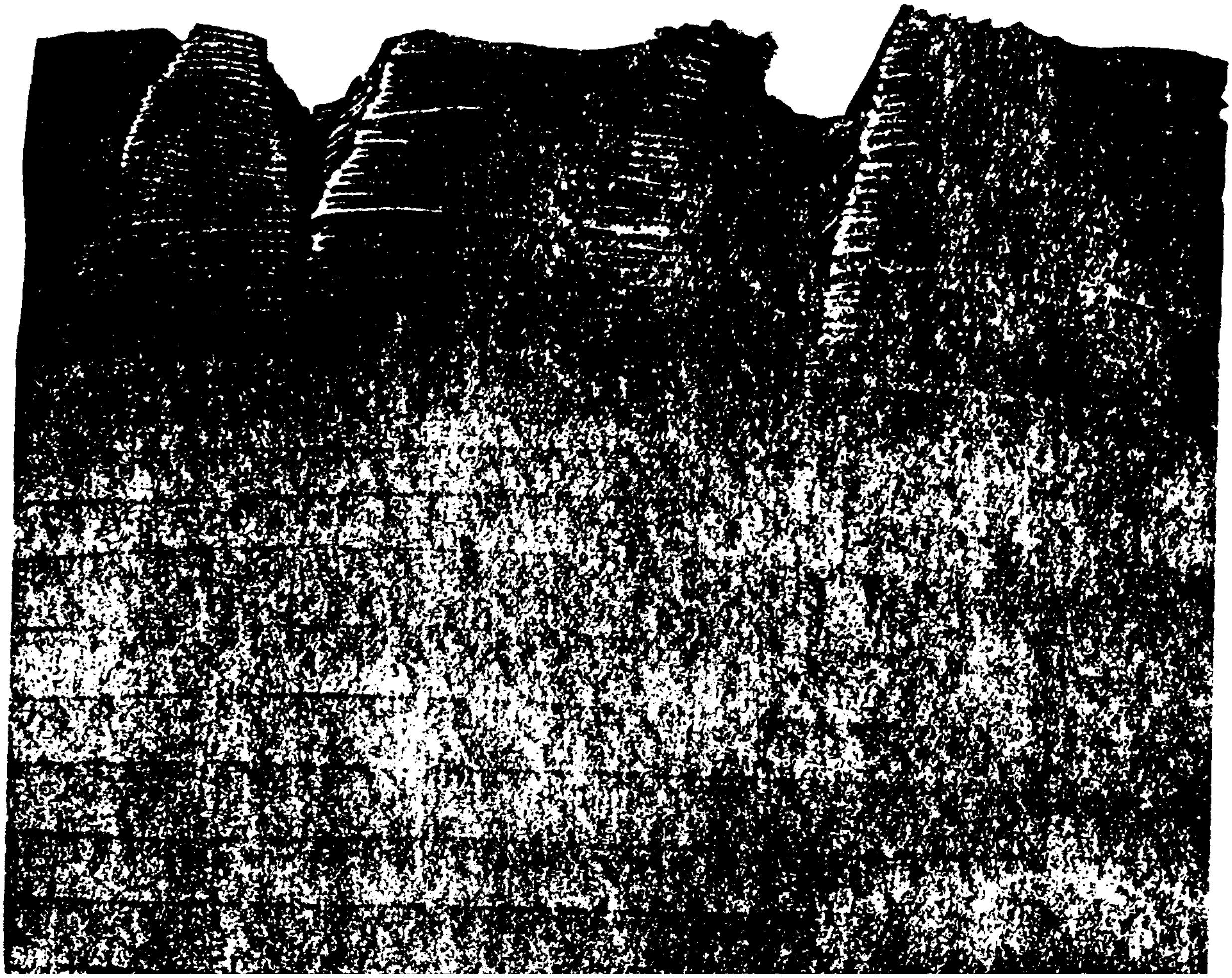
U. S. FOREST SERVICE
RESEARCH PAPER
FPL 69
APRIL 1967

U.S. DEPARTMENT OF AGRICULTURE ·
FOREST SERVICE ·
FOREST PRODUCTS LABORATORY ·
MADISON, WISCONSIN

charring rate of selected woods -- transverse to grain



ABSTRACT

Much of the information relating to fire endurance of heavy timber construction has been developed empirically. To remain competitive with other construction materials, precise data are needed for designing and predicting fire endurance of wood assemblies. This study was designed to determine the charring rates for wood normal to the grain, and to evaluate the effect of fire intensity, species, specific gravity, moisture content, and annual ring orientation on these rates. Other material variables studied were the springwood to summerwood ratio and volatile extractive content. The effect of variation in moisture permeability, however, was not evaluated.

Laminated wood slabs, 3 inches thick, of Douglas-fir, southern pine, and white oak were vertically exposed to fire on one surface. The rate of char development was constant when the specimens were exposed to uniformly increasing fire temperatures; charring rates at three constant fire exposure temperatures were described by a pseudo-first-order reaction equation with an Arrhenius temperature-dependent rate constant. Rates of char development in each species were related to the specific gravity and moisture content of the wood. The other material characteristics considered were directly related to specific gravity and moisture content or had no significant effect on the charring rate.

CONTENTS

NOMENCLATURE

Symbol	Description	Dimensions
A	frequency factor, a material constant	1/sec.
B	constant	-------------
a,b, c	regression constants	-------------
D	constant	-------------
E	activation energy	cal./g.-mole
J	Joule's mechanical equivalent of heat	ergs/cal.
k	thermal conductivity	cal./sec. cm. °K.
M	moisture content	percent
R	gas constant	cal./deg. g.-mole
T	absolute temperature	°K.
t	time	sec.
v	volume	$cm.^3$
v	rate of char formation	------------
w	mass weight	g.
x	material coordinate	------------
α	thermal diffusivity	**cm^2/sec.**
β	regression constant	------------
ρ	specific gravity	------------
ϕ	fraction of material	------------

SUBSCRIPTS

Symbol	
c	char
D	dry
d	decomposed material
o	initial condition (t = o)
ss	steady state
W	wet

charring rate of selected woods -- transverse to grain[1]

by E. L. SCHAFFER, Research Engineer

U. S. Department of Agriculture
Forest Service
Forest Products Laboratory [2]

INTRODUCTION

The excellent fire endurance of buildings constructed with heavy timber for columns, beams, girders, floors, and joists has long been recognized and proven. A slow rate of charring and slow loss of strength of wood under fire exposure allow large members to perform their intended function despite intense heat and fire. However, designing wood members for a specific degree of fire endurance has been quite empirical. To remain competitive with other construction materials more precise data should be obtained upon which to design and predict fire endurance of wood assemblies. A long-range program to obtain these data has begun as part of the fire research studies at the U. S. Forest Products Laboratory.

A review of the literature relating to the charring rate of wood (3)[3] revealed that the effects of material characteristics and exposure conditions on the fire endurance of wood are not well defined. Some of the more pertinent studies are summarized here.

Research by Vorreiter (17) and more recent work in Great Britain (6, 7) indicate that the density (specific gravity) of the wood has a pronounced effect on the rate of charring. The British (6, 7) also cite permeability along the grain, moisture content, and dimension as important parameters. Their work shows that the charring rate is proportional to density but is not as dependent upon moisture content in the 0 to 30 percent range as might be expected. No relative figure of merit for these factors is given by them, however. The effect of specimen thickness appeared to be small over the range of 0.6 through 5.0 centimeters (0.25 to 2 inches). For the same range of specimen thickness Akita (1) provides quantitative support for the apparent small effect of thickness on char rate. By recording the temperature distribution in wood boards, he found that the thickness or depth of the char layer does not depend upon the board thickness if the board is thick enough. One can assume

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[1] This research was performed in cooperation with the National Forest Products Association.

[2] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[3] Underlined numbers in parentheses refer to literature cited at the end of this report.

that if the thickness of the specimen is greater than 1/4 inch it will have negligible influence on the char rate for developed char depths that are less than the thickness of the board.

In another study relating the rate of degradation of wood to density, Wolgast (19) discussed the surface flammability of building materials. He recognized that decreasing thermal conductivity coefficients in wood are directly due to increasing void volume. Increased void volume speeds flame spread because of localized overheating and simultaneous heat accumulation at the solid lattice. If the term "thermal degradation" is analogous to "flame spread," then one should be able to assume that the volumetric rate of degradation will increase with increasing void volume as well. The heat capacity of the wood solids can be assumed constant for any wood, which means that the more mass available to absorb heat energy, the slower will be the degradation

Permeability apparently affects the rate of charring also, as the rate of the weight loss to density ratio was found to increase with increasing permeability along the grain (6, 7). Specimens (2.5 centimeters thick) of a highly permeable wood, Abura, and a highly impermeable wood, Makore, which have very different charring rates but approximately the same densities, were sealed on all surfaces except the heated one and exposed to intensities of radiation of 0.5 and 1.0 calorie per square centimeter per second. The rates of charring of both woods were reduced and the difference between them was reduced, but not eliminated.

