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THERMOPHYSICAL PROPERTIES OF BARK OF SHORTLEAF, LONGLEAF, AND RED PINE

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New Haven: Yale University
1967

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2012

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A number of graduate students assisted with the laboratory work and subsequent analyses. Chief among these were Leonard C. Rolph, Henry F. Barbour, James A. Rydelius, Thomas C. Eidson, and Roy E. Trent. David Bruce and George R. Fahnestock provided technical and editorial assistance during their periods of tenure at the Southern Forest Experiment Station.

We wish to acknowledge the assistance of George M. Furnival in establishing the statistical procedures used to evaluate our experimental data.

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ABSTRACT

THE ROLE of bark in modulating the transfer of heat to the cambium is dependent on its thermal and physical properties. This study evaluates a number of these properties for the bark of three species of pine.

Thermal conductivity was determined experimentally as a function of bark density and moisture content. Results indicate that although thermal conductivity of bark is less than that of wood for particular values of density and moisture content, the differences are not great. However, the thermal conductivity of red pine bark was found to be significantly less than that of shortleaf and longleaf pine bark.

Density and specific heat of the three barks was also measured. Red pine bark was less dense than that of the two southern pines which differed but little from each other. Specific heat was found to be very similar to that of wood.

Thermal diffusivity, the parameter that expresses the rate at which a temperature wave will penetrate bark, was calculated on the basis of measured values of conductivity, density and specific heat. Thermal diffusivity of the bark of the two southern pines was about eleven percent less than wood of the same density and moisture content. Red pine bark showed lower values than the southern pines.

Moisture diffusion through bark was measured to be about one-quarter to one-eighth that of wood of the same density. Equilibrium moisture content of the three barks was higher at low and medium moistures, but appeared to be somewhat lower at the fiber saturation point.

Seasonal distribution of the thermal diffusivity of red pine bark based on measured moisture content showed a variation of only about ten percent from the year's average, with lowest values in the winter.

INTRODUCTION

FOR MORE than 40 years forestry literature has contained reference to the fire resistance of trees, including the role of bark as insulation for the living tissues of the stem. Most published information consists of observations and subjective estimates of relative fire resistance. Only two investigators are known to have measured heat transmission through bark in its natural condition prior to 1963; their work was empirical and yielded only relative transmission rates—actually relative thermal diffusivities—for a few species. During this period most available information on thermal properties of bark was for shredded or granulated material or corkboard. (Spalt and Reifsnyder, 1962).

In 1963, Martin (1963a, 1963b) reported on the thermal conductivities of the bark of 10 species of North American trees and the specific heats for 8 species. He found that the thermal conductivity of bark was essentially isotropic and was about 20 percent less than that of wood having the same density. Average thermal conductivity of shortleaf pine (*Pinus echinata* Mill.) and loblolly pine (*P. taeda* L.) bark having densities of .371 and .380 gm cm^{-3}, respectively, was calculated to be approximately 1.80×10^{-4} cal cm^{-2} sec^{-1} $°C^{-1}$ at 25°C. Specific heat of bark was very close to that of wood, with elevation due to sorbed moisture somewhat less for bark than for wood. Thermal diffusivity was nearly constant at about 13×10^{-4} cm^2 sec^{-1} over wide ranges of density, moisture content, and temperature. Martin suggested that bark could be utilized extensively as an insulation material, whereas now it is largely a waste product.

The present study parallels Martin's work to a considerable extent. It was begun at about the same time but was carried out completely independently. The focus, however, is on the role of bark in protecting trees from forest fire heat rather than on its possible commercial utility. Therefore, considerably more attention is given to the effect of water on heat transmission and on the amount of water likely to be present under natural conditions. The findings differ somewhat from Martin's, especially as regards thermal diffusivity.

The characteristics of bark that influence heat flow and temperature patterns in tree stems can be clarified by reference to Fourier's equation for heat conduction. For a homogeneous, isotropic solid whose thermal properties are independent of temperature, this equation in differential form is

$$\frac{\partial T}{\partial t} = \kappa\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \qquad (1)$$

where T is temperature; t is time; κ is thermal diffusivity or thermometric conductivity; and x, y, and z are orthogonal coordinates. The thermal diffusivity is the quotient of the thermal conductivity and the volumetric heat capacity

$$\kappa = \frac{k}{c\rho} \qquad (2)$$

where c is the heat capacity of the material, and ρ its density. Thermal conductivity is defined as the amount of heat that will flow across a unit area in unit time under steady-state conditions when driven by a unit temperature gradient. In the cgs system, the units of k are cal cm^{-1} sec^{-1} deg^{-1}. Since heat capacity is expressed in cal gm^{-1} and density in gm cm^{-3}, thermal diffusivity is expressed in $cm^2\,sec^{-1}$.

In general, thermal conductivity and heat capacity are functions of temperature. For many substances, however, the temperature dependence can be neglected if the temperature range is small. In studying the penetration of a lethal temperature wave of 65°C into tree bark, thermal conductivity and heat capacity may thus be considered invariant with temperature, at least for a first approximation.

Over the years, much effort has been expended in developing solutions of equation (1) that are applicable to practical problems in heat-conduction. For example, Carslaw and Jaeger (1959) present hundreds of solutions for various physical and thermal conditions. Typical of these, and of interest in the present context of heat flow in tree bark, is a solution for heat flow in a semi-infinite cylinder: one that extends to infinity in both directions along the axis, with axial homogeneity and no variation of surface properties in the axial direction. In cylindrical coordinates, Fourier's equation becomes

$$\frac{\partial T}{\partial t} = \kappa \left(\frac{\partial T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} \right) \qquad (3)$$

where r is the radial coordinate and θ is the angular coordinate. A solution for a cylinder with a uniform initial temperature T_i, and with the surface temperature rapidly raised to and maintained at T_s independently of angular position, is given by

$$T = T_s - \frac{2(T_s - T_i)}{a} \cdot \sum_{n=1}^{\infty} \left[\left(e^{-\kappa \alpha_n^2 t} \right) \left(\frac{J_0(r\alpha_n)}{\alpha_n J_1(a\alpha_n)} \right) \right] \qquad (4)$$

where a is the radius of the cylinder and α_n is the nth positive root of the Bessel function, J_0. This equation approximates the case in which a tree is rapidly enveloped by flame, and the bark surface is heated quickly to the temperature of the flame.

For a particular cylinder of radius a the temperature-time distribution at any point, r (say, the cambium), is a function only of the thermal diffusivity, and, therefore, of its constituent properties: thermal conductivity, heat capacity, and density. The research reported herein had as its objective the determination of these three properties for conifer bark of three species. Because of the influence of moisture on thermal conductivity and heat capacity, several studies of moisture content were also made.

STUDY MATERIALS

THE BARKS of longleaf pine *(Pinus palustris* Mill.) and shortleaf pine *(P. echinata* Mill.) were studied in order to compare thermal properties of the superficially similar barks of two species. The bark of red pine *(P. resinosa* Ait.) grown in plantation near New Haven was also studied because of its higher density and different general characteristics from the southern species. Red pine is less fire resistant than either of the southern pines studied.

Samples of shortleaf and longleaf bark approximately 6 inches high by 4 inches wide were cut. The shortleaf pines were 16 inches d.b.h. and 65-75 years old. They grew near each other on a portion of the Alexander State Forest, Woodworth, Louisiana, in an area that had not burned for a long time, perhaps 25 years. Consequently, bark thickness was probably near the maximum attained by mature shortleaf. The samples were taken near the ground on live, standing trees.

Similar samples were cut from longleaf pines that were 80- to Ioo-year-old residuals growing near Gardner, Louisiana. Diameters were 16 to 20 inches. Although heavily burned·in the past, the area had had only light fires in recent years and had not burned at all for 5 years. The bark samples were from recently cut butt logs.

Red pine bark samples were obtained from a 40-year-old plantation near New Haven that had been completely protected from fire. The trees ranged from 8-12 inches d.b.h.

THERMAL CONDUCTIVITY

THE THERMAL conductivity of a porous hygroscopic material such as bark is a function of its moisture content. No fully satisfactory method of making measurements on moist samples has been developed, but a method involving transient heating of a line source offers some advantages (Joy, 1957). A device utilizing this method was developed by D'Eustachio and Schreiner (1952) and is commercially available. We used this device, described below, in our determinations.

If a line infinitely long and embedded in physically and thermally uniform material is the source of a quantity of heat generated at constant rate starting at a time t_0, then the temperature, T, at any subsequent time, t, can be shown to be

$$T - T_0 = \frac{Q}{4\pi k} \ln(t - t_0) \tag{5}$$

where Q is the heating rate per unit length of line source, and k is the thermal conductivity of the material surrounding the line source. The slope of the curve of the logarithm of time versus temperature will be a straight line and will uniquely determine k.

The line source can be approximated by small cylindrical probe, 0.02 inch in diameter, containing a heater and thermocouple. Since energy is supplied to the probe by passing an electrical current through a resistance wire, the equation for thermal conductivity is

$$k = C\, I^2R \frac{\ln \Delta t}{\Delta T} \tag{6}$$

where C is a constant; I is the current through R, the heater resistance per unit length of probe; and the last quantity is the slope of the line.

The probe was inserted in 4-inch long holes drilled parallel to the vertical axis of the sample (Figure 1). Drill bits were manufactured from piano wire 0.02 inch in diameter, flattened and pointed at one end, and then annealed by heating and plunging into water. A small hand drill was used to drive the bit, which was guided into the end of the bark piece by a jig.

Because the probe was fragile and a snug fit was required to reduce errors resulting from poor thermal contact with the specimen, a dummy probe was first inserted. If it went in with reasonable ease, it was withdrawn and the measurement probe inserted (Figure 1).

