

TRANSIENT MOISTURE GRADIENT IN FIRE-EXPOSED WOOD SLAB

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ABSTRACT

Improved fire endurance design procedures for heavy timber members may require the input of moisture content-dependent allowable stresses. Therefore, experiments were conducted to characterize the transient moisture gradient in a wood slab subjected to fire on one face. Electrodes and thermocouples embedded within the wood sections monitored moisture and temperature levels at selected locations. Time-moisture content curves indicated an increase in moisture content that appeared to be associated with the vaporization of the bound water in the wood. For the eight slabs tested, the average peak moisture content was 1.26 to 2.00 times greater than the initial moisture content.

Keywords: Moisture content, charring, fire endurance, fire resistance, permeability, southern pine, Douglas-fir, white oak, heat transfer, mass transfer.

INTRODUCTION

As with most wood properties, the existence of moisture has an effect on the fire performance of wood. Past research has shown that the char rate decreases with an increase in moisture content and a dwell occurs in the temperature rise within a fire-exposed wood slab at about 100 C, the boiling point of water. Thus, there is a need to incorporate the effect of moisture into theoretical char rate and temperature distribution models. Improved fire endurance design procedures for heavy timber members may also require the input of moisture content-dependent allowable stresses. In this study, experiments were conducted to obtain data on the transient moisture gradient in a wood slab subjected to fire on one face. The results are shown as time-moisture content curves for different locations within fire-exposed wood slabs.

METHODS

The general approach consisted of fire exposing one side of wood slabs 86-mm (3.4 in) thick in a gas-fired furnace. Southern pine (sapwood), Douglas-fir (heartwood), and white oak (heartwood) at various initial equilibrium moisture contents and ring orientation were used (Table 1). Electrodes and thermocouples embedded within the wood sections monitored moisture content and temperature levels at selected locations.

Wood slabs and furnace

Eight 86- × 254- × 508-mm (3.4- × 10- × 20-in.) slabs (Table 1) were constructed and exposed to fire in a small vertical furnace. The southern pine and Douglas-fir slabs consisted of three 86- × 86- × 508-mm (3.4- × 3.4- × 20-in.) sections glued together with phenol-resorcinol glue. The white oak slab consisted of six 41- × 86- × 508-mm (1.6- × 3.4- × 20-in.) sections. The sides of the slabs

¹ Maintained at Madison, WI, in cooperation with the University of Wisconsin.

TABLE 1. Description of slabs tested.

Test no.	Species	Conditioning	Furnace temperature	Specific gravity ¹	Ring orientation ²
1	Southern pine	27 C, 65% RH	E 119 ³	0.51	90
2	Southern pine	27 C, 65% RH	927 C	0.53	40
3	Southern pine	27 C, 65% RH	538 C	0.52	55
4	Douglas-fir	27 C, 65% RH	E 119	0.48	45
5	White oak	27 C, 65% RH	E 119	0.79	0
6	Southern pine	27 C, 90% RH	E 119	0.55	0
7	Southern pine	oven-dry ⁴	E 119	0.55	90
8	Southern pine	27 C, 65% RH	E 119	0.49	0

¹ Based on oven-dry weight and oven-dry volume.

² Approximate angle (degrees) of annual rings to the fire-exposed surface.

³ Standard time-temperature curve specified in ANSI/ASTM Standard E 119-78 (ASTM, 1978).

⁴ Specimen dried in oven for 10 days at 65 C, 14 days at 100 C before and 3 days at 65 C after gluing of three sections of specimen.

were coated with a coating (rock tar) to limit end-grain moisture loss. The slabs were placed between two concrete blocks in the 515-mm (20.3-in.) square opening on one side of the furnace (Fig. 1). The furnace was equipped with pipe outlets for discharging natural gas into the interior of the furnace. All air for combustion was admitted by natural draft through vents at the bottom of the furnace with baffling to get proper distribution. The input of natural gas was regulated to control the temperature inside the furnace. The temperature inside the furnace