Work at the U. S. Forest Products Laboratory in 1936 on l-inch-thick specimens of southern pine subjected to ASTM E-119 fire exposure conditions indicated that density and annual rings per inch have little or no effect upon rate of char development. From rate data on white oak however, a marked influence of ring orientation was observed. A higher rate of char development (1.62 inches per hour) was observed when the rings were oriented parallel to the exposed face than the rate when they were oriented normal (1.39 inches per hour). An orientation at 45° to the exposed face showed a rate (1.50 inches per hour), midway between the two orientations.

In a kinetic study of the thermal decomposition of wood, Wright and Hayward (20) found that the decomposition rate for disks cut across the grain was approximately twice that for disks cut along the grain. The reaction rate was found to be substantially the same for both cedar and hemlock, which suggested to them that the factor which controls the overall rate of the decomposition reaction is not the chemical composition of the wood, but rather its physics characteristics.

According to Hawley (8), moisture content values on the order of 50 to 100 percent are effective in retarding the rate of combustion because of the large amount of supplied heat required for vaporization of the water. Even at low concentrations moisture still decreases the rate--a fire consumes wood at 10 percent moisture content noticeably faster than wood at 20 percent moisture content. He further states that low specific gravity will speed combustion partly because of more rapid heat penetration and partly because it gives a greater surface area per unit weight.

The influence of moisture can be observed even in initially dry material freely burning in air. This phenomenon was noted by Blackshear and Murty (4) during the burning of dry-pressed cellulose cylinders up to 2.5 inches in diameter. Water and other condensable vapors are produced

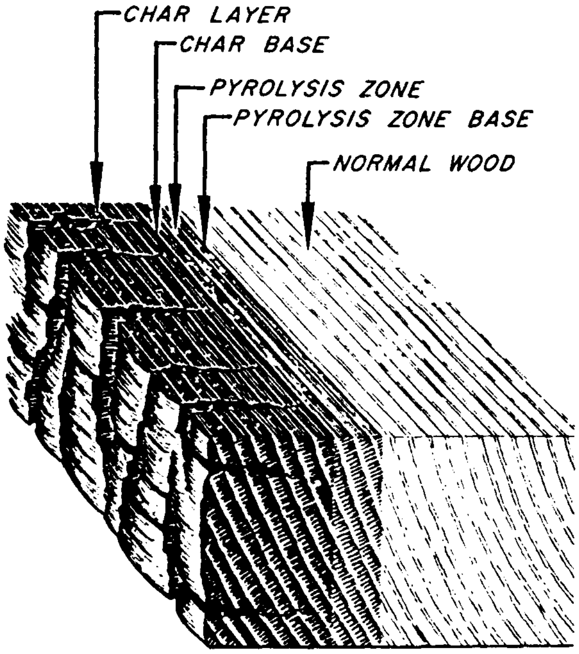

Figure 1.--Degradation zones in a wood section.

(M 130 020)

by the combustion process in cellulose, and some of the vapor diffuses into the solid and condenses while the rest leaves through the surface. The migration, condensation, and subsequent regasification as the material degrades has a pronounced effect on the temperature-time histories of the interior of the cylinder. A second result of their work (4) was that the burning rate, as measured by rate of mass loss, was dependent upon the diameter of the cylinders.

Shorter (15) considers the spallation of concrete on prestressed concrete beams under fire exposure to cause failure of the sections to support load. The base material would be inadequately protected by the surface material. In similar fashion, if char is spalled from a fire-exposed surface due to thermal stress rupture, the insulative value of the char layer is reduced, and additional char development would be possible.

Truax (16) reports that on the basis of temperature developed in the 7-1/2 -inch-thick laminated Douglas-fir section exposed to fire, the temperature characterizing the base of the amorphous char layer (fig. 1) was 550° F. (288° C.) after 20 minutes' exposure to ASTM E-119 fire conditions (fig. 2). An estimate of temperature at this point, before 20 minutes elapsed, varied from 615° to 550° F. This was termed the charring temperature. Therefore, the more rapidly this point is raised to these temperatures the more rapid will be the rate of char development. Hence, exposure temperature will be of importance.

The fissures that occur in the char layer will govern both volatile release and heat transfer, thereby affecting the rate of degradation of wood to char. Earlier work at the U. S. Forest Products Laboratory on 1-inch-thick boards, however, showed the char base to be quite uniform in location in denser woods (such as red oak and maple) but with lighter woods (such as the pines

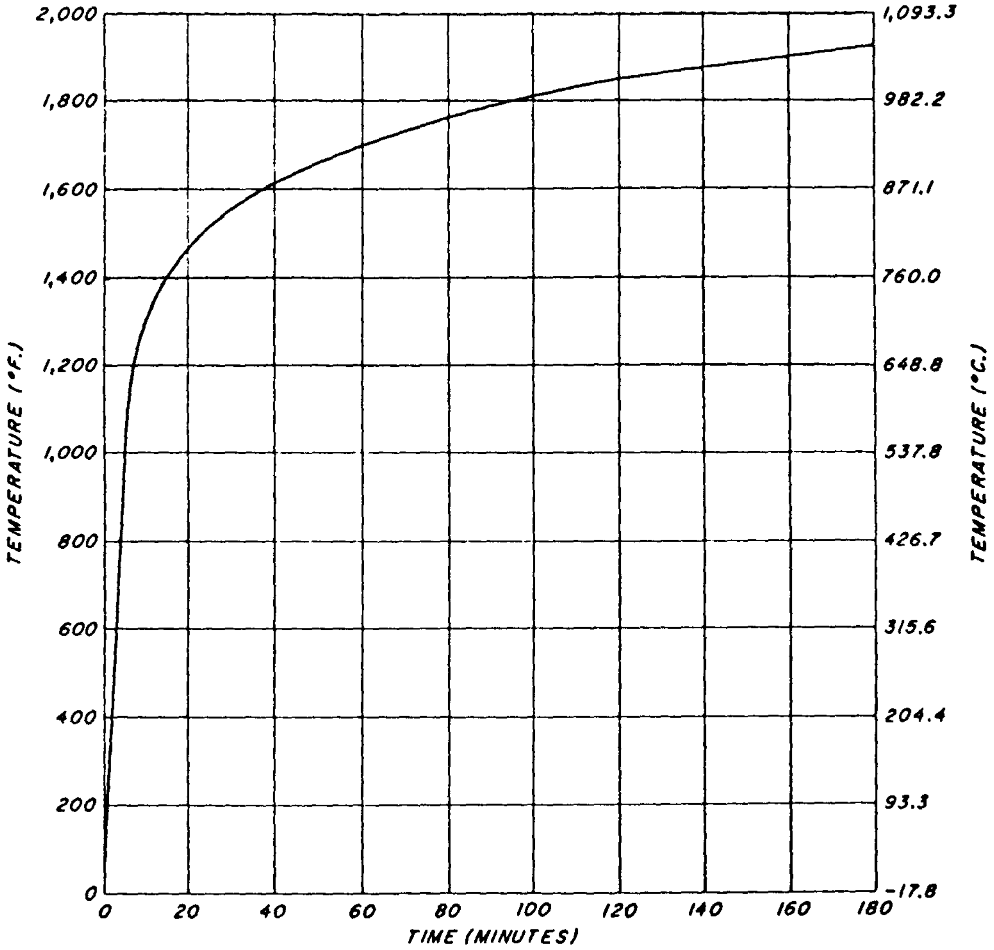

Figure 2.--Standard ASTM E-119-61 (2) time-temperature fire exposure.

(M 28856)

and basswood) the char depth was slightly deeper at the base of fissures.

Combustible volatile content is linked to spread of flames on a material (8) and may therefore influence the rate of char development.

In summary, the wood properties that may influence the rate of char development under fire exposure include density, thermal conductivity, moisture content, permeability, ring orientation, thickness of specimen, charring temperature, combustible volatile content, and char layer characteristics (thickness, fissure depths and widths, permeability, and thermal conductivity). Also, the environmental conditions such as exposure temperature and type of heat source are of importance. The degree to which each affects the rate, however, has only been qualitatively examined in the past.

OBJECTIVE & SCOPE

The objectives of this study were to determine the rate of char development in wood normal to the grain under fire exposure, and to relate the rates obtained to inherent properties of the material such as species, density, moisture content, and annual ring orientation.

Massive structural wood members in an actual fire are generally exposed to fire on three surfaces, but since the dimensions are large (greater than 6 inches) the influence of heat transferred from one exposed surface to another through the member may be considered negligible for short fire exposures (less than 1 hour). Therefore to eliminate the effect of heat transfer through the specimen and to represent the upper bound of resistance to char development under fire exposure, it was concluded that in this study thick plates of laminated wood should be exposed to fire on one face only. The thickness of the plate should be sufficient to approximate the performance of a large structural member for the duration of the exposure to fire.