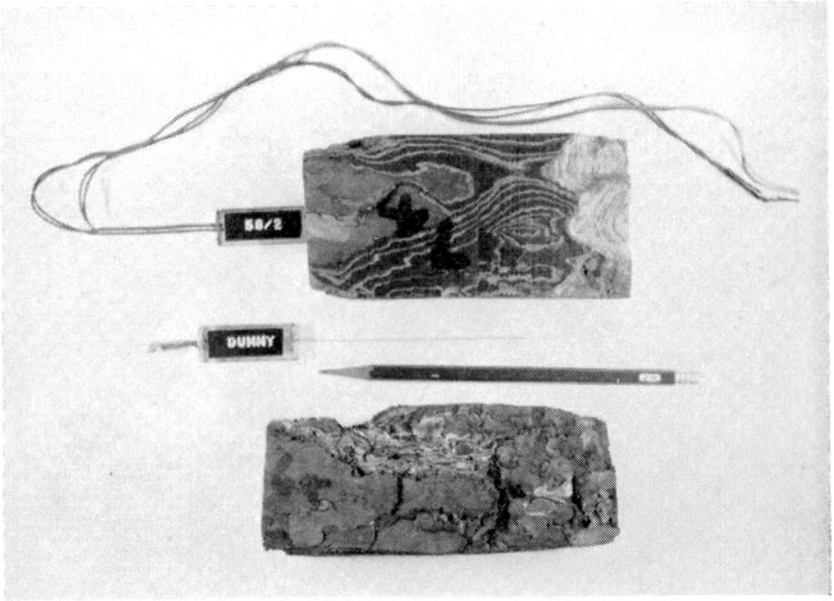

FIGURE 1. Pieces of bark with thermal conductivity probe inserted in top piece. Dummy probe also shown.

The sample and probe assembly were placed in a heat sink, a box made of ½-inch aluminum, and the entire unit placed in an insulated stainless steel box which, with the recording equipment, was kept in a controlled-environment room where humidity could be held at a level appropriate to the equilibrium moisture content of the bark sample being studied. The reference junction of the probe thermocouple was kept in a quart vacuum flask of water in the same insulated box. Thus, after sufficient time, the reference and measuring junctions were at the same temperature. Such extreme precautions were necessary because of the extremely small temperature differences being measured. Normally, the total rise in temperature of the probe during a ten-minute observation was less than one Celsius degree.

Temperature fluctuations in the controlled-temperature room caused occasional difficulties in maintaining constant probe and reference junction temperature immediately prior to the test. Some of the difficulty was due to the different thermal response of the probe in the bark and the reference junction in the vacuum flask. These two thermal systems had different lags and so responded differently to a fluctuating temperature on their surfaces.

Output of the probe thermocouple was fed to a D.C. amplifier and thence to a recording potentiometer. Heater current was monitored by a recording milliammeter. Variation in heater current was held to one percent or less during a test.

Preliminary tests indicated that heater currents of about five milliamperes would produce temperature rises on the order of one Celsius degree in ten minutes. All tests were, therefore, run for ten minutes. Figure 2 is a reproduction of the two chart records for one of the tests.

The thermocouple output was read for each minute from one to ten, plotted on semi-log paper, and checked visually for marked deviations from a straight line. A straight line was then fitted by regression analysis. Figure 3 shows a plot of the data from Figure 2 together with the line of best fit.

Thermal conductivity determinations were made on three bark samples from four trees each of red pine, longleaf pine, and shortleaf pine. Each sample was conditioned to equilibrium moisture contents corresponding to 80%, 40% and 0% relative humidity. The lowest moisture content was produced by drying the samples over silica gel at 70°C until no further weight loss was measured. (Oven-drying at 105°C caused distillation of volatiles and a continuous weight loss.) Three determinations were planned for each combination of species, tree sample, and moisture content-a total of 324 separate determinations. Inasmuch as there was no change in experimental conditions between any of the three repeated determinations, the values were averaged. Because some specimens broke during the testing, only 294 determinations were made, yielding 98 average values. Of these, 36 were for red pine, 32 for shortleaf and 30 for longleaf (Table I).

Most tests, but not all, were run at a sample temperature of *720P* (22°C). We corrected all thermal conductivity determinations to 20°C by means of Kollman's (1951) curve for wood. Although we do not know how accurate this procedure is for bark, the maximum correction was 5%. Certainly the correction removed some of the error due to the temperature differences.

Bark, like wood, swells as it absorbs moisture. Therefore, moist bark has a lower density than oven-dry bark. We corrected for this density variation by assuming that bark had a moisture coefficient of expansion equal to that of wood of the same species. Corrections, based on data in the *Wood Handbook* (U.S. Forest Products Laboratory, 1955), were (0.383 m) for red pine and (0.4°7 m) for shortleaf and longleaf pine, where m is the moisture content of the bark expressed as a fraction of the dry weight.

Moisture contents based on density of oven-dry bark were also corrected for moisture-induced density changes in order that thermal conductivity could be expressed as a function of the actual bark density and water vapor density existing at the time of each test.

Thermal conductivity of a complex mixture of bark substance, water vapor, and air is not a simple average of the conductivities of the constituents weighted by their relative proportions in a particular sample. Although the proper weighting is a function of the arrangement and shape of the constituents (see, for example, van Wijk, 1963), a weighting on the basis of relative proportions can be used as a first approximation. This suggests that linear multiple regression of thermal conductivity on density of swollen (wet) bark and water vapor density would be a suitable model for statistical analysis. When bark density and water vapor density are zero, the regression plane should pass through the value of the thermal conductivity of dry air. As a check of this hypothesis, linear multiple regressions with no intercept restriction can be compared with the model.

Regressions were calculated for the three species with and without the intercept restriction by the regression routine of Frampton and others (1963) at the Yale Computer Center. Since the calculated regression coefficients for shortlea£ and longleaf pine bark were not significantly different from each other, the data were pooled and a combined regression calculated. Red pine was significantly different from the two southern pines. The equations for the two groups with the intercept

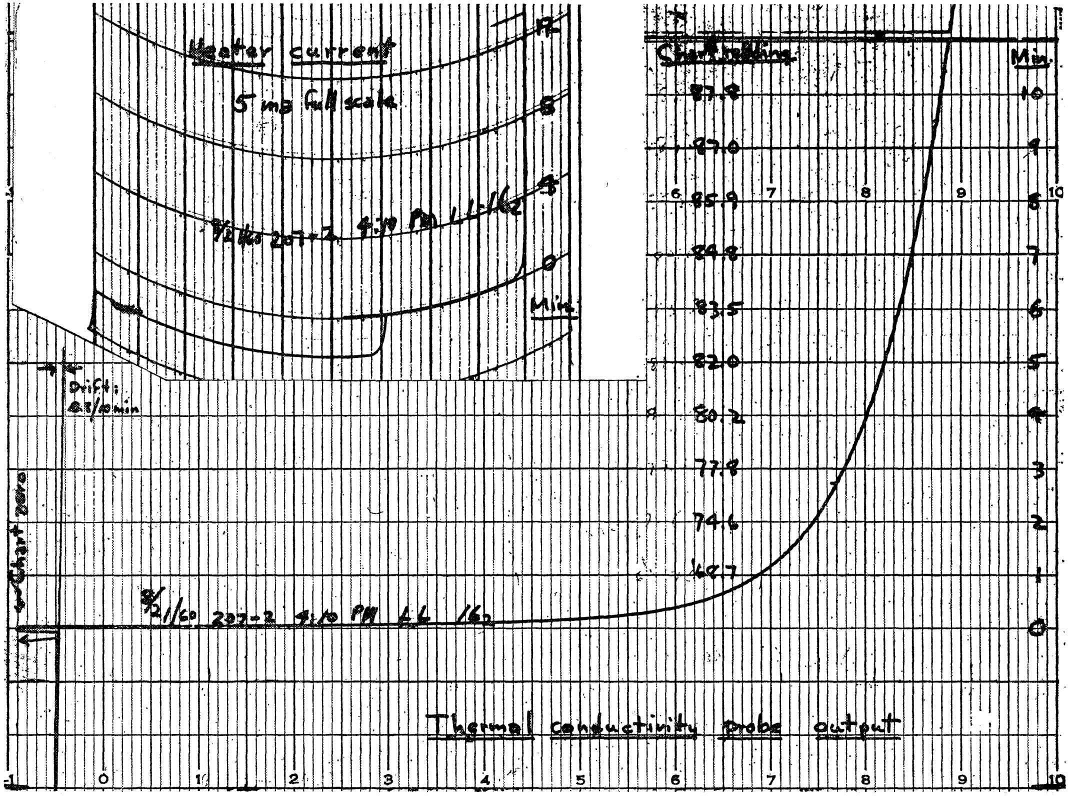

FIGURE 2. Chart records for run 207–2. Full scale for probe output is 100 microvolts, corresponding to approximately 3 Fahrenheit degrees.

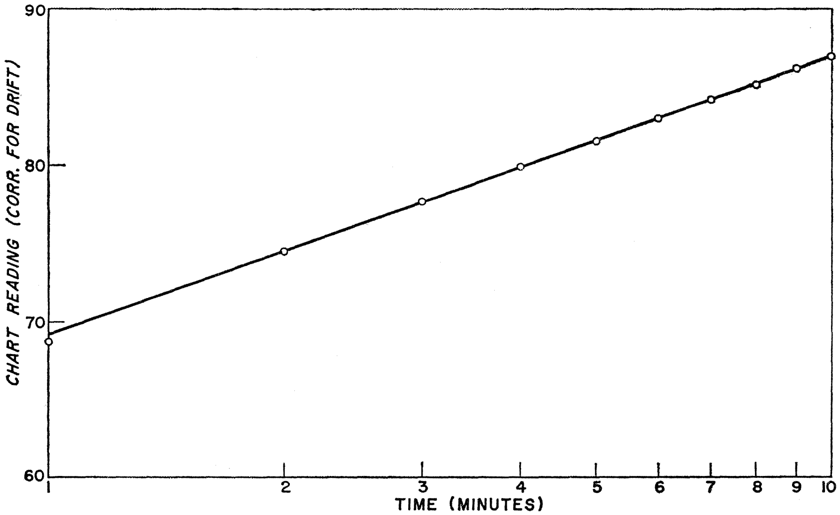

FIGURE 3. Data from run 207–2, plotted on semi-log paper, with regression line.

restriction (i.e., the regression planes passing through the value of thermal conductivity of air at the origin), are:

$$\text{RP: } k = 0.614 + 2.617\,\rho(m) + 2.818\,\rho_m \qquad (7)$$
$$\text{LL} + \text{SL: } k = 0.614 + 3.394\,\rho(m) + 4.927\,\rho_m \qquad (8)$$

where k is in cal $\text{cm}^{-1}\ \text{sec}^{-1}\ \text{deg}^{-1} \times 10^4$, $\rho(m)$ is the swollen (wet) density in gm cm^{-3} and ρ_m is the moisture density in gm cm^{-3}.

Thus, the thermal conductivity is correlated positively with both bark density and moisture content, with red pine apparently less sensitive to both of these effects as compared with longleaf and shortleaf bark.