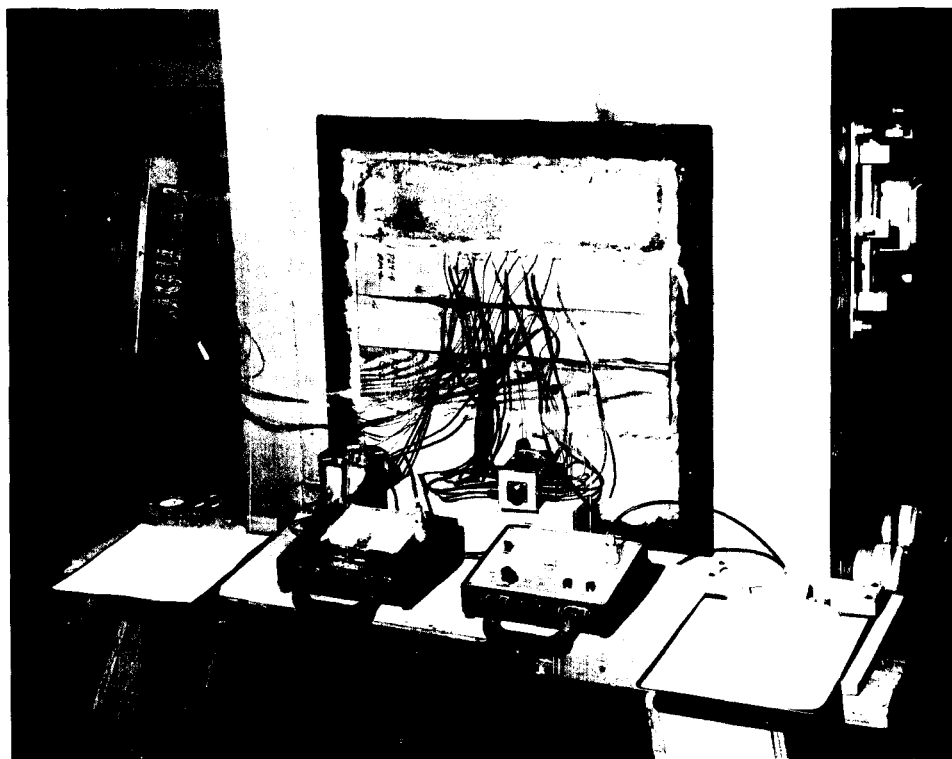


FIG. 1. Wood slab in small vertical furnace and moisture meters used to measure the moisture content within the slab.

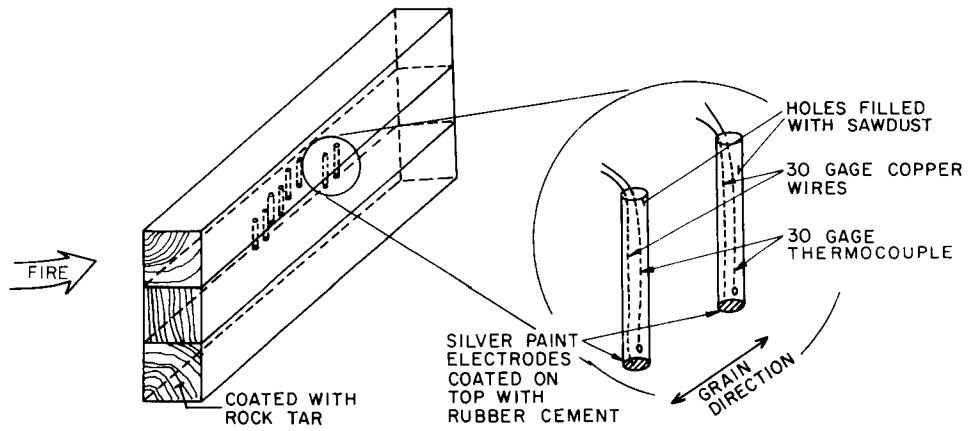


FIG. 2. Instrumentation within the wood slabs. Silver conductive paint coated on the bottom of a pair of holes which were used to obtain the moisture content measurements.