Because the relative effects of certain properties of the wood and fire on the rate of char development were unknown, a partial factorial statistical experiment was designed so that data obtained could be analyzed for levels of significance. The species selected for the study were Douglas-fir (Coast type), southern pine, and white oak. Three parameters were controlled for each species as follows:

1. Fire exposure temperatures:
    - 1000° F. (538° C.)
    - 1500° F. (816° C.)
    - 1700° F. (927° C.)
    - ASTME- 119-61 standard time-temperature fire conditions (2)
2. Equilibrium moisture content values as obtained in environments of:
    - 80° F., 30 percent relative humidity
    - 80° F., 65 percent relative humidity
    - 80° F., 80 percent relative humidity
3. Annual ring orientation
    - Parallel (0°) to fire-exposed surface
    - Normal (90°) to fire-exposed surface

Other parameters expected to be of importance, but difficult to control in wood, were included in the design as random variables. These were the specific gravity, springwood to summerwood ratio, and volatile extractive content. The analysis of the effect of these parameters on the char development rate was accomplished with statistical covariance techniques.

The permeability of the species was not included in the parametric effects considered because of its large variation among wood specimens of even the same species. Extensive experimental work is required for each determination, and therefore, expressions relating the charring rate to permeability were not developed.

Replicates under each of the controlled parameters selected led to a total requirement of 48 test specimens for each species.

PROCEDURE

Douglas-fir and southern pine were selected for this study because of their common usage in the structural member laminating industry in the United States. White oak was selected because it is a hardwood and would provide data in a higher density range.

The material for each species was divided into three lots and conditioned to equilibrium in environmental chambers at 80° F., 30 percent relative humidity; 80° F., 65 percent relative humidity; and 80° F., 80 percent relative humidity. These environments produce equilibrium moisture content values of about 6, 12, and 18 percent within wood.

Accurate determinations of moisture content and specific gravity were made on l-inch-thick sections that were cut from each of the laminates of a specimen before the specimen was constructed. Each section was weighed (W_w) and placed in an oven at 212° F. (100° C.) to dry. The ovendried sections were then weighed (W_D) and dipped into hot paraffin. When paraffin on the sections had cooled, the sections were submerged in water to obtain ovendry volume (V_D). The moisture content (based upon ovendry weight) was determined by the following equation:

$$M = \left(\frac{W_W - W_D}{W_D}\right) 100 \quad \text{(percent)}$$

Dry specific gravity (based upon ovendry volume) was determined by:

$$\rho_D = \frac{W_D}{\gamma V_D}$$

where γ is the density of water.

Springwood to summerwood ratios were calculated for the intended center laminate of each specimen. This was accomplished by summing the individual thicknesses of spring-wood and summerwood bands on a double integrating microscope across the specimen thickness. The ratio is then given by:

$$R = \frac{\Sigma \text{ springwood thicknesses}}{\Sigma \text{ summerwood thicknesses}}$$

An ASTM procedure (ASTM D1105-56) for removing extractives from wood was followed to determine the percent of volatile extractives by weight in Douglas-fir and southern pine material. Analyses were made on samples from each species at varying specific gravities.

After the above determinations were made, thick plates for fire exposure were constructed by laminating together 20-inch lengths of each species of equivalent density and moisture content, with the annual rings oriented either parallel or normal to the exposed surface. A phenol-resorcinol adhesive was used for the bonding. In preliminary work this adhesive, as well as others, resisted delamination of the wood or char layer under fire exposure. This insured that the structural homogeneity of the material would be preserved under fire exposure. The adhesive line did not appear to hinder or speed char development in the specimens.

The size of the specimens after lamination and surface planing was 10 by 20 by 3 inches, with the grain oriented along the 20-inch dimension. A typical specimen is shown in figure 3. Care was exercised to minimize the presence of structural defects in the center laminate (or laminates), as it was this laminate that was used in measuring the rate of char development.

The completed specimens were again stored in the conditioning rooms.

Exposure Furnace

Fire resistance evaluations of various wood-based materials have been carried out at the U. S. Forest Products Laboratory in a natural gas-fired furnace (fig. 4) that has a 20- by 20-inch vertical opening for specimen exposure.

Natural gas of heat value equal to about 1,000 British thermal units per cubic foot was fed to furnace burners through a volumetric control valve. The gas was allowed to burn freely in the furnace atmosphere, and air was supplied naturally through vents along the base of the furnace. The gas volumetric control valve was regulated automatically by a servomechmism that was keyed to furnace thermocouples.

Thermocouple Placement

Furnace temperatures.--Thermocouples were located 1/4 inch away from the specimen surf ace to permit an accurate determination of the temperature conditions near the surface of the specimen. Six iron-constantan thermocouples were employed and were only partially protected along their length by stainless steel pipes. Thermocouple junctions protruded 1/4 inch beyond the end of the pipe.

Specimen temperatures. --The progress of charring was obtained by thermocouples that measured the wood temperature at various depths in the specimen. The thermocouples were inserted into l/8-inch-diameter holes from the surface that was not exposed to fire. A small length of the thermocouple was carefully bent, 1/8 inch from the thermocouple junction, so as to be parallel

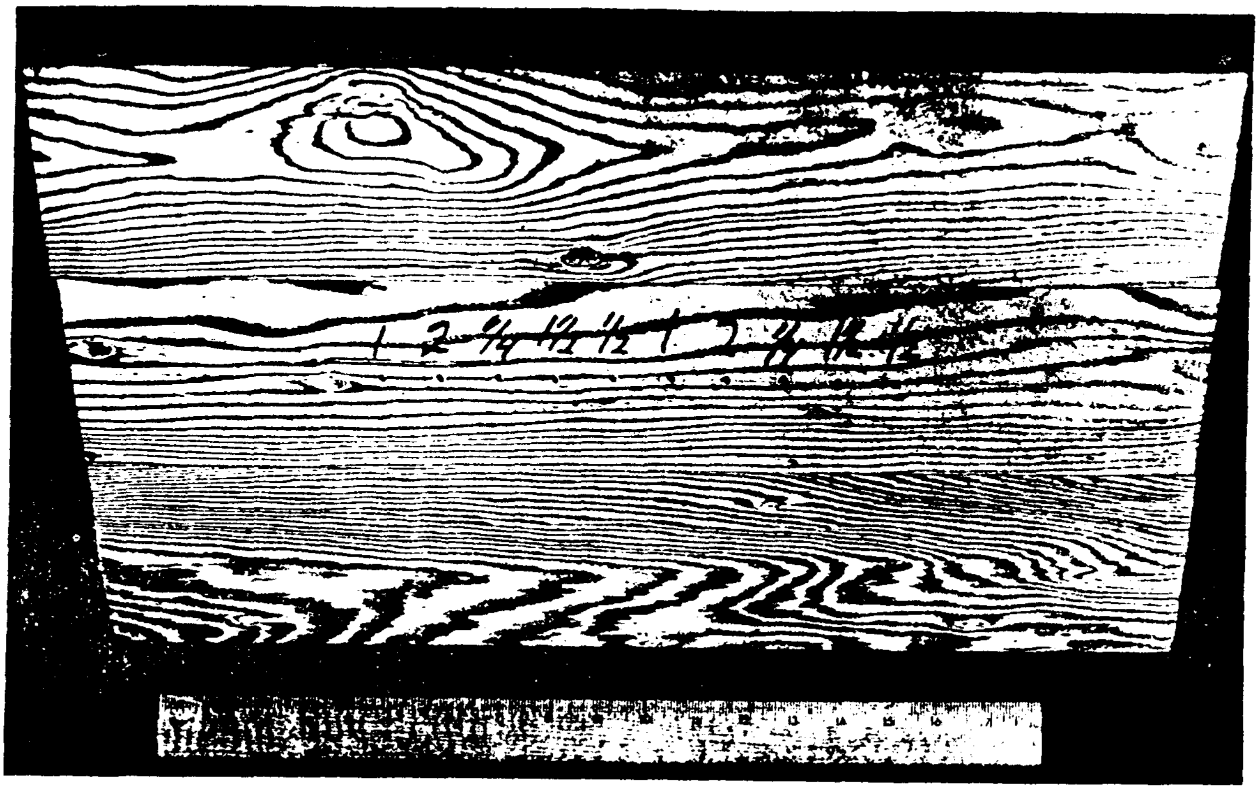

Figure 3.--Laminated southern pine specimen with holes for thermocouples drilled in the center laminate.

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Figure 4.--Specimen in place in furnace with sensing equipment attached.

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to the exposed face of the specimen when emplaced When the thermocouple leads were placed totally normal to the exposed face, errors in measurement of as much as 90° F. below actual were observed Such errors were attributed to the steep temperature gradient produced as char developed to the depth of the thermocouple tip and to the difference in thermal conductivities of the wood and thermocouple. A full discourse of thermocouple temperature measurements in low-conductivity materials is discussed by Beck (3). Other preliminary work yielded the conclusion that a 30-gage (Brown and Sharpe) iron-constantan thermocouple insulated with high-temperature Teflon along the lead wires and bent at the tip could satisfactorily record temperatures in the charring wood.