If current moisture content, m, is expressed as a fraction of oven-dry weight, and the bark density is that of oven-dry bark (ρ_d) the equations become

$$\text{RP: } k = 0.614 + (1 - 0.383m)\,(2.617 + 2.818m)\,\rho_d \qquad (9)$$
$$\text{LL} + \text{SL: } k = 0.614 + (1 - 0.407m)\,(3.394 + 4.927m)\,\rho_d \qquad (10)$$

If the regressions are run so that the regression plane intercepts the Y–axis where it will, the equations take the form

$$\text{RP: } k = 1.113 + 1.213\,\rho(m) + 2.152\,\rho_m \qquad (11)$$
$$\text{LL} + \text{SL: } k = 0.717 + 4.234\,\rho(m) + 5.393\,\rho_m \qquad (12)$$

TABLE I. MEASURED VALUES OF THERMAL CONDUCTIVITY

Tree Number	*Sample Number*	*Dry Density gm cm^{-3}*	*Moisture Content %*	*Temp. of Test °C*	*Thermal Conductivity* *1* × 10^{-4} cal cm^{-1} sec^{-1} deg^{-1}	*2*	*3*	*Ave.*
				Red Pine				
1	2	.424	17.63	22	1.826	1.850	1.850	1.842
			10.53	22	1.809	1.816	1.802	1.809
			.14	22	1.754	1.757	1.740	1.750
1	3	.366	18.78	22	1.592	1.609	1.644	1.615
			9.52	22	1.516	1.540	1.547	1.534
			.14	22	1.716	1.623	1.633	1.657
1	4	.374	17.75	22	1.737	1.723	1.716	1.725
			10.14	22	1.771	1.733	1.737	1.747
			.33	22	1.533	1.526	1.564	1.541
2	1	.387	17.48	22	1.936	1.912	1.916	1.921
			9.31	22	1.664	1.657	1.647	1.656
			.69	22	1.785	1.799	1.726	1.770
2	2	.395	17.35	22	2.116	2.105	2.071	2.097
			9.50	22	1.516	1.516	1.516	1.516
			.96	22	1.750	1.723	1.730	1.734
2	3	.415	16.74	22	1.733	1.719	1.757	1.736
			9.55	22	1.433	1.433	1.313	1.393
			.38	22	1.568	1.630	1.668	1.622
3	2	.326	21.62	22	1.647	1.664	1.699	1.670
			9.23	22	1.557	1.540	1.561	1.553
			.52	22	1.554	1.633	1.630	1.605
3	4	.340	16.54	22	1.726	1.743	1.716	1.728
			8.73	22	1.461	1.492	1.464	1.472
			.71	22	1.730	1.706	1.685	1.707
3	5	.313	17.93	22	1.626	1.633	1.564	1.608
			9.17	22	1.712	1.688	1.692	1.697
			.31	22	1.644	—	—	1.644
4	1	.358	19.26	22	1.571	1.564	1.588	1.574
			9.99	22	1.482	1.468	1.488	1.479
			.53	22	1.623	1.606	1.564	1.597
4	2	.333	19.60	22	1.905	1.912	1.909	1.909
			9.63	22	1.278	1.358	1.392	1.342
			.82	22	1.568	1.595	1.595	1.586
4	4	.348	19.69	22	1.557	1.533	1.554	1.548
			9.61	22	1.547	1.561	1.540	1.549
			.81	22	1.716	1.650	1.830	1.732

Table 1 (continued)

Tree Number	*Sample Number*	*Dry Density* *gm cm^{-3}*	*Moisture Content* %	*Temp. of Test* °*C*	*Thermal Conductivity*			
					1	*2*	*3*	*Ave.*
					× *10^{-4} cal cm^{-1} sec^{-1} deg^{-1}*			
				Shortleaf Pine				
7	1	.461	19.76	22	2.622	2.615	2.564	2.600
			10.02	22	2.519	2.495	2.539	2.518
			.09	22	2.350	2.312	2.374	2.345
7	2	.492	19.68	22	2.701	2.639	2.674	2.671
			9.88	22	2.522	2.522	2.536	2.527
			—		—	—	—	—
7	3	.471	19.11	22	2.529	2.495	2.543	2.522
			10.25	22	2.381	2.408	2.398	2.396
			.30	22	2.229	2.246	2.143	2.206
13	1	.637	16.18	22	3.321	3.339	3.287	3.316
			8.72	22	3.222	3.166	3.198	3.195
			—					
13	2	.610	22.45	22	3.484	3.556	3.544	3.514
			9.27	22	3.173	3.077	3.094	3.115
			.26	22	2.887	2.870	3.018	2.925
13	2	.579	19.34	22	2.639	2.698	2.670	2.669
			9.34	22	2.632	2.594	2.680	2.635
			—					
14	1	.392	19.50	22	2.019	2.026	1.981	2.008
			9.96	22	1.957	1.892	1.902	1.917
			—					
14	2	.449	19.66	22	2.408	1.402	2.367	2.059
			10.09	22	2.278	2.281	2.278	2.279
			.16	22				
14	3	.392	20.24	22	2.288	2.116	2.102	2.168
			10.47	22	2.060	2.074	2.060	2.064
			.52	22	2.040	2.085	2.057	2.060
15	1	.443	19.27	22	2.284	2.164	2.191	2.213
			8.95	22	2.160	2.150	2.143	2.154
			—					
15	2	.477	19.39	22	2.805	2.760	2.780	2.781
			9.07	22	2.322	2.295	2.295	2.304
			.28	22	2.095	2.036	2.126	2.085
15	3	.565	21.54	22	3.129	3.094	3.091	3.104
			8.88	22	2.756	2.829	2.829	2.804
			0.28	22	2.646	2.829	2.643	2.706

Table 1 (continued)

Tree Number	Sample Number	Dry Density gm cm^{-3}	Moisture Content %	Temp. of Test °C	Thermal Conductivity			
					1	2	3	Ave.
					× 10^{-4} cal cm^{-1} sec^{-1} deg^{-1}			
				Longleaf Pine				
6	1	.597	18.52	22	3.056	3.032	3.015	3.034
			9.20	22	2.922	2.887	2.812	2.873
			4.51	29.4	2.464	2.505	2.622	2.530
6	2	.510	20.24	22	2.770	2.929	2.787	2.828
			9.27	22	2.684	2.670	2.715	2.689
			4.28	29.4	2.453	2.378	—	2.415
6	3	.542	17.78	22	2.901	2.925	2.939	2.921
			9.16	22	2.770	2.791	2.822	2.794
			—					
12	1	.534	17.74	22	2.701	2.708	2.743	2.717
			8.92	22	2.732	2.632	2.739	2.701
			3.39	29.4	2.619	2.584	2.567	2.590
12	2	.519	19.71	22	2.836	2.750	2.781	2.789
			10.12	22	2.612	2.698	2.708	2.672
			—					
12	3	.468	18.51	22	2.591	2.612	2.570	2.591
			9.88	22	2.574	2.536	2.670	2.593
			3.59	29.4	2.453	2.419	2.388	2.420
16	1	.480	22.04	22	2.522	2.667	2.622	2.603
			10.26	22	2.457	2.515	2.477	2.483
			—					
16	2	.467	21.73	22	2.412	2.322	2.388	2.374
			16.42	22	2.219	2.326	2.302	2.282
			—					
16	4	.452	19.79	22	2.508	2.515	2.484	2.502
			9.78	22	2.392	2.329	2.357	2.359
			2.91	29.4	2.253	2.240	2.246	2.246
17	1	.540	19.03	22	2.550	2.719	2.715	2.661
			9.76	22	2.646	2.608	2.650	2.634
			—					
17	2	.552	18.90	22	2.446	2.484	2.429	2.453
			9.21	22	2.364	2.378	2.371	2.371
			—					
17	3	.576	19.32	22	2.998	3.029	2.980	3.001
			9.33	22	3.122	3.074	3.129	3.108
			3.80	29.4	2.887	2.915	2.884	2.895

An analysis of the variance due to shift in origin shows that both shifts are significant, the red pine at the 5 percent level and the pooled longleaf—shortleaf at the 1 percent level. Thus, there is little question but that the unrestrained regressions fit the data better.

These regressions can be compared with those obtained by Martin (1963a) for bark of a group of species that included shortleaf pine as well as other pines and hardwoods. Martin's equation for thermal conductivity in comparable units (but at 25°C) is,

$$k = -0.268 + 5.329\,\rho(m) + 10.266\,\rho_m \qquad (13)$$

It can best be compared, perhaps, with our equation for all three species combined,

$$k = -0.232 + 4.964\,\rho(m) + 5.558\,\rho_m \qquad (14)$$

The similarity of the two equations is marked. The moisture density coefficients differ, but they have less effect on thermal conductivity than does bark density. For example, for a bark-substance of density 0.5 gm cm^{-3} and a moisture density of 0.05 gm cm^{-3} (corresponding to a moisture fraction of about 10 percent), Martin's equation yields a conductivity of 2.912×10^{-4} cal cm^{-1} sec^{-1} deg^{-1} while ours yields 2.528×10^{-4} cal cm^{-1} sec^{-1} deg^{-1} with the moisture term contributing about half the difference. We have no explanation for the difference in moisture coefficients, especially in view of the similarity of our results in other respects. Our results were based on a larger number of determinations, however, but on fewer species.

Because heat is conducted radially from the probe used in these determinations, the thermal conductivity measured is a composite of the tangential and radial values. If pieces of bark greater than 4 inches on a side (the length of the probe) were available, it would be possible to measure the tangential, radial and longitudinal components separately. Since such pieces are not available from most species, including the ones we studied, it was not possible to separate tangential from radial conductivity. It is possible that these two conductivities are nearly equal in bark, however. Thermal conductivity of wood is approximately the same in these two directions (U.S. Forest Products Laboratory, 1955). Bark, with its more amorphous structure, would be expected to show even less systematic variation than wood.

Why is red pine bark different from longleaf and shortleaf? Our results showed highly significant differences, with the red pine bark having a higher Y-intercept and smaller density and moisture coefficients. In some specimens of red pine bark, conductivities when oven-dry equalled or exceeded values obtained at higher moisture contents. This result is unexpected on physical grounds as well as on the experimental evidence of Martin and ourselves with other species. Perhaps the thinness of the red pine bark introduced spurious edge effects. We can offer no satisfactory reason for the anomaly, but must conclude that the red pine regressions are less reliable than those for longleaf and shortleaf pine. Firm conclusions concerning the relative heat resistance of the two groups are not warranted on the basis of the present evidence. Certainly there is no evidence of a difference between longleaf and shortleaf bark; we can find no reason why red pine bark should behave in a completely different manner.

