,000
5		.465	2.15	.110	3.48	638,000
6		.393	2.55	.115	4.42	689,000
7		.396	2.53	.114	4.55	714,000
8		.389	2.57	.115	4.52	701,000
9		.390	2.56	.115	4.42	689,000
1M	Magnolia	.445	2.25	.111	3.89	679,000
2M		.472	2.12	.110	3.78	701,000
3M		.511	1.96	.108	3.43	688,000
4M		.548	1.83	.107	2.92	628,000
5M		.453	2.21	.111	3.96	704,000
1B	Basswood	.361	2.77	.117	6.71	916,000
2B		.407	2.46	.113	5.13	792,000
3B		.453	2.21	.111	4.70	806,000
4B		.496	2.02	.109	4.14	779,000
5B		.408	2.45	.114	5.21	804,000
1S	Sugar maple	.687	1.46	.103	2.24	608,000
2S		.724	1.38	.102	2.09	596,000
3S		.771	1.30	.101	1.87	569,000
4S		.724	1.38	.102	2.18	623,000
1Y	Longleaf pine	.515	1.94	.108	2.74	576,000
2Y		.569	1.76	.106	2.36	549,000
3Y		.629	1.59	.105	2.20	565,000
4Y		.663	1.51	.104	1.94	524,000
5Y		.752	1.33	.102	1.70	522,000

1/ Calculated for wood of zero moisture content.

2/ Maximum possible rate of heat release, from equation (6) Q=RHW/L, not the actual rate of heat release during test period.

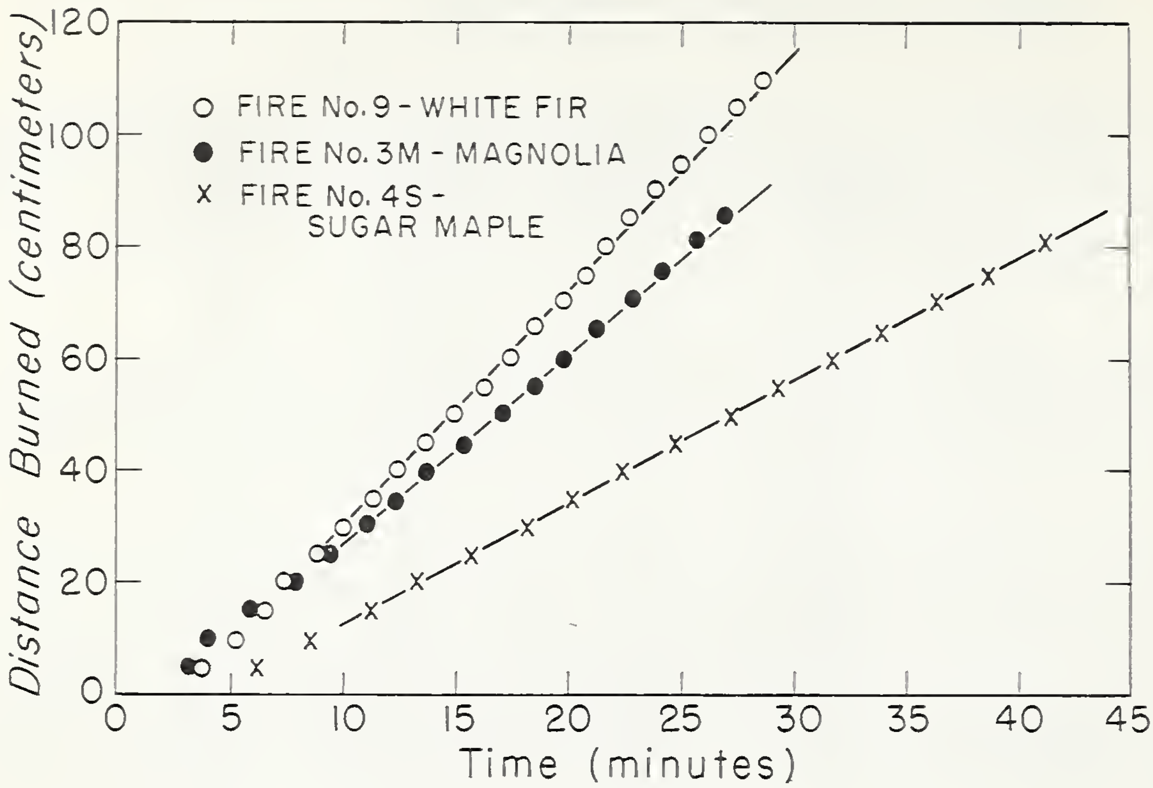

Figure 2.--Typical plots of the rate of spread of fire through wood cribs.