The thermocouples were arranged along a horizontal line at the center of the specimen. Thermocouple junctions were located 1/4, 1/2, 1, 1-1/2, and 2 inches from the exposed face and were spaced 1 inch apart. Two thermocouples at each distance were used to provide duplicate measurements.

Fire Exposure Method

At time of test, the following data were recorded for the specimen properties:

1. Species
2. Ring orientation
3. Specimen dimensions
4. Specimen weight
5. Thermocouple placement pattern

The following properties were determined for the laminate in which the thermocouples were embedded:

6. Specific gravity (dry)
7. Number of rings per inch
8. Moisture content (percent)

The specimen was then placed in the furnace opening and the edges were talked with fiberglass insulation. Each of the ten thermocouples was inserted into a prepared hole and held in position while small wood sticks were inserted into the holes to seal the well. The thermocouple leads were connected by input jacks and cable to an automatic potentiometer recorder calibrated for temperature. The specimen, as installed in the furnace, is shown in figure 4.

The furnace was ignited manually with the aid of a pilot gas flame inserted through one of the observation ports. After ignition the observation port was sealed. At time of burner ignition, the following functions were done as simultaneously as possible

1. Automatic temperature recorder was started.
2. Stop watches started.
3. Furnace temperature controller started.
4. Initial gas meter reading was taken.

As the fire exposure test progressed, the following observations were recorded:

(a) Time of specimen surface ignition.

(b) Times that embedded thermocouples reached temperatures of 550° F. and 800° F. at a given distance from exposed surface.

(c) Appearance of specimen and exposed surface.

In comparing the location of the inner char zone in the specimen to the internal temperature recorded by thermocouples, it was found that a temperature of 550° F. could be employed to locate the char zone base for distances from the fire-exposed face ranging from 1/4 to 2 inches,

This method of locating the char zone base was successful, and was used because no other continuous way of determining this point was feasible.

Each thermocouple was removed from the specimen as it recorded 800° F. in order to prevent thermocouple damage. The thermocouples that were located 1/4 inch from the exposed surface were removed and placed beneath soft l/2-inch-thick asbestos pads On the unexposed surface to record the temperature of that surface.

RESULTS[4]

Specimen Properties

The measured dry specific gravities, moisture content values, and number of rings per inch of each specimen were recorded and utilized to determine their effect on rate of char. The ratio of springwood to summerwood showed a fairly direct correspondence to dry specific gravity in both Douglas-fir and southern pine (figs. 5 and 6). The white oak springwood to summerwood ratios were not as clearly related to dry specific gravity, however (fig. 7).

The percent of volatile extractives (based upon ovendry weight) obtained from a range of density in Douglas-fir and southern pine specimens are shown in table 1. The range of volatile extractives is 1.6 to 3.3 percent in Douglas-fir samples and 2.7 to 4.2 percent in southern pine. The results obtained for the Douglas-fir are consistent with those obtained by Wilson and Campbell (18). They found, by the same extractive method, that Douglas-fir sapwood contained an average of 2 percent of resinous extractives.

Effect of Fire Exposure

Constant exposure temperatures of 1000° F., 1500° F., and 1700° F. were reached in less than 20 seconds, 1.2 minutes, and 3 minutes, respectively, after gas ignition in the furnace. The

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[4] Many of the data gathered during this study were voluminous and complex and it was deemed unnecessary to formally present them here. Rather, general trends and observations based on the data are discussed and will perhaps be of greatest value to the reader.

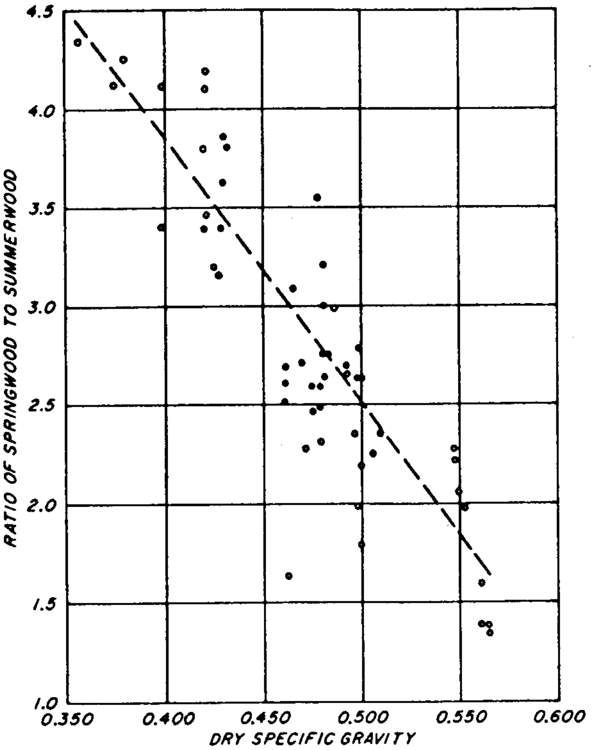

Figure 5.--Douglas-fir: Correspondence of springwood to summerwood ratio with dry specific gravity.

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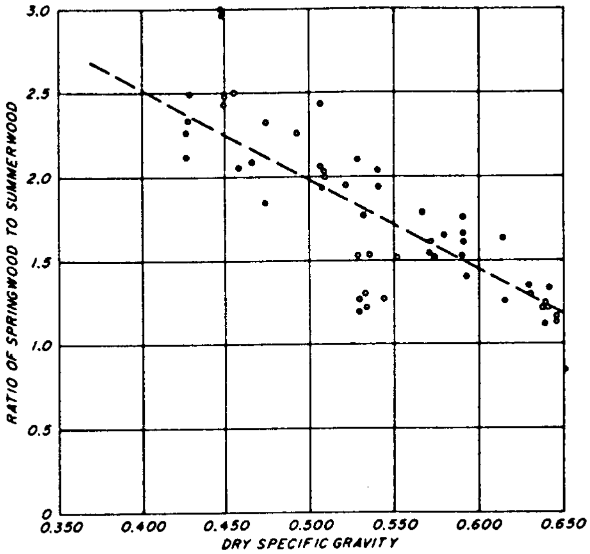

Figure 6.--Southern pine: Correspondence of springwood to summerwood ratio with dry specific gravity.

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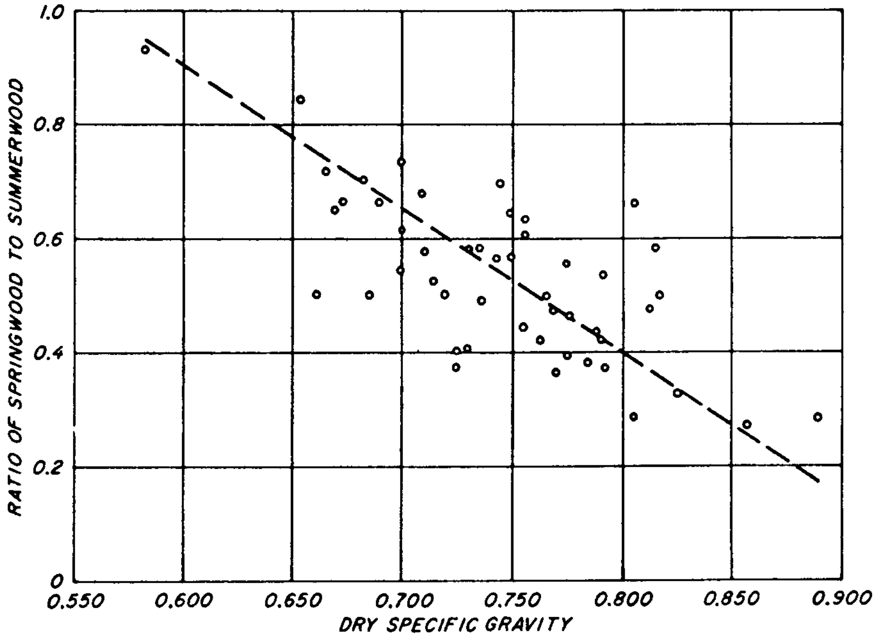

Figure 7.--White oak: Correspondence of springwood to summerwood ratio with dry specific gravity.

(M 130 367)

Table 1.--Volatile extractives in selected Douglas-fir and southern pine samples

Dry specific gravity	Volatile extractive content[1] 1	2	Average
	Pct.	Pct.	Pct.
DOUGLAS-FIR			
0.359	2.337	3.453	2.895
.425	2.523	4.110	3.317
.490	1.480	1.696	1.588
.542	2.666	2.828	2.747
.622	2.823	3.093	2.958
SOUTHERN PINE			
.384	3.650	3.609	3.630
.460	4.089	4.222	4.156
.540	3.600	3.443	3.522
.618	3.260	2.976	3.118
.697	2.807	2.66	2.734

[1] Based upon ovendry weight.

usual time to reach 1700°F. was about 1.8 minutes for all tests.