For routine thermal conductivity calculations, we recommend equation (10) for shortleaf and longleaf pine. Even though equation (12) fits the data better, physical reasoning supports use of the equation with the Y–axis restraint.

MOISTURE CONTENT OF BARK

THE meager literature on moisture relations of bark (Spalt and Reifsnyder, 1962) tentatively suggests the following relationships:

1. Bark has a higher equilibrium moisture content than its corresponding wood (based on redwood only);
2. Moisture diffusion through bark is considerably slower than through wood; and
3. Moisture content of whole bark (inner plus outer) on living trees shows considerable seasonal variation, with maxima in summer and minima in fall and winter.

Most reports on bark moisture content contain no distinction between inner and outer bark. Such data as are available show that inner bark may have moisture contents in excess of 100 percent (dry weight basis), compared to 10 to 20 percent for outer bark. Therefore, measurements of total bark moisture content are strongly influenced by the relative proportions of inner and outer bark in the particular sample.

Because of the influence of moisture content on the thermal properties of bark, we investigated equilibrium moisture content and moisture diffusion rates for the outer bark of the three species in the study, and the seasonal variation of moisture content of inner and outer bark of red pine.

Equilibrium Moisture Content

Equilibrium moisture contents were studied by subjecting small samples of bark to a series of relative humidities long enough to reach moisture equilibrium. Both adsorption and desorption conditions were represented. Frequent weighing of the samples also provided information on the rate at which equilibrium was approached, and diffusion coefficients were calculated.

Samples of outer bark approximately 2.5 cm (1 inch) square were cut from additional bark pieces. Cuts were made so that each sample was approximately uniform in thickness which ranged from 0.6 cm to 1.9 cm (¼″ to ¾″). Edges and inner faces were coated with paraffin so that moisture exchange would be through the outer face only, which was left in the natural state.

Five conditions of relative humidity were obtained by circulating air over saturated solutions of various salts in sealed dessicator jars maintained at 30°C (86°F). Humidity in each jar was estimated by using small blocks of white spruce as hygrometers, using standard curves of relative humidity versus equilibrium moisture content. The five humidities were determined to be 14, 28, 56, 68 and 89 percent.

Paired samples were placed in the jars and weighed periodically until they showed negligible weight change. They were then shifted to another jar with a higher or lower humidity in order to obtain information on equilibrium moisture content under both adsorption and desorption conditions. At the end of all tests, samples were vacuum-dried over P_2O_5 in order to determine oven-dry weights which were used to calculate moisture contents of the samples at intermediate weighings. Equilibrium moisture contents were determined by drawing moisture content—time curves for each sample (Figure 4) and estimating the asymptote to the nearest hundredth percent (Table 2).

TABLE 2. EQUILIBRIUM MOISTURE CONTENT

Relative Humidity, %	*14*	*28*		*56*		*68*	*89*
	Des. Ads.	*Des.*	*Ads.*	*Des.*	*Ads.*	*Des. Ads.*	*Des. Ads.*
	Percent	*Percent*		*Percent*		*Percent*	*Percent*
Shortleaf	8.60	9.80	9.21	15.62	14.16	18.40	23.70
	8.30	9.50	8.90	14.55	13.66	17.33	23.44
	7.50	9.24			13.50	16.96	22.50
	6.79	9.15			13.09	16.70	21.10
		9.00			12.36	16.60	
		8.98			11.91	16.32	
						16.16	
						15.40	
Ave.	7.80	9.28	9.05	15.08	13.11	16.73	22.68
Longleaf	8.20	9.60	8.85	13.60	13.90	17.07	23.60
	6.90	9.20	7.50	13.56	13.10	15.90	22.20
	6.65	9.10			12.90	15.60	20.90
	6.40	8.70			12.75	15.45	20.90
		8.50			11.30	15.40	
		8.26			11.18	15.30	
						15.00	
						14.79	
Ave.	7.04	8.89	8.18	13.58	12.52	15.56	21.90
Red pine	6.7	8.8	7.5	17.8	13.3	20.7	21.7
	6.2	8.4		13.4	13.0	16.5	21.5
	5.7	8.2			12.2	16.4	21.0
		8.2			11.2	16.2	
		8.1				16.1	
		7.8				15.1	
						14.3	
Ave.	6.2	8.25	7.5	15.6	12.4	16.5	21.4

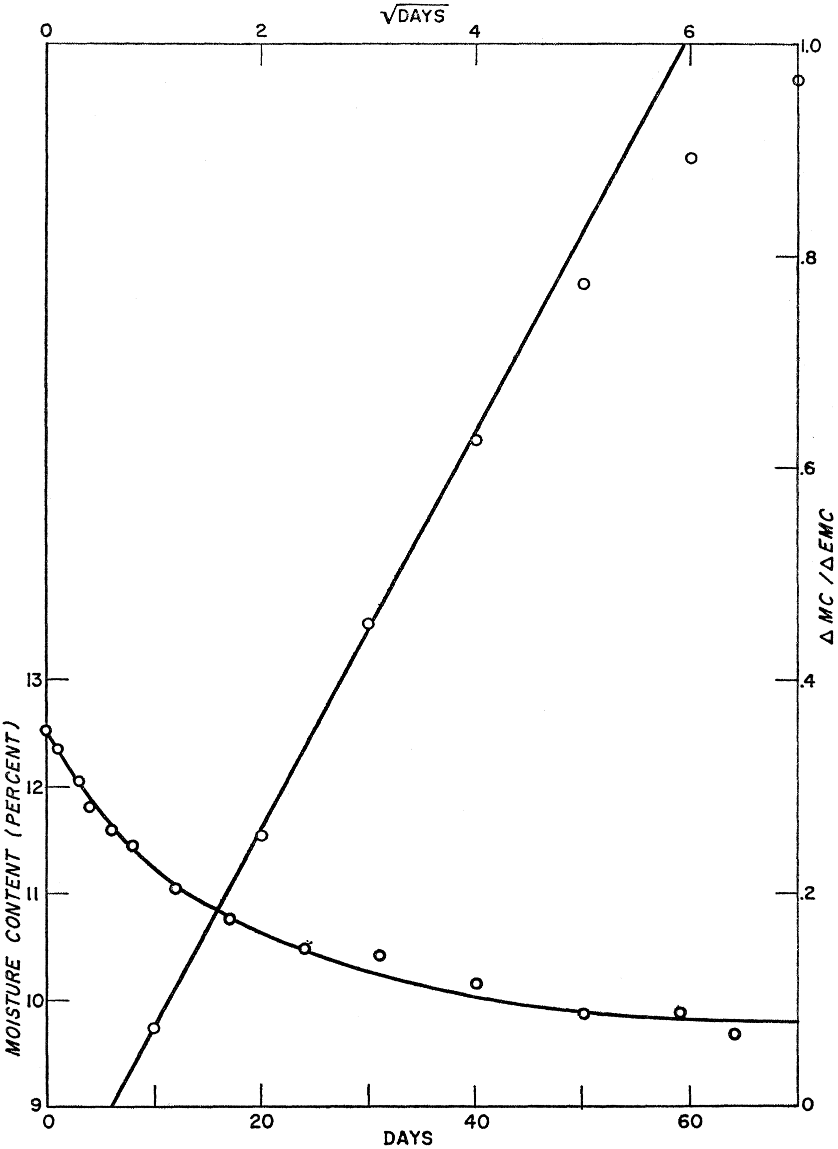

FIGURE 4. Moisture content as a function of time for a shortleaf pine bark specimen (curve, with scales at bottom and left); and moisture content change as portion of total change, plotted against square root of time (straight line, with scales at top and right).

Averages of the EMC determinations at each relative humidity were used to define the shape of the adsorption-desorption curve for each species (Figure 5). Curves were fitted by eye with the Stamm and Woodruff (1941) curve for spruce as a general guide. Each point represents two to eight determinations of the EMC of separate samples. Vertical lines show the range of the data.

Moisture Diffusion in Bark

Bark is generally considered to be rather impermeable to moisture, and loss of internal moisture through the bark is thought to occur primarily through lenticels and breaks (Kramer and Kozlowski, 1960). So far as we could determine, however, no measurements of moisture diffusivities have been published.

It is possible to calculate diffusion coefficients from the data we obtained on adsorption and desorption rates. The Boltzmann form of the Fickian diffusion equation can be written as (Stamm and Nelson, 1961),

$$D = \frac{a^2E^2}{4t} \tag{15}$$

where D is the moisture diffusivity, a is the thickness of the material, E is the moisture content change at time, t, expressed as a fraction of the total possible moisture content change. Equation 15 applies to a semi-infinite slab, that is, one that extends to infinity in all directions along the surface.

If thickness, a, is expressed in centimeters, and the drying time, t, in days, equation (15) becomes for a sample coated on all edges and on one face with a moisture barrier

$$D = 0.909\, a^2\, (E^2/t) \times 10^{-5}\, \mathrm{cm}^2\, \mathrm{sec}^{-1} \tag{16}$$

These equations imply that the ratio of E^2 to t (or E to $\sqrt{t}$) should be constant for a particular diffusion process, so long as the thickness of the material does not change. Although bark thickness changes slightly with moisture content, the error introduced by considering thickness constant is small and can be ignored.