The rate of spread is plotted against density in figure 3A and against the reciprocal of the density in figure 3B. One basswood crib had an unusually low moisture content (see table 3), and, probably for this reason, its rate of spread (6.71 cm. per min.) was abnormally high. The plotted points for this crib are marked by an arrow.

Mathematical Relations

The rate of spread of fire through a wood crib was found to bear a straight line relation to the reciprocal of the density of the wood (fig. 3B) such that,

$$R = \frac{a}{\rho} + b \qquad (1)$$

where

R = rate of fire spread through a wood crib averaging 10.5 percent moisture content (cm./min).

ρ = density of the wood at zero moisture content (gm./cc.).

$\underline{a}$ and $\underline{b}$ = equation constants for the fuel, crib, and atmosphere conditions of the experiments, with different values for each species.

To express the rate of spread in terms of the thermal diffusivity of the wood,

$$\alpha = \frac{k}{\rho C_p} \qquad (2)$$

where

α = thermal diffusivity of the wood at zero moisture content (cm.^{2}/min.).

k = thermal conductivity of the wood at zero moisture content (cal./min. cm.°C.).

ρ = density of the wood at zero moisture content (gm./cc.).

C_p = specific heat of the wood at zero moisture content (cal./gm.°C.).

Combining equations (1) and (2) to eliminate ρ

$$R = \frac{aC_p}{k}\alpha + b \qquad (3)$$

According to MacLean (1941),

$$k = 0.02875\rho + 0.003412 \qquad (4)$$

Combining equations (2), (3), and (4) to eliminate ρ and k

$$R = \frac{aC_p}{0.003412}\alpha + b - 8.426a \qquad (5)$$

The rate of combustion is related to the rate of spread by

$$Q = \frac{W}{L} HR \qquad (6)$$

where

Q = the rate of combustion of total fuel calories (cal./min.).

W = the weight of the crib at zero moisture content (gm.).

L = the length of the crib (cm.).

R = the rate of spread (cm./min.).

H = the low heat value of the wood (cal./gm.).