Surface charring was observed simultaneously with the ignition of the specimen. The thermocouples, located 1/4, 1/2, 1, 1-1/2, and 2 inches from the fire-exposed face, provided a means to calculate the rate of char penetration in the specimen. A characteristic temperature of 550° F, (288° C.) indicated that the plane of the char base had progressed to the depth of thethermocouple. A typical char depth-time plot for Douglas-fir at each temperature condition is shown in figure 8. Southern pine and white oak produced curves of similar shape and relative location.

After initial charring of the surface had begun, irregular hairline cracks began to appear. As the test progressed, these crocks continued to widen as the char layer increased in depth. By the end of the exposure, when the char base had reached n depth of 1-1/2 inches, the cracks were from l/8 to 1/4 inch wide. These cracks extended as a fissure through the amorphous char layer to the char base. As in the case of past work at the U. S. Forest Products Laboratory, the char was slightly greater in depth at fissure locations only in the two species of lower specific gravity, Douglas-fir and southern pine. In the white oak, the char base was relatively smooth and apparently not influenced by the char fissures.

When equilibrium moisture content values were at or above 14 percent in Douglas-fir, 16 percent in southern pine, and 10 percent in white oak, other char layer phenomena and specimen effects, proportionate in magnitude to moisture level, were noted: (1) Char spallation, (2) specimen checking (cracking) along the grain at the fire-exposed face, and (3) bowing inward (to the fire) in the plane normal to the grain. In the Douglas-fir, char spollation was noted for specimens exposed with the rings oriented normal to the fire-exposed face. So bowig or checking was observed. The char layer on the southern pine specimens did not span at any level of esposure, but checking of the material was pronounced. At times, checking occurred along the thermocouple placement line and resulted in more rapid char development. The white oak specimens spallled at random lociltions on the fire-exposed face at moisture content values above 10 percent and bowed inward to the fire in the plane normal to the grain. With increasing moisture content, a deflection inward of the center of 1/2 inch on 10-inch length was common. Bowing of the oak specimens was noted primarily when the annual rings were oriented

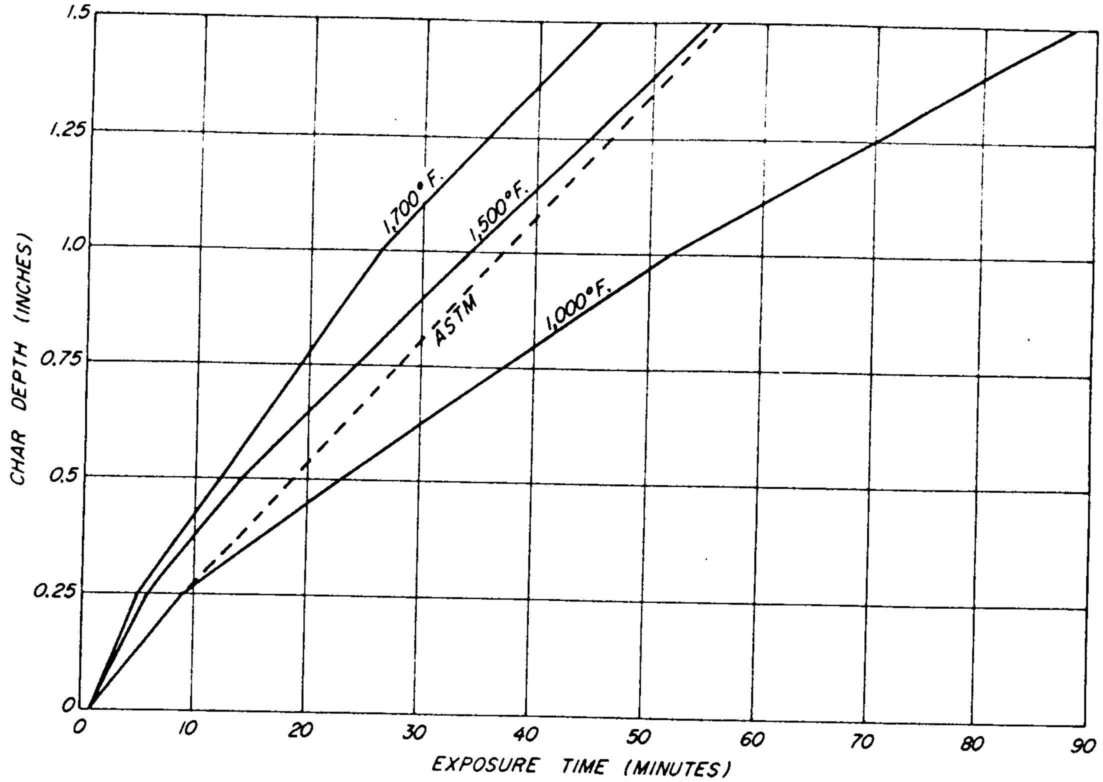

Figure 8.--Douglas-fir typical char depth variation with time under four fire-exposure conditions (specific gravity about 0.43, moisture content about 7 percent).

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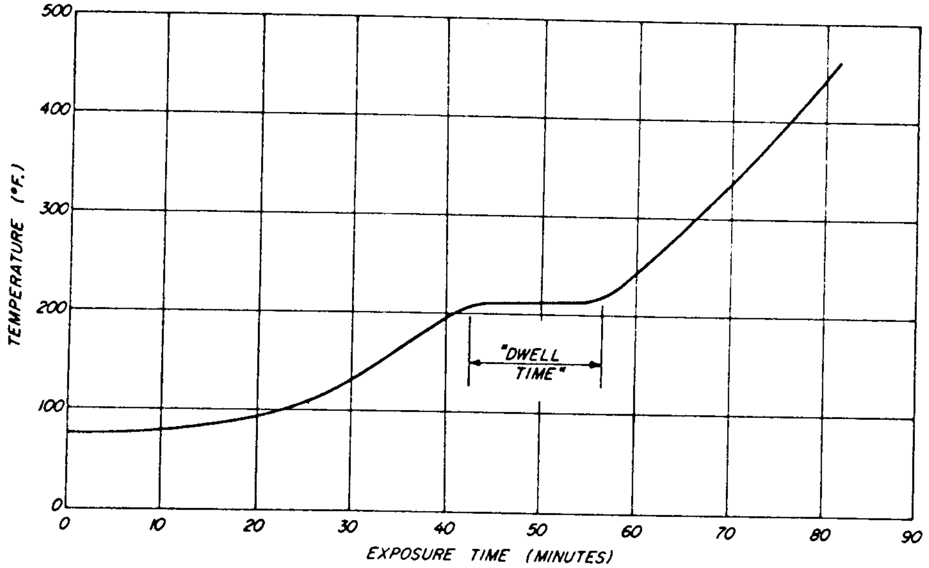

Figure 9.--Leveling of temperature-time curve for a given thermocouple location in a specimen exposed to fire.

(M 130 374)

parallel to the fire-exposed face.

Char-layer appearance for all species was dependent upon the fire-exposure temperature. The char formed at 1000° F. was of a finer texture than that formed at higher temperatures (and ASTM E-119-61 conditions) for all species. Fissures in the char layer were not as wide at the surface at 1000° F. exposure and the fissure pattern was regular compared to that at higher temperatures. The effect of fissures on the char base plane were noted to be proportionately less at the lower temperature.

Chipping the char layer from the residual uncharred section revealed two structurally distinct sublayers that had developed at exposure temperatures above 1000° F. At 1000° F. no distinction between layers was possible by the chipping method used. Generally, the surface layer, comprising about one-half the char layer thickness, had a lower structural strength than the base layer. The surface layer also was easily separated from the base sublayer. In the case of southern pine, the base sublayer was quite difficult to remove with a putty knife because of its sound structure.

Of particular importance in the observation of temperature rise at the thermocouple locations in the specimen was that between 200° to 280° F., the rate of change of the temperature-time curves was zero for a period of time. This thermostatic effect was proportional to the distance from the fire-exposed face, the equilibrium moisture content, and exposure temperature of the specimen. Figure 9 illustrates this leveling of the temperature-time curve at a given thermocouple location; this time portion of the curve is termed the 'dwell time.' This delay in rise of temperature at a given point in the wood may be attributed to the heat absorbed by the vaporization of condensed moisture.

ANALYSIS

Degradation to Char

A previous report (13) reviews two basic approaches that have been used to describe the rate of degradation to char. One method of expressing the charring rate utilizes the weight or mass loss per unit time, and the second expresses the rate as a dimensional change of the material per unit time. Because of the indications in past work at the U. S. Forest Products Laboratory (in 1936) that a direct correlation between the mass loss and dimensional change may exist after a quasi-steady-state of the combustion process is reached, only an analysis of models characterizing, dimensional change is presented.