The smoothed curves of moisture content over time used in the determination of equilibrium moisture content were used to derive curves of E against $\sqrt{t}$. These curves generally had a linear segment in the early portion of the diffusion process and this segment was used to calculate the ratio E^2/t. Curves which did not have a linear segment, approximately one fourth of the total, were discarded and not used in the diffusivity calculations. Although this process of slope

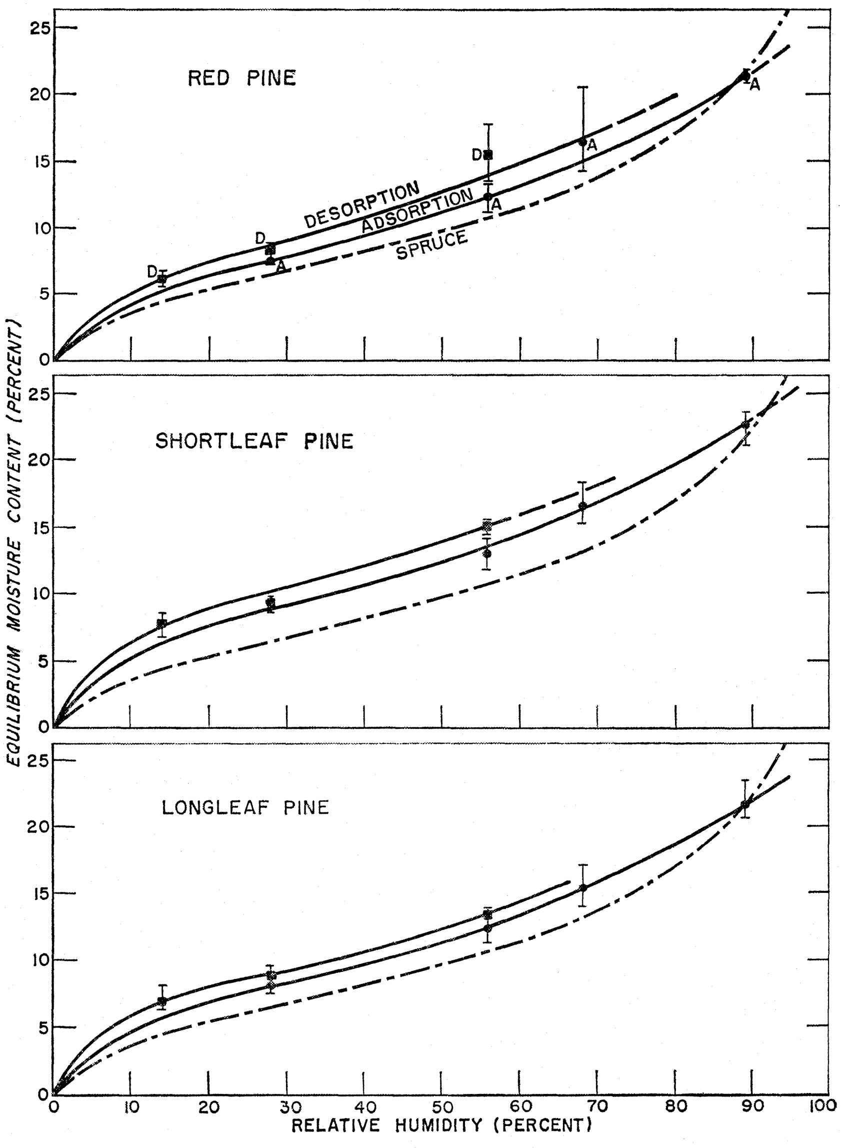

FIGURE 5. Adsorption and desorption equilibrium moisture content as a function of ambient relative humidity. Vertical lines show range of data; squares are averages for desorption (D) and circles are averages for adsorption (A). Average curve for spruce wood also shown for comparison. Spruce curve is for oscillating vapor pressure.

determination was necessarily subjective, estimations by different persons did not vary more than ten percent.

Samples of red pine bark were too variable in thickness to be used in calculating diffusivities. Therefore, the analysis was confined to the barks of longleaf and shortleaf pine.

The results of the diffusivity calculations are presented in Table 3. An analysis of variance showed the difference in diffusivities between species to be highly

TABLE 3. MOISTURE DIFFUSION COEFFICIENTS OF BARK

	Longleaf Pine Bark $\times 10^{-5}\ cm^2\ sec^{-1}$	*Shortleaf Pine Bark* $\times 10^{-5}\ cm^2\ sec^{-1}$	*Combined*
Desorption	0.0299	0.0160	
	.0750	.0381	
	.0557	.0420	
	.0554	.0516	
	.0389	.0240	
	.0408	.0199	
	.0544	.0065	
	.0404	.0155	
	.0444	.0155	
	.0327	.0440	
	.1058		
	.1051		
Ave.	0.0565	0.0273	0.0433
Adsorption	0.0637	0.0054	
	.1634	.0196	
	.1159	.0443	
	.1514	.0167	
	.1008	.0586	
	.0435	.0586	
	.1523	.0469	
	.1571	.0184	
	.1392	.0074	
	.0856	.0271	
	.0926	.0536	
	.0591	.0528	
	.0522	.0304	
	.1200	.0371	
	.0619		
	.0753		
	.1431		
Ave.	0.1045	0.0337	0.0726
Combined Ave.	0.0847	0.0310	0.0604

TABLE 4. MOISTURE CONTENT OF RED PINE BARK FROM VARIOUS HEIGHTS AND EXPOSURES

	Exposure				*Height*
Height	*North*	*East*	*South*	*West*	*Average*
1 foot	24.4	12.9	24.0	16.5	
	29.2	27.9	22.2	26.4	
	26.1	22.6	29.6	27.7	
Ave.	26.6	21.1	25.3	23.5	24.1
4½ feet	18.5	21.4	23.4	14.5	
	19.7	12.3	27.4	10.3	
	27.1	18.1	26.5	16.4	
Ave.	21.8	17.3	25.8	13.7	19.6
Exposure Average	24.2	19.2	25.5	18.6	(21.9)

significant, with the weighted average for longleaf more than two and a half times that for shortleaf. Diffusivities calculated from adsorption data averaged about fifty percent higher than those from desorption data, a difference that was highly significant statistically.

The diffusivity values for bark are considerably lower than theoretical and experimental values for softwood. For a wood density of 0.5 and a drying temperature of 30°C, Stamm (1946) gives the value of the drying diffusion coefficient as about 0.2×10^{-5} cm^2 sec^{-1}. The desorption coefficient for longleaf bark of the same average density is about one-quarter of this value, and that for shortleaf bark about one-eighth. Thus, it appears that bark indeed acts as a barrier to moisture diffusion, as compared with the underlying wood.

SEASONAL VARIATION OF MOISTURE CONTENT

The thermal conductivity of outer bark is strongly influenced by its moisture content (Equations 9–14). The previous section presented information on equilibrium moisture content. But what are the actual moisture contents found in bark in its natural state? And how does it vary through the course of a year? Is it influenced by the moisture content of the inner living bark?

To answer these questions, the moisture content of the inner and outer bark of red pine was measured from July 1959 through August 1960. The same red pine plantation that furnished the thermal conductivity specimens also provided the moisture content specimens.

Samples were taken weekly until late October of 1959, and then monthly. Two trees were sampled at each date, and two samples were taken from each tree—one 1 foot above ground, and the other at 4½ feet. In a limited preliminary test, both exposure (north, south, east, or west) and height (1 or 4½ feet) were significant at the five-percent level, but limitations of time and laboratory equipment precluded sampling all exposures. The north side was selected in the belief that microclimate would be most uniform there, and diurnal fluctuation consequently at minimum. All samples were taken between noon and 2 P.M.; none was taken when the bark was wet with rain, even though the low moisture diffusivity of the bark could be expected to prevent the water from soaking in.

Bark pieces about 2 inches wide and 6 inches long were removed with a chisel. The inner bark and cambium were separated from the outer bark, and the separate samples immediately placed in stoppered distillation flasks. Moisture contents were determined by the xylene distillation process (Buck and Hughes, 1939), and calculated as a percentage of the dry weight of bark (Table 5). An analysis of the differences between observations at 1 foot and 4½ feet by Student's "t" test showed that with the longer series there was probably no difference between the two groups. Accordingly, the two levels were combined and averaged (Figure 6).

The dead outer bark stayed rather moist, the average moisture content for the study period being 24½ percent. During August of both 1959 and 1960, the moisture content rose above 30 percent and must have been at the fiber saturation point. Only at the beginning of the period, in late July and early August, 1959, and in late September, 1959, did the moisture content fall below 20 percent.

The average, 24½ percent, corresponds to an atmospheric relative humidity of about 90 percent (Figure 5). The average annual relative humidity at New Haven is 79 percent at 7 A.M. and 65 at 1 P.M. (Brumbach, 1965), corresponding with EMC's of 15 and 19 percent, respectively. Since the inner surface of the outer bark is in contact with wet inner bark, it would be expected that the average moisture content of the outer bark would be between the EMC corresponding to atmospheric humidity and the fiber saturation point. The lowest value found in the study was 13 percent, and only 3 of the 25 measured values were below 20 percent.

It would be expected that outer bark moisture would follow seasonal trends in atmospheric relative humidity. Climatic data for New Haven show minimum average humidities in the Spring, corresponding to the minimum bark moisture in April. Maximum humidities are found in the summer, corresponding with the bark maxima in August.

Since there is always free water in the inner bark, it would not be expected

TABLE 5. SEASONAL DISTRIBUTION OF MOISTURE CONTENT OF RED PINE BARK[1]

	Percent of Dry Weight			*Percent of Dry Weight*		
	Outer Bark			*Inner Bark*		
Date	*1'*	*4½'*	*Average*[2]	*1'*	*4½'*	*Average*[2]
14 July 1959	26.5	21.8	24.2	—	—	—
29 July	13.3	12.4	12.8	—	—	—
3 Aug.	(12.2)	19.4	17.0	131.0	88.3	109.6
11 Aug.	32.8	31.6	32.2	220.1	176.7	198.4
16 Aug.	35.7	29.4	32.6	214.4	180.7	197.5
28 Aug.	29.2	27.4	27.8	176.4	252.5	214.5
8 Sept.	27.0	26.8	26.9	221.6	215.8	218.7
14 Sept.	21.1	23.8	22.5	184.5	183.7	181.3
16 Sept.	(32.1)	(24.6)	28.4	(184.9)	(175.7)	180.3
22 Sept.	14.4	20.6	17.5	144.4	84.7	114.6
28 Sept.	24.3	25.2	29.7	181.7	164.9	173.3
12 Oct.	27.1	24.9	26.0	136.9	159.8	148.4
19 Oct.	20.8	23.7	22.3	157.8	135.0	146.4
29 Oct.	22.1	21.2	21.6	160.0	—	160.0
24 Nov.	23.9	20.9	22.4	119.2	188.8	154.0
20 Dec.	24.0	25.0	24.6	283.6	199.0	241.4
29 Jan. 1960	28.7	27.5	28.2	192.5	223.8	208.2
17 Feb.	30.0	21.8	25.9	187.0	213.2	200.1
22 Mar.	21.4	19.7	20.6	208.1	185.4	196.7
23 Aug.	16.9	23.4	20.2	147.6	168.8	155.7
20 May	22.3	19.0	20.6	183.9	211.2	197.6
10 June	22.5	20.1	21.3	177.6	193.1	185.4
1 July	26.2	29.4	27.8	240.4	195.1	217.8
29 July	27.9	30.3	27.8	(105.9)	211.6	176.4
31 Aug.	35.6	30.1	32.8	220.4	192.0	206.3
Average	24.72	24.00	24.55	181.73	181.81	181.85

that fluctuations of its moisture content would have much effect on outer bark moisture. Our data generally confirm this, although there does appear to be some correspondence between the two seasonal curves (Figure 6). It is likely that the moisture contents of the two portions of the bark are related through a third variable, the humidity of the surrounding air.