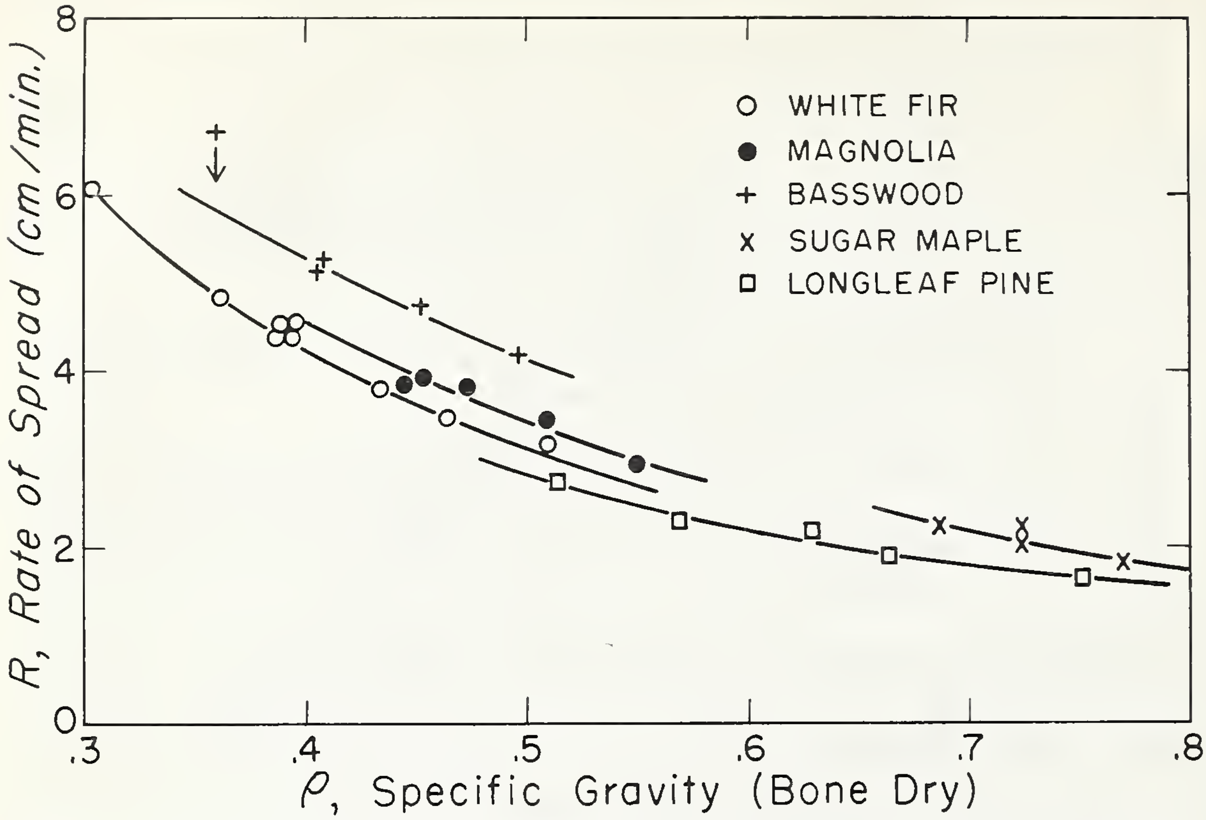

Figure 3A.--Rate of fire spread through cribs of wood (average moisture content, 10.5 percent) of different species and specific gravity.