Among the explicit models proposed for dimensional rates of char development is that used by Vorreiter (17) to describe the depth of char, *x*, developed on a 1-centimeter-thick plate. His expression was of the form:

$$x = \frac{D}{\rho - \rho_c} t^n \qquad (1)$$

when D = constant

ρ = specific gravity (subscript c denotes char)

t = time

In this and the following models presented for both char depth and rate of char development, the notation *x* implies both char depth and location of the char base from a fixed co-ordinate system that begins at the fire-exposed surface. Therefore, *x* represents an apparent char layer thickness and not the true thickness. The true char layer thickness is slightly less than the apparent thickness because of degradation of the char at the fire-exposed surface.

As a special case of equation (1), the results of work in Great Britain (6) and by Truax (16) imply that n = 1.0, or a uniform rate of char development. Truax, however, described the rate of charring under ASTM E-119 fire temperatures (2), while the British worked with three intensities of radiant heat flux (0.5, 0.7, and 1.0 calories per square centimeter per second).

If the constant *D* is a rate constant assumed to obey an Arrhenius-type law:

$$D = A \exp\left[-\frac{E}{RT}\right] \qquad (2)$$

then equation (1) becomes:

$$x = \frac{A}{(\rho - \rho_c)} t^n \exp\left[-\frac{E}{RT}\right] \qquad (3)$$

where *A* is a frequency factor (constant), *E* is a pseudo-activation energy, R is a gas constant, and T is the exposure temperature (°K).

Attempts to fit the char depth-time data to the degradation expressions previously discussed led to the adoption of two models--one for degradation under ASTM E-119 temperature exposure and the other for the rate of degradation to char under constant temperature exposures.

ASTM E-119-61 Exposure Conditions

Vorreitert's (17) general equation with n = 1.0 relatively satisfied the char depth-time data for all specimens when subjected to ASTM E-119-61 exposure (2). This equation was:

$$t = Bx \qquad (4)$$

in which the specific gravity term $\rho - \rho_c$ is incorporated in the coefficient B. The satisfaction of the char depth-time data by an equation of this type was not all chance, as the rate of gas consumption to heat the furnace interior to the prescribed temperatures was discovered to be nearly constant for an inert asbestos specimen. The same conditions are produced with an active wood specimen, independent of the heat liberated by the specimen. It is possible, then, that the constant rate of degradation to char under these conditions is linearly coupled to the heat supplied, but a more complete energy balance would be required to confirm this relationship.

In obtaining a similar form of equation (4), an equation of the type

$$t = \beta_0 + \beta_1 x \qquad (5)$$

was fit to each of the specimens exposed to ASTM E-119-61 conditions by linear regression analysis (5) to obtain the regression constants β_0 and β_1. It was found that β_0, the apparent time to ignition, was very nearly zero or fluctuated slightly about the origin. Another regression was then performed on each test considering β_0 equal to zero, or fitting the form of equation (4) exactly.

Evidently the rate of degradation immediately after the specimen ignites is higher than at later times when a constant rate exists, so that the average rate is constant with no apparent ignition time lag. Jean (9) states that a char depth of approximately 1/4 inch must be developed before the rate of degradation becomes constant. This is the depth at which the first experimental determinations of char base location were obtained in this study; hence, no record of the higher initial rate of degradation was obtained. Equation (4) applies in reality, therefore, only to char depth developments 1/4-inch deep and greater. An estimate of the transient temperature response period and, hence, the assumed approximate time required to develop a steady char rate, t_{ss}, can be further estimated by:

$$t_{ss} \approx \frac{\alpha}{v^2} \qquad (6)$$

where α is the thermal diffusivity and v the rate of char development at steady-state (14). For Douglas-fir the time required to develop a steady char rate is on the order of 22 minutes of fire exposure or 1/2-inch char depth. This period of time is almost exactly that suggested by Truax (16) for the temperature at the base of the char zone to become stable at 550° F.

The constant B of equation (4) was correlated to density and moisture content of specimens by regression analysis. Other material parameters, such as ring orientation or the ratio of springwood to summerwood, did not significantly affect charring rate or were accounted for by the density of the material. For example, plots of density versus the ratio of springwood to summerwood showed a linear relationship. Volatile extractive content was not significantly variable in these specimens, hence was not correlated. The factor B as related to dry specific gravity, ρ, and percent moisture content, M, in each species was derived as:

$$B = 2\{(a + bM)\rho + c\} \text{ (minutes per inch)} \qquad (7)$$

where a, b, and c are constants given in table 2.

The rate of char development v may be obtained from equation (4) by simple differentiation

$$v = \frac{dx}{dt} = \frac{1}{B} \text{ (inches per minute)} \qquad (8)$$

As an aid for rapidly determining the charring rate in Douglas-fir, southern pine, or white oak when the dry specific gravity and moisture con-

Table 2.--Species constants for char development equations

Species	Regression constants a	b	c	$\frac{JE}{R}$
				°K
ASTM E-119 CONDITIONS				
Douglas-fir	28.726	0.578	4.187	NA
Southern pine	5.832	.120	12.862	NA
White oak	20.036	.403	7.519	NA
CONSTANT EXPOSURE TEMPERATURES				
Douglas-fir	28.576	.576	4.548	1,564
Southern pine	7.587	.153	9.000	1,744
White oak	19.563	.394	7.789	1,739

tent of the wood are known, graphic illustrations of equation (8) for each species are presented in figures 10, 11, and 12.

Constant Fire Temperature Conditions

The char depth-time data obtained under the constant temperature fire exposures were compared with the characteristics of each model presented by other investigators. An attempt to regression fit Vorreiter's (17) equation (1) in the form

$$x = \frac{D}{\rho - \rho_c}(t - t_o)^n$$

where t_o suggests an ignition time correction and $\rho_c = 0.35\,\rho$, was unsuccessful The results indicated that the exponent, n, was not a constant but varied between 0.7 and 1,0. This exponent, then, evidently included the effect of material properties or exposure conditions. Considering that the constant D in the above equation obeys an Arrhenius temperature dependence law did not change the variation of n, therefore, this model was disregarded.

Lapple (10) proposed a model for ablating plastics that considered the charring rate as dependent upon the amount of undecomposed material remaining and Arrhenius temperature dependence. This equation is:

$$\frac{d\phi_d}{dt} = \frac{1}{A}(1 - \phi_d)\exp\left[-\frac{JE}{RT}\right] \qquad (9)$$

where ϕ_d = decomposed fraction of material

J = Joule's constant

In the above expression $1 - \phi_d$ is equivalent to the undecomposed fraction of material. Integrating this equation, with the assumption that at zero time the decomposed fraction, ϕ_d, is zero, yields:

$$t = -A\ \ln\ (1 - \phi_d)\exp\left[\frac{JE}{RT}\right] \qquad (10)$$

In the experiments conducted, the decomposed fraction of material, ϕ_d, may be considered as the char base location, x, as measured from the initially undecomposed surface, divided by a characteristic reactive length, x_o, or