There are few published data to compare our figures with. Stickel (1941) found that the moisture content of whole bark of pitch pine and eastern hemlock reached a maximum in late summer after a spring minimum. Although these data were for whole bark, they probably reflected primarily the moisture changes in the inner bark. Our data agree with Stickel's in the spring minimum, but show

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[1] Each value is average of 2 samples except those in parentheses which are from one sample only.

[2] Means are calculated as simple averages of all individual measurements.

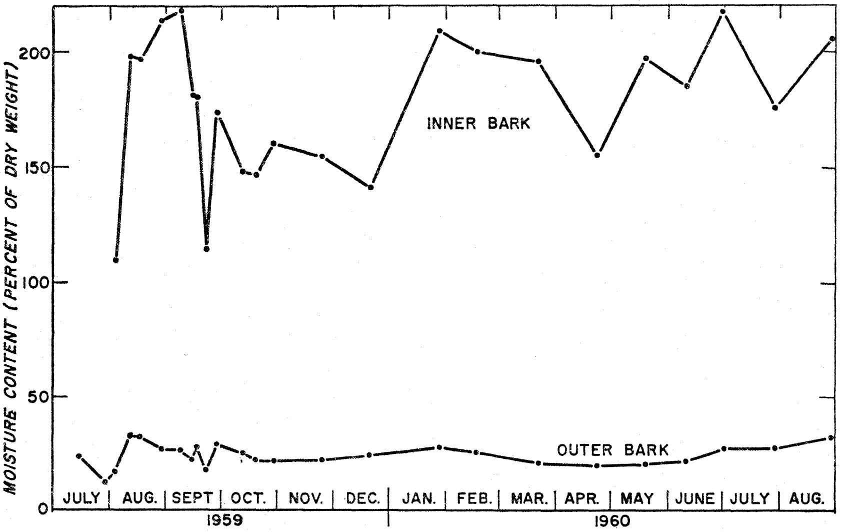

FIGURE 6. Seasonal distribution of moisture content of red pine inner bark (upper curve) and outer bark (lower curve).

a double maximum—one in August, agreeing with the pitch pine and hemlock, and one in mid-winter.

Few generalizations are possible on the basis of our data. It appears that moisture content of the outer bark of red pine generally lies between the equilibrium moisture content appropriate to the average humidity of the ambient air and the fiber saturation point. Because of the low moisture diffusivity of bark, the moisture content generally varies slowly throughout the year. It appears to follow seasonal changes in average atmospheric relative humidity.

DENSITY OF BARK

AS SHOWN in the section on thermal conductivity, bark density significantly influences conductivity. In addition, density enters into the calculation of volumetric heat capacity, one of the parameters needed to calculate thermal diffusivity.

Although we could find no reference to bark density of the species in this study, values for a number of other species range from 0.30 gm cm^{-3} for tamarack and pond pine to 0.54 gm cm^{-3} for jack pine (Spalt and Reifsnyder, 1962). As might be expected, the amount of cork in a bark influences density strongly. Douglas-fir bark may depart as much as ±40 percent from an average density of about 0.44 gm cm^{-3}, depending on the size of cork lunes. Some researchers have found relationships of density with age, size of stem, and position on stem, but none of these relationships is very strong.

The density of the specimens used in the thermal conductivity determinations was measured. They were coated with paraffin after a final drying, and immersed in water to determine volume and mass. Three specimens from each of four trees from the three species were used in the measurements (Table 6). An analysis of variance showed that although there was highly significant variability between trees of a particular species, there were also highly significant differences between species means. Thus bark from red pine, with a mean of 0.365 gm cm^{-3}, was highly significantly different from that of shortleaf (0.497 gm cm^{-3}) and of longleaf (0.520 gm cm^{-3}). However, the differences between the two southern pines were not significant. These measurements were of outer bark only, and were based on oven dry weight and volume.

A second series of density determinations was run on samples of shortleaf and longleaf pine bark to provide a more sensitive test of species differences. Also tested were position on stem (1 foot versus 4½ foot) and bark type (outer vs. inner). Approximately five samples were used to determine a mean for each of the eight categories for each of three trees (Table 7). Samples were smaller than the thermal conductivity specimens used in the first series, averaging about 6 grams for outer bark and one-half gram for inner bark. The same method of determining density was used.

An analysis of variance showed that the inner bark was more dense than outer bark in both species; the difference was more pronounced with shortleaf pine. Although the grand averages for the two species were not significantly different (0.602 and 0.622 for shortleaf and longleaf, respectively), this is not a meaning-

TABLE 6. DENSITY OF THERMAL CONDUCTIVITY SPECIMENS

Tree	*Sample Density, gm/cm*^{3}			*Mean*
		Red Pine		
1	.424	.366	.374	.388
2	.387	.395	.415	.399
3	.326	.340	.348	.326
4	.358	.333	.348	.346
Species Mean				.365
		Shortleaf Pine		
7	.461	.492	.471	.475
13	.637	.610	.579	.609
14	.392	.449	.392	.411
15	.443	.477	.565	.495
Species Mean				.497
		Longleaf Pine		
6	.597	.510	.542	.550
12	.534	.519	.468	.507
16	.480	.467	.452	.466
17	.540	.552	.576	.556
Species Mean				.520

ful comparison to make. In total volume, outer bark constitutes more than 90 percent; thus average density would have to be calculated on a weighted basis. As far as heat transfer is concerned, the thick outer bark is the important layer.

A highly significant interaction between species and layer indicates that there are real differences in density between the two species. Thus the outer bark of shortleaf (0.409 gm cm^{-3}) is less dense than the outer bark of longleaf (0.573 gm cm^{-3}); but the situation is reversed for the inner bark, with the values being 0.796 gm cm^{-3} and 0.672 gm cm^{-3} respectively.

The difference in outer bark density is in the same direction as in the first series. However, the between-tree variation is considerable, and the density distributions of the two species overlap. Also, inspection of the individual sample data for the second series (not presented here) indicates that a single sample is not adequate to estimate the bark density of any particular tree with reasonable precision. About five randomly distributed samples of about 10 grams each should be adequate to estimate the outer bark density within about ±2 percent.

A third series of determinations was made of the density of red pine bark, primarily to determine if there were real differences in the density of inner bark

TABLE 7. DENSITY OF SHORTLEAF AND LONGLEAF PINE BARK[1]

	1′ Height				*4½′ Height*			
	Outer Bark		*Inner Bark*		*Outer Bark*		*Inner Bark*	
Tree	*Number*	*Average*	*Number*	*Average*	*Number*	*Average*	*Number*	*Average*
				Shortleaf				
1	6	.488	4	.862	6	.423	6	.857
2	6	.364	4	.775	6	.385	6	.680
3	5	.412	4	.856	4	.381	6	.744
Average		.421		.831		.396		.760
Type Average			0.409				0.796	
Species Average				0.602				
				Longleaf				
4	5	.607	6	.673	6	.599	6	.622
5	6	.513	6	.702	3	.560	6	.723
6	4	.517	6	.652	4	.640	6	.663
Average		.546		.676		.600		.669
Type Average			.572				.672	
Species Average				.622				

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[1] Values in gm cm^{-3}. Based on oven-dry weight and volume.

as compared with outer bark. Samples were taken at two heights (1′ and 4½ feet) from 14 trees (Table 8). Only one set of samples was taken from each tree, and the inner bark was separated from the outer at time of collection. Here again, height of the sample was of no significance, but the inner bark was significantly denser. Compared with the density determined from the thermal conductivity specimens, these values for outer bark were slightly less, 0.322 compared with 0.365. Considering the magnitude of the between-tree variation, this does not seem great.

Taking these three series together, certain conclusions appear to be warranted. Average density of the outer bark of shortleaf was less than that of longleaf, but not by very much. Red pine outer bark density was much less than either of the

TABLE 8. DENSITY OF RED PINE BARK[1]

Tree Number	*1′ Height* Outer Bark			*4.5′ Height* Outer Bark		
	Outer Bark	*Inner Bark*	*Complete Bark*	*Outer Bark*	*Inner Bark*	*Complete Bark*
8	0.311	0.636	0.393	0.320	0.563	0.396
9	.317	.607	.320	.324	.622	.375
10	.312	.490	.387	.343	.505	.355
11	.331	.559	.326	.305	.513	.322
12	.332	.576	.401	.345	.435	.330
13	.287	.510	.317	.284	.603	.340
14	.295	.645	.293	.252	.555	.327
15	.364	.649	.332	.326	.578	.414
16	.348	.490	.372	.311	.647	.317
17	.335	.632	.374	.353	.449	.359
18	.345	.624	.391	.273	.612	.322
19	.332	.471	.444	.325	.443	.411
20	.355	.508	.344	.365	.459	.361
21	.307	.469	.353	.331	.595	.366
Average	.326	.562	.360	.318	.541	.357
Type Average	.322	.552				

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[1] Values in gm cm^{-3}. Based on oven-dry weight and volume.

southern pines, however. For all three species, outer bark was much less dense than inner bark. Finally, no differences of statistical significance were noted between samples taken at one foot as compared with those taken at 4½ feet above the ground.

SPECIFIC HEAT AND HEAT OF WETTING

THERMAL diffusivity is related to specific heat through the relationship expressed in equation 2:

$$\kappa = \frac{k}{c\rho} \qquad (2)$$

Since we could find few values of specific heat of bark in the literature, it was necessary to determine values for our material experimentally. The objective was two-fold: to obtain specific heats that could be used to calculate thermal diffusivities, and to determine if there were differences in specific heats between bark of the three species used in the study.

When this study was initiated, the only data on bark specific heat that we could find (Spalt and Reifsnyder, 1962) were for shredded eucalyptus bark, 0.32, and shredded redwood bark, 0.215 (Wilkes, 1950). These compare with 0.327, the mean value determined by Dunlap (1912) for a large number of woods. Dunlap's determinations were for oven-dry specimens; no information is available on the moisture content of the values quoted by Wilkes.

In order to determine the specific heat of bark, we used the classic method of mixtures in a simple calorimeter. However, when water is added to cellulosic material that is below the fiber saturation point, heat is evolved, the so-called heat of wetting (Hearmon and Burcham, 1956). Therefore, in order to obtain the true specific heat of the bark, we corrected our calorimeter data for this evolved heat.

Specific heat determinations were made on four samples from each of five trees of longleaf and shortleaf pine, and on four samples from each of four red pine trees. One of the red pine determinations could not be used; a total of 55 tests produced usable data.