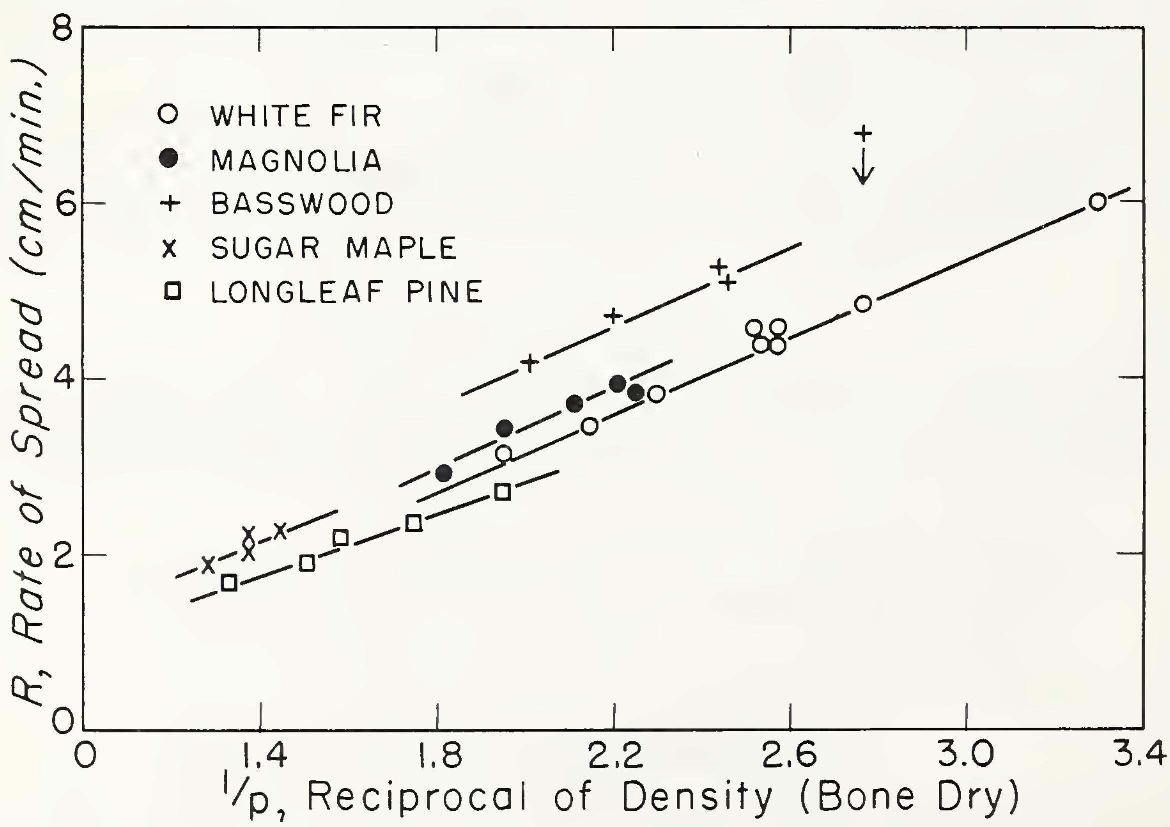

Figure 3B.--Rate of fire spread through wood cribs plotted against the reciprocal of the specific gravity of the wood.

Discussion

The rate of spread of fire through a wood crib decreased in a curvilinear manner as the density of the wood increased (fig. 3A). Plotting rate of spread against the reciprocal of the density (fig. 3B) resulted in a relation that appears to be rectilinear through the range of densities covered by the experiments. However, the fire-test data of the five species did not fall upon one rate of spread-density curve; each species had its own individual graph.

Thermal diffusivity may play a more fundamental role than density in the burning of solid fuel. The diffusivity of the wood in the cribs is not certain because some of the sticks run longitudinally and some run laterally, and the thermal conductivity of wood is not the same across the grain as it is along the grain (MacLean, 1941). However, from the many observations during each of the crib fires, we concluded that for the purpose of calculating diffusivity values the conductivity across the grain is the more important.

In considering thermal diffusivity, due consideration was also given to the specific heat of the wood. Reliable values for this property are lacking for most of the species of wood tested. A specific heat value of 0.327 cal./gm. °C has been determined for sugar maple (Dunlap, 1912). A value of 0.337 is reported for longleaf pine (Dunlap, 1912) but is considered by Dunlap to be less reliable than the average for all woods of 0.327.

Using the across-grain thermal conductivity values calculated by equation (4), an average specific heat value of 0.327 (Dunlap, 1912), and known values of the density, thermal diffusivity values for the wood were calculated. They are presented in table 4.

When rate of spread was plotted against the thermal diffusivity of the wood (fig. 4), linear relations similar to the $R\text{-}1/\rho$ relations in figure 3B resulted. This is expected since k/C_p is constant for a given density. However, when the specific heat value of 0.337 is used in calculating α for longleaf pine, a plot of these values (see fig. 4, dash curve) lies much closer to sugar maple ($C_p = 0.327$) in line with the other species (except basswood). This shift indicates that the correlation between R and α may be better than the correlation between R and $1/\rho$. Substantiation of this relationship would require more reliable values for the specific heat of different species of wood.

Rate-of-combustion plots, involving Q, are not presented in this paper. However, the plots QL/HW versus $1/\rho$ and α are identical to figure 3B and figure 4 respectively. Such identity would be expected from equation (6), which shows that QL/HW equals R.

It is evident from figure 4, that basswood had a higher rate of burning than the other species tested. Some wood property other than thermal diffusivity may play a significant role in the rate of burning of this wood. The basswood had a higher benzene-soluble content (table 1) than the other species, and this fact would indicate that the chemical nature and amount of the extractives in wood may influence appreciably its rate of burning without a corresponding influence on the thermal diffusivity.