$$\phi_d = \frac{x}{x_o}$$

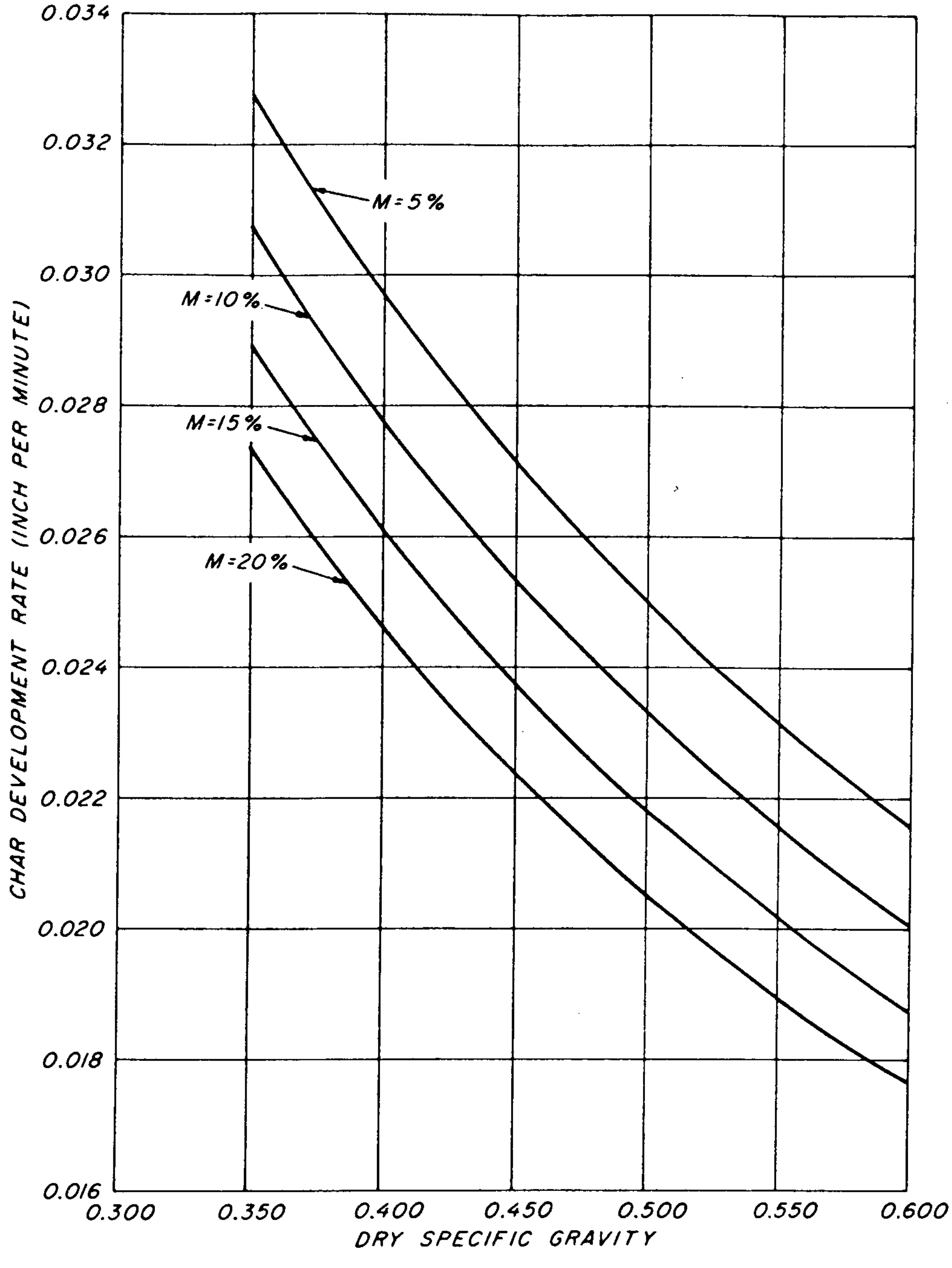

Figure 10.--Douglas-fir: Variation of char development rate with dry specific gravity and moisture content, $\underline{M}$, under ASTM E-119-61 fire exposure temperatures.
(M 130 376)

The characteristic reactive length may be interpreted as the depth of material per unit area of surface that influences the rate of decomposition.

Equation (10) then takes the form:

$$t = -A \ln\left(1 - \frac{x}{x_0}\right) \exp\left[\frac{JE}{RT}\right] \qquad (11)$$

The characteristic reactive length was at first estimated to be the specimen thickness of 3.0 inches. A test of the experimental data indicated that the 3.0 inch reactive length led to excellent agreement for depths of char to 1.5 inches. However, this model is probably not true when extrapolated to a char depth of 3.0 inches. Equation (11) predicts that it requires an "infinite" time under any constant temperature $\underline{T}$, for the char rate to approach zero at 3.0 inches of char depth.

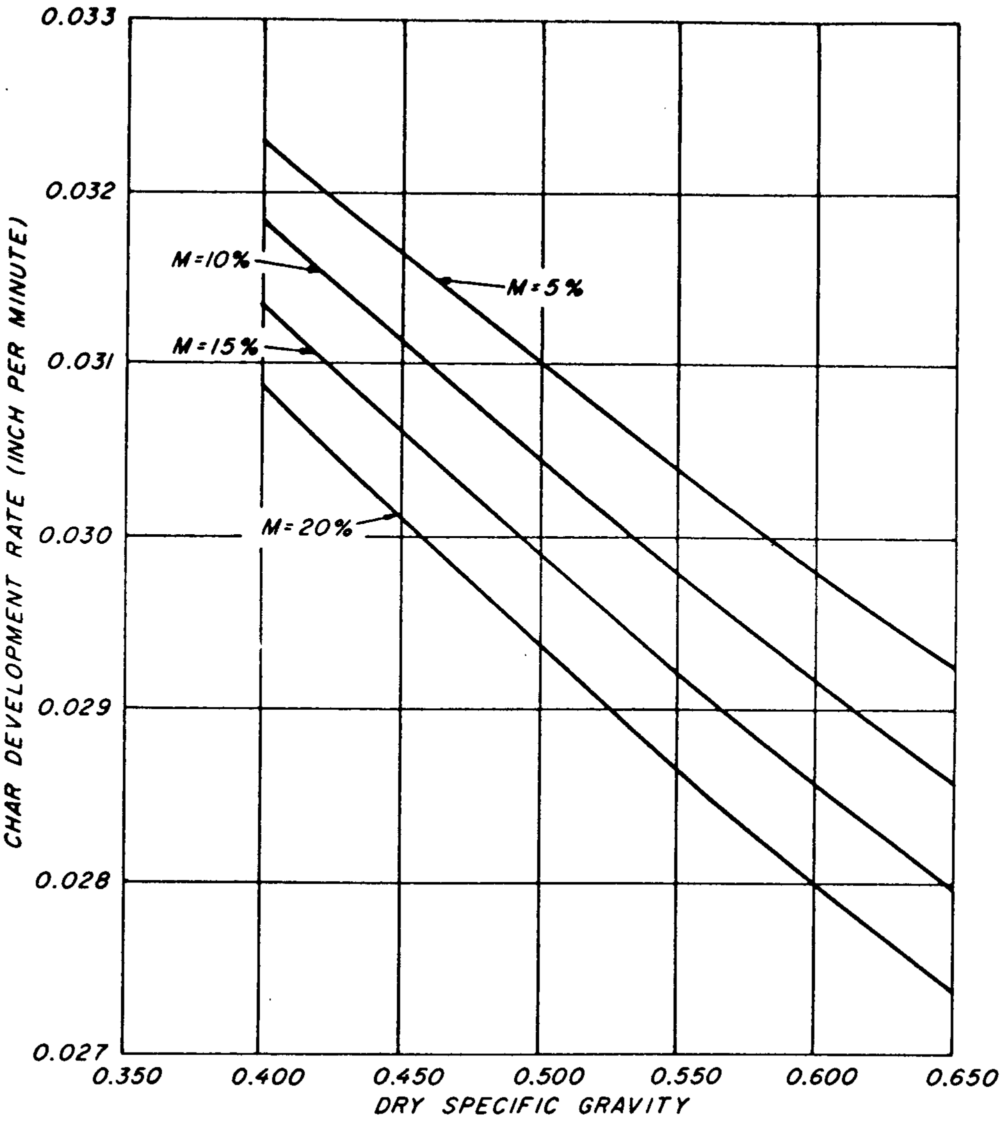

Figure 11.--Southern pine: Variation of char development rate with dry specific gravity and moisture content, M, under ASTM E-119-61 fire exposure temperatures.

(M 130 377)

Evidently the char layer grows in depth without significant loss of char at the fire-exposed surface until approximately a 2-inch layer is formed. Hence for char depths exceeding 2 inches, the rate of degradation of the surface char governs the rate of charring. Because of its good "fit" to the char depth-time data to a char depth of 1.5 inches, however, it was decided to retain the 3-inch value for x_o. Char depth was assumed to be related to time, and straight line regressions were used to fit the experimental data to the form:

$$t = \beta_o \ln \left(1 - \frac{x}{3.0}\right) + \beta_1 \qquad (12)$$

where β_o and β_1 were determined for each specimen. At zero time the intercept β_1 was nearly equal to zero and was therefore set equal to zero. A new regression was run to redetermine β_o for each specimen using