Six grams of pulverized oven-dry bark were heated in a container immersed in steam until the temperature reached approximately 96°C. The heated bark was then rapidly transferred to the calorimeter which contained 100 grams of water at slightly below room temperature. The mixture was carefully stirred for two or three minutes, until the temperature of the mixture reached equilibrium, usually about 24°C. Moisture content of the sample was estimated by xylene distillation of a sample of bark from the same piece that was used in the calorimeter (Buck and Hughes, 1939).

Since no data on the heat of wetting of bark could be found, we made several determinations. Samples of approximately ten grams of bark were ground in a

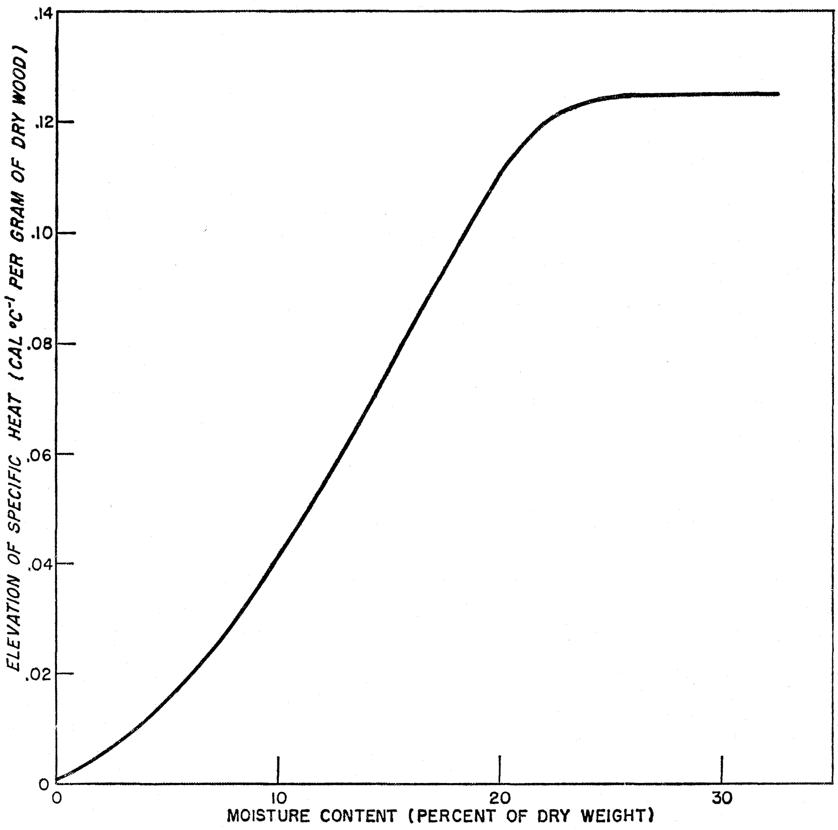

FIGURE 7. Elevation of specific heat (adapted from Byram and others, 1952).

Wiley mill to pass through a 40 mesh standard screen and dried in a vacuum oven over P_2O_5, at a temperature of 50°C and a vacuum of 29″. Dried samples were then sealed in small plastic jars and immersed in water at room temperature in a vacuum flask. When temperature equilibrium was reached, the contents of the jar were dumped rapidly into the water (to which a drop of non-ionic detergent had been added to hasten the wetting process), and the mixture was stirred until a new temperature equilibrium was reached. From these data, the total heat of wetting (i.e., the heat evolved in completely saturating dry material) could be calculated: 19.5 cal gm^{-1} for shortleaf and 20.4 cal gm^{-1} for longleaf bark. For comparison and a check on the method two samples of white spruce wood were included in these determinations. Heat of wetting values for these samples were 17.6 and 18.0 cal gm^{-1} of dry wood. These compare with the value of 18.15 cal gm^{-1} determined by Skey (1939) for white spruce flour extracted with alcohol and benzene.

Heat of wetting is a function of the number of sites available for water molecules to become bound to the cellulose molecules, and thus is related to equilibrium moisture content and to the fiber saturation point. Although we did not determine the fiber saturation point for bark, our equilibrium moisture content curves (Figure 5) suggest that it is about 26 percent, considerably lower than for spruce wood. As wood is heated, it shows a decreasing equilibrium moisture content and fiber saturation point. Curves of heat of wetting against initial moisture content also show decreasing values for a given moisture content as the temperature increases. It might be expected that a substance such as bark, with a lower fiber saturation point than that of wood, would show heat of wetting characteristics similar to wood at a higher temperature, at least to a first approximation. Therefore, the measured heat of wetting of bark was used to determine the appropriate heat of wetting versus moisture content curve for wood to use in correcting the bark specific heat data for heat of wetting.

Curves of heat of desorption versus moisture content for spruce wood, as given by Byram and others (1952) were used to provide these corrections. The curve for 80°C, with a heat of desorption (or wetting) of 20 cal gm^{-1} of dry wood, corresponding to our laboratory determinations of the heat of wetting of bark of 20 cal gm^{-1} of dry bark, was used.

The specific heat values corrected to oven-dry condition are given in Table 9. An analysis of variance showed that the between-tree variation was highly significant, but that the between-species variation was not significant.

These values can be compared with those derived by Dunlap (1912) for oven-dry wood. His calculated values for wood at a temperature of 60°C, the average temperature of our tests, is 0.336. The average of all our tests was 0.316. Martin (1963a) also determined the specific heat of various barks. His mean specific heat for 60 specimens of 8 species was 0.329, and the average temperature of his tests was 56°C. The mean for his twelve specimens of shortleaf pine bark alone was also 0.329, compared with our 0.322.

Considering the differences of methods and assumptions used in measuring the specific heat of dry bark, the agreement between these various values is extremely good. For the purposes of calculating thermal diffusivity of bark,

TABLE 9. HEAT CAPACATY OF DRY BARK

Red Pine		*Longleaf Pine*		*Shortleaf Pine*	
Tree Number	*Heat Cap. cal/gm*	*Tree Number*	*Heat Cap. cal/gm*	*Tree Number*	*Heat Cap. cal/gm*
1	.336	4	.290	2	.282
	.302		.276		.291
	.338		.303		.325
	.329		.279		.314
	(.326)[1]		(.287)		(.303)
2	.308	6	.265	3	.301
	.310		.279		.315
	.341		.265		.316
	.332		.264		.316
	(.323)		(.268)		(.312)
3	.357	10	.338	7	.342
	.326		.325		.316
	.330		.315		.304
	.324		.353		.313
	(.334)		(.333)		(.319)
4	.305	11	.314	8	.354
	.309		.312		.341
	.312		.301		.342
	.309		.327		.352
	(.309)		(.314)		(.347)
		12	.313	9	.320
			.313		.337
			.319		.322
			.305		.337
			(.312)		(.329)
Species Average	.323		.303		.322

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[1] Figures in parenthesis are tree averages.

therefore, it appears that Dunlap's equation is satisfactory:

$$c = 0.266 + 0.00116T \tag{17}$$

where T is in °C. To this must be added the specific heat of the contained water, corrected for elevation of specific heat by the method of Byram and others (1952). The appropriate correction can be read from Figure 7 adapted from Byram's work.

THERMAL DIFFUSIVITY

THERMAL diffusivity is defined by the Fourier heat-conduction equation (1). If time is expressed in seconds and distance in centimeters, the dimensions of diffusivity are cm^2 sec^{-1}. The significance of diffusivity can more readily be seen if it is expressed in an alternate form,

$$\kappa = \frac{k}{c\rho} \tag{2}$$

where k is thermal conductivity in cal cm^{-1} sec^{-1} deg^{-1}, c is heat capacity in cal gm^{-1} deg^{-1}, and ρ is density in gm cm^{-3}. The product of density and heat capacity is sometimes referred to as the volumetric heat capacity, with the units cal cm^{-3} deg^{-1}.

A material with a high thermal conductivity will conduct heat readily, and heat applied to the surface of such a material will progress rapidly inward. The rate of inward progression of temperature, however, depends also on the volumetric heat capacity. For a given amount of heat flowing into a volume of material, the temperature change will be greater in the material with the lower volumetric heat capacity. Thus, the thermal diffusivity can be seen to be related to the way in which a temperature wave progresses through a material; one with a high diffusivity (i.e., high conductivity and low volumetric heat capacity) will transmit a temperature wave readily compared with low diffusivity material.

Little information on the thermal diffusivity of bark is to be found in the literature. At the start of the present study, no published values could be found (Spalt and Reifsnyder, 1962). We made rough calculations of diffusivity based on published data. Values ranged from 1.2×10^{-4} cm^2 sec^{-1} for the bark of pond pine, to 11.7×10^{-4} cm^2 sec^{-1} for the bark of white ash. Martin (1963a, 1963b) in his study initiated at the same time as ours, found values close to 13×10^{-4} cm^2 sec^{-1} over a wide range of moisture contents, densities and temperatures. Martin's data will be discussed in more detail later.

The measurements and calculations of the previous sections have given us values for the parameters of equation (2) and we can now calculate the thermal diffusivity of bark of various densities and moisture contents. With information on how bark moisture content varies through a season or a year, we can also investigate how the diffusivity varies through the same period. This may provide insight into the seasonal variation of the susceptibility of cambium to heat injury as the outer surface of bark is heated by a fire.

Thermal conductivity can be calculated for a range of densities and moisture contents by means of equations (9) and (10), for red pine and longleaf-shortleaf pine, respectively. Volumetric heat capacity of the bark and the contained water must be calculated separately and added to find the total heat capacity of a unit volume of moist bark. Corrections must also be made for the swelling of bark as it changes moisture content. The equation for calculating total heat capacity is,

$$C = \rho_d (1 - \alpha m)(c_b + \Delta c + m) \tag{18}$$

where C is volumetric heat capacity in cal cm^{-3} deg^{-1}, α is the volumetric coefficient of expansion, c_b is the heat capacity of dry bark calculated according to equation (17), Δc is the elevated specific heat, and m is the moisture fraction. Heat capacity of contained air is neglected since it is only about 3×10^{-4} cal cm^{-3} deg^{-1}, a negligible quantity.

Thermal diffusivities calculated in this matter are presented graphically in Figure 8.

As moisture is added to bark below the fiber saturation point, thermal diffusivity drops rapidly, largely as a result of the elevation of specific heat due to bound water. With further increases in moisture content, however, thermal diffusivity would approach that of pure water, approximately 14×10^{-4} cm^2 sec^{-1}. Thus the curves would be bowl shaped, concave upwards. As bark density decreases, thermal diffusivity increases at an accelerated rate, and would equal the value of dry air, approximately 0.2 cm^2 sec^{-1}, at zero bark density. Within the range of densities of interest, however, values range from about 6 to 16×10^{-4} cm^2 sec^{-1}.