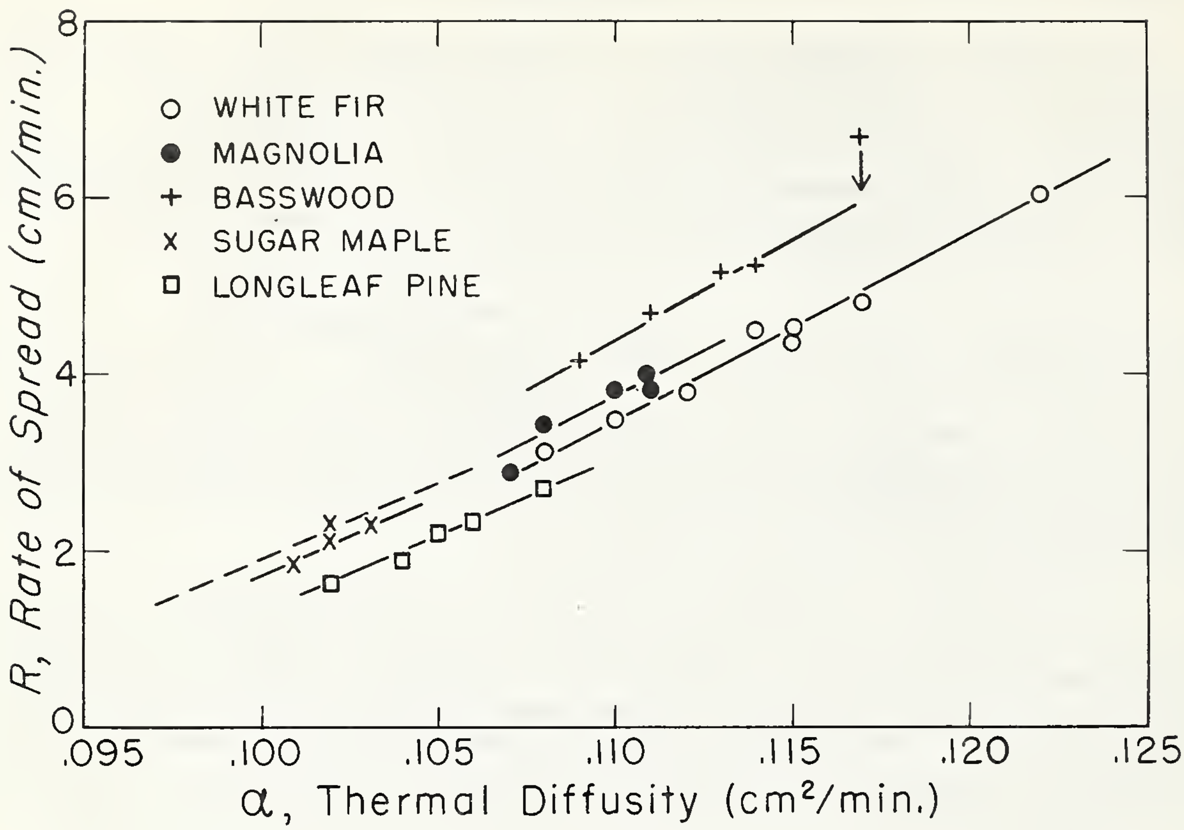

Figure 4.--Rate of fire spread through wood cribs (average moisture content, 10.5 percent) plotted against the thermal diffusivity of the bone-dry wood.

The constants a and b, appearing in equations (1), (3), and (5), are different for the different species. Because cribs in this study were of nearly the same moisture content and of essentially the same construction in width, height, stick size, and spacing, it is not known how a or b may also depend on the moisture content and crib characteristics.

Conclusions

Based on the experimental results, the following conclusions appear to be valid for the type of crib and method of test described in this paper.

1. The rate at which fire moves through a wood crib decreases as the density of the wood increases, and the rate of flame spread is linearly related to the reciprocal of the density.

2. The rate at which flame moves through a wood crib is linearly related to the thermal diffusivity of the wood.

3. Because rate of spread is related to rate of combustion through the relation $R = QL/HW$, rate of combustion plots involving Q in the quantity QL/HW are identical to those obtained for R vs. $1/\rho$ and R vs. α.

4. The rate at which a wood crib burns may be more closely related to the thermal diffusivity than to the density of the wood.

5. Accurate specific heat values of each species of wood tested by this method are needed to correlate the test data with the thermal diffusivity and to substantiate conclusion No. 4.

6. The nature and amount of the extractives in wood may affect the rate at which a wood crib burns without necessarily affecting the density or thermal diffusivity of the wood.

7. The values of $\underline{a}$ and $\underline{b}$ in equation (1) are characteristic for each species, but further work should be done to learn why they vary with species, also how they may vary with moisture content, stick size, spacing, and other crib characteristics.

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