$$t = \beta_o \ln \left(1 - \frac{x}{3.0}\right) \qquad (13)$$

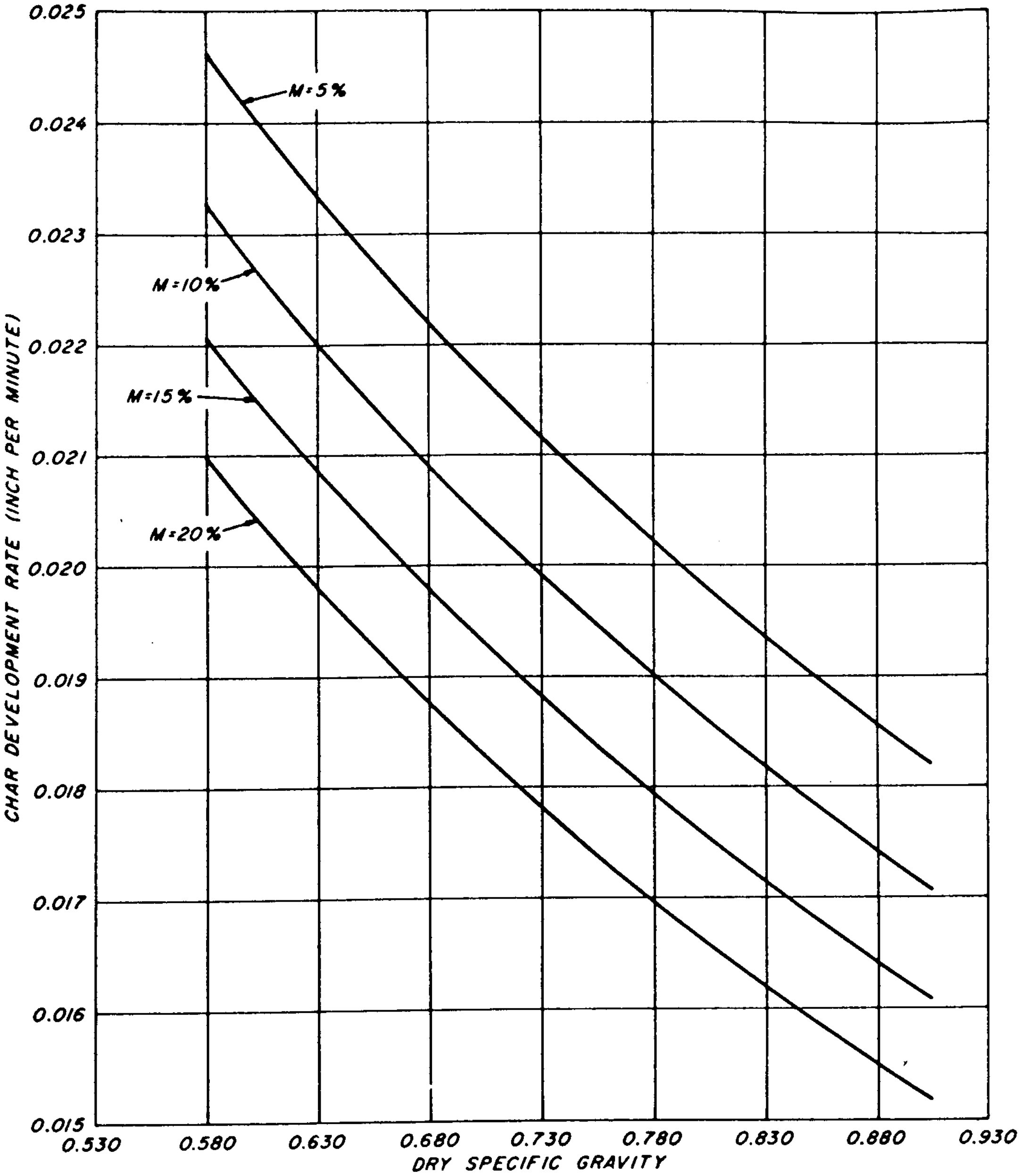

Figure 12.--White oak: Variation of char development rate with dry specific gravity and moisture content, M, under ASTM E-119-61 fire exposure temperatures.

(M 130 378)

The β_o values obtained for each constant temperature exposure test were then assumed to be Arrhenius temperature dependent, or

$$\beta_o = - A \exp\left[\frac{JE}{RT}\right] \tag{14}$$

according to equation (11).

The term $\frac{JE}{R}$ was then related to all β_o values for a given species by regression analysis. This resulted in an effective; $\frac{JE}{R}$ value for each species as follows:

Douglas-fir $\frac{JE}{R} = 1564$ (°K)

Southern pine $\frac{JE}{R} = 1744$ (°K)

White oak $\frac{JE}{R} = 1739$ (°K)

The pseudo-activation energies E may be determined from these results if the following equivalents are applied

J = Joule's constant = 4.184 (joules per calorie)
R = gas constant = 8.14 (joules per gram-mole per °K)

This results in values of E for each species:

Douglas-fir E = 3108 calories per gram-mole
Southern pine: E = 3465 calories per gram-mole
White oak E = 3455 calories per gram-mole

These pseudo-activation energies lack physical significance since a mole of wood is undefined, but are included to show how the rate of charring depends upon the heat level. Having obtained the $\frac{JE}{R}$ term of equation (14) for each species, it remained to determine the relationship between the term A (frequency factor) and material or test parameters. Significance plots of the values of A for each test after least squares fits of equation (14) to char depth-time data indicated that only specific gravity and moisture content affected the value of A. The resulting expression for A after their effect was included statistically was of the form obtained for the ASTM E-119-61 temperature conditions:

$$A = (a + bM)\rho + c \qquad (15)$$

where a, b, and c differ for each species and are given in table 2.

The equations for each species relating exposure time, t, in minutes to apparent char depth, x, in inches under constant exposure temperature, T, (°K) may then be summarized as follows:

Time to char depth:

$$t = - A \ln \left(1 - \frac{x}{3.0}\right) \exp \left[\frac{JE}{RT}\right] \text{ (minutes)} \qquad (16)$$

Charring rate :

$$v = \frac{1}{A} (3.0 - x) \exp \left[- \frac{JE}{RT}\right] \text{ (inch per minute)} \qquad (17)$$

An interesting result was noted in the constants (table 2) relating the rates of char development to dry specific gravity and moisture content. If MacLean's (12) equation for thermal conductivity of wood.

$$k = (1.39 + .028M)\rho + .165 \text{ (BTU's per foot per hour per °F.)}$$

is compared to the form of equations (7) and (15),

$$A = (a + bM)\rho + c$$

the following may be noted:

$$\frac{a}{b} \doteq \frac{1.39}{0.028} .$$

This result suggests that the dry specific gravity and moisture content of the wood affect both the heat conduction property and transverse charring rate of wood in the same ratio.

Variance

The sum of the squares of the differences in observed and predicted times for char to reach a given depth for each species and exposure condition were utilized to determine the standard deviation between predicted and observed time. The standard deviation, σ, is given by (5):

$$\sigma = \left[\frac{\sum_{n=1}^{N} \left(t_n - \bar{t}_n\right)^2}{N - 1}\right]^{1/2}$$

where t_n = predicted time,

$\bar{t}_n$ = observed time,

and N = number of observations.

The standard deviation, σ, determined in minutes for each species and exposure condition is given in table 3, and varies between 2.62 and 5.14 minutes. Generally, the deviation between predicted and actually observed time to develop a certain depth of char increased with increasing depth of char. The predicted times to develop a char depth of 1/4 inch under constant temperature exposures was consistently greater than the observed times by about 1.0 to 3.0 minutes. This could be due to a fallibility of the model to predict the amount of time elapsed between ignition and a char depth of 1/4 inch, or the temperature of the char base at this depth is slightly higher than the 550° F. assumed for locating the char base.

Table 3.--Standard deviation, σ, between observed ($\bar{t}_n$) and predicted (t_n) times to develop a given char depth

Species	ASTM E-119 conditions (2)			Constant temperature conditions		
	$\Sigma(t_n-\bar{t}_n)^2$	Degrees of freedom	Standard deviation σ	$\Sigma(t_n-\bar{t}_n)^2$	Degrees of freedom	Standard deviation σ
		N-1	Min.		N-1	Min.
Douglas-fir	489	71	2.6	2585	199	3.6
Southern pine	495	47	3.2	2557	143	4.2
White oak	627	47	3.6	3773	143	5.1

CONCLUSIONS

1. The rate of char development after ignition of the wood surface was quite rapid under ASTM E-119-61. conditions and decreased to a uniform rate after approximately 1/4 inch of char was formed. A characteristic char base temperature of 550° F. (288° C.) was useful in locating the char base under all temperature exposures after this l/4-inch-thick layer of char was formed.

2. Crack and fissure dimensions in the char layer depended upon the exposure temperature and density of the wood. Increases in crack width were associated with higher exposure temperatures, and char development was slightly greater (on the order of 1/8 inch) in depth at fissure locations with increasing exposure temperatures and decreasing density of the wood. This was readily observable in the two lighter species, Douglas-fir and southern pine. The depth of char was quite uniform for white oak at all exposure temperatures.

3. Equilibrium moisture content values at or above 14 percent in Douglas-fir, 16 percent in southern pine, and 10 percent in white oak caused char to span in arens of the exposed surface, increased the occurrence of specimen checking along the grain at the fire-exposed face, and caused deformation of the specimen. The levels of moisture content cited reflect the correlative effect of moisture permeability of the species on char spallation; white oak is less permeable than Douglas-fir, which is less permeable than southern pine.

4. Two models describing the rate of char development in each species are proposed: one for ASTM E-119-61 fire conditions and the other for constant fire temperature exposures on one surface of thick wood plates (greater than or equal to 3 inches thick). Wood parameters found to affect the rate of char were the dry specific gravity and moisture content. Standard deviations for the difference between the observed times to a given char depth and those predicted by the equations developed indicate that the models chosen will predict the time to a given char depth within 2.6 to 5.1 minutes.

5. The diffusion of moisture, composed of the initial moisture content and possibly of moisture produced by the combustion process, limits the rate of temperature rise to degradation in proportion to initial content and duration of fire exposure (or increasing char depth), The effect is to increase the dwell in temperature at the apparent boiling point of water with increasing initial moisture content.

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