Martin's (1963a) data are in the same general range, from 12.17×10^{-4} cm^2 sec^{-1} for a moisture content of 30 percent and dry density of 0.3 gm cm^{-3}, to 16.45×10^{-4} cm^2 sec^{-1} for zero moisture content and a density of 0.8 gm cm^{-3}, and at a temperature of 20°C. The greater range of our figures can be explained on two counts. We found a greater variation of thermal conductivity with moisture content than did Martin. Also, we calculated the volumetric heat capacities of oven-dry bark and water separately and added them to get the composite value, whereas Martin calculated an average specific heat for bark and contained water, then multiplied this by an average bark-water density. Since the specific heat of bark is considerably different from that of water (about 0.3 compared with 1.0), and the bark density is always greater than moisture density (at moisture fractions less than 1), calculating the averages first will lead to significant errors. Thus, it would appear that thermal diffusivity actually does vary considerably from Martin's average value of 13×10^{-4} cm^2 sec^{-1}.

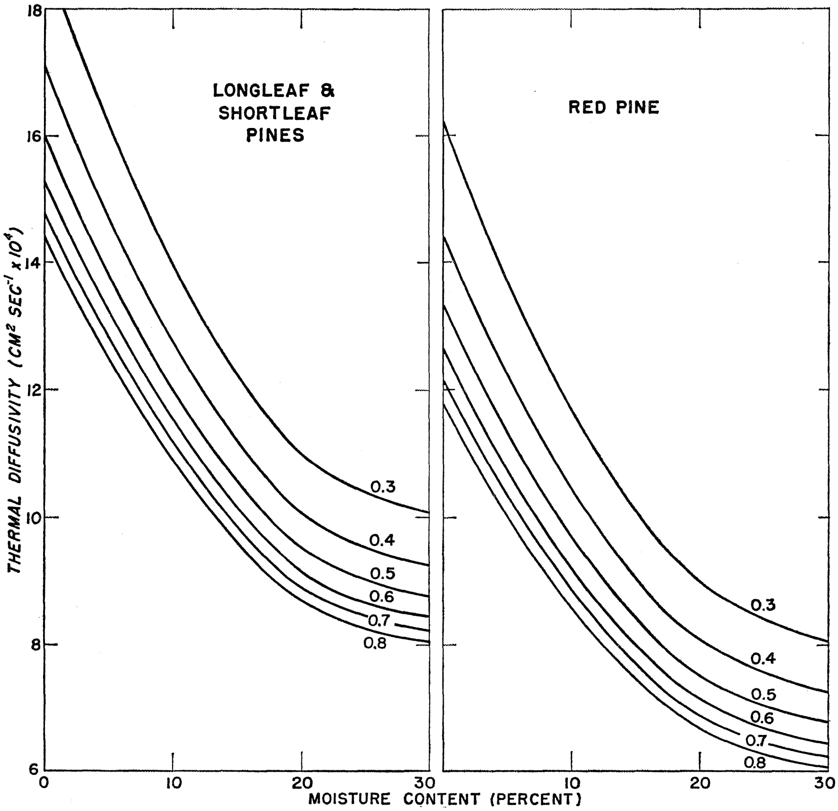

FIGURE 8. Thermal diffusivity of bark as a function of moisture content and dry density.

The low moisture diffusivity of bark, and the slow seasonal changes in the moisture content of outer bark (Figure 4) indicate that thermal diffusivity does not exhibit large and rapid changes over time. Some idea of the magnitude of the changes can be obtained by calculating seasonal variation in the thermal diffusivity of red pine outer bark from the moisture data presented in Figure 4. Assuming a bark density of 0.4 gm cm^{-3} (slightly higher than our measured values), the seasonal trend appears as in Figure 9.

It does not seem likely that marked variations in susceptibility to heat injury can be explained on the basis of large variations in thermal diffusivity. However,

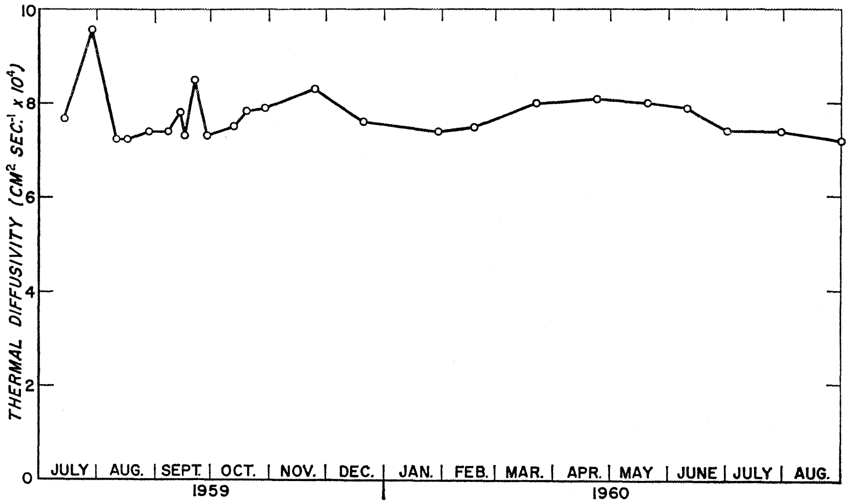

FIGURE 9. Seasonal distribution of the thermal diffusivity of red pine bark, based on measured moisture contents of Figure 4.

the variations are real, and of the order of ten percent from the average, in the case of the red pine. Lowest values appear to be in winter. Thus, heat from winter fires may penetrate the bark less readily than that from summer fires. It has been noted (Byram, 1948) that winter fires are less damaging to southern pines. The explanation given was that with a cold cambium, more heat would be required to heat it to a lethal temperature. A low diffusivity at this time would reinforce this phenomenon.

It appears that there are no marked differences in the thermal properties of the bark of longleaf and shortleaf pine. If there are differences in the fire resistance of mature longleaf pine as compared with shortleaf pine, present information indicates that this is not the result of differences in thermal diffusivity of the bark. Further study of average thickness, bark configuration, and perhaps moisture content of these two barks would have to be made.

SUMMARY AND CONCLUSIONS

THE THERMAL regime of the cambium, or of any other internal region of a stem, is dependent on the heat exchange at the surface of the bark, and the thermal, physical and geometrical properties of the bark and the wood inside the bark. The studies presented in this report analyzed several thermal and physical properties of three species of pine bark: two Southern species and one Northeastern species. Of particular interest is the general correspondence between our results and those of Martin (1963a, 1963b) in a parallel but independently conceived and executed study. Thus, we have considerable confidence that the results of both studies have validity that extends beyond their immediate confines.

1. With the range of bark density and moisture content likely to be found in nature, there is about a twofold difference between lowest and highest values of thermal diffusivity, for the species included in this study. There was little difference in thermal diffusivity between the two southern species (longleaf and shortleaf pine). Values for red pine bark of the same density and moisture content were only about ten percent lower. However, this is counterbalanced by the lower bark density of red pine which leads to higher thermal diffusivities.

2. Because of the relative imperviousness of bark to moisture diffusion (we found values of moisture diffusivity one-quarter to one-eighth of the corresponding values of wood), bark moisture content varies only slightly throughout the year. Thus, for the red pine bark, calculated thermal diffusivity values for natural bark at its driest (in early summer and fall) were only about twenty-five percent less than at the time of maximum moisture content, in mid-summer. Little variation occurred during the long winter and spring seasons.

3. Although the bulk density of shortleaf pine bark was slightly less than that of longleaf bark (about four percent), the difference was so much less than the within-species and within-tree variation that it was not statistically significant. Thus it would appear that the individual tree characteristics are much more important in determining the thermal regime of stem interiors, with these two species. Density of the red pine bark was about twenty-five percent lower than the other two, however. Thus, species differences in density can be important and must be considered in assessing the influence of bark on stem heat transfer.

4. The heat capacity (or specific heat) of bark appears to be sufficiently close to that of wood that no distinction need be made between bark and wood, or between the various species of pine.

5. There were no differences in the thermal conductivities between the two

southern species that could not be accounted for by differences in density and moisture content. It would appear that insofar as heat transfer is concerned, the internal structure of these two barks is similar. Red pine bark behaved differently, however, with lower thermal conductivities for a given density and moisture content. There is some question as to the validity of this comparison, though, because the thinness of red pine bark specimens may have introduced considerable error in the measurements.

How does the thermal conductivity of bark compare with that of wood? MacLean (1941) developed an empirical equation for the thermal conductivity of moist wood below the fiber saturation point. Transformed to make it comparable to our Equations 7 and 8, his expression is:

$$k = 0.568 + 4.79\,\rho(m) + 9.65\,\rho_m \qquad (19)$$

This can be compared with our Equation 8 for longleaf and shortleaf combined:

$$k = 0.614 + 3.394\,\rho(m) + 4.927\,\rho_m \qquad (8)$$

where $\rho(m)$ is the swollen density and ρ_m is the miosture density. (It is not clear whether MacLean forced his curve through the conductivity for dry air at zero moisture, or even whether he calculated a regression or fitted the straight line by eye.)

There is some suggestion that the pine bark has a lower conductivity than wood, at least in the range of normal densities and moisture contents. However, the differences are not great. Even if they are real, it is apparent that natural bark of the species tested does not have a much better insulating value than wood.

The same conclusion is reached if the thermal diffusivities of bark and wood are compared. Calculated diffusivities for oven-dry longleaf and shortleaf pine wood are about 18×10^{-4} cm^2 sec^{-1} (Spalt and Reifsnyder, 1962), compared with about 16×10^{-4} cm^2 sec^{-1} for bark of a similar density (Figure 8). Thus this bark diffusivity is only 11 percent less. These values are lower than comparable values for dry soil, for example, but only about one-third less (van Wijk, 1963; Table 5.4).

The conclusion in inescapable, therefore, that these pine barks do not have any special characteristics that make them better in protecting the cambium from heat injury than wood of a comparable density and moisture content. Bark thickness appears to be the primary factor determining whether a tree is fire resistant or not. This is not to say that small differences may not be important in certain cases. And some barks, by virtue of low density and "flakiness" or other peculiarities of structure and surface conformation, may provide better heat protection than the ones we examined. These characteristics should be investigated in future work.

But it is clear that the barks we examined have no peculiarities in their thermal properties that would make them unusually effective in protecting the cambium from the heat of a fire.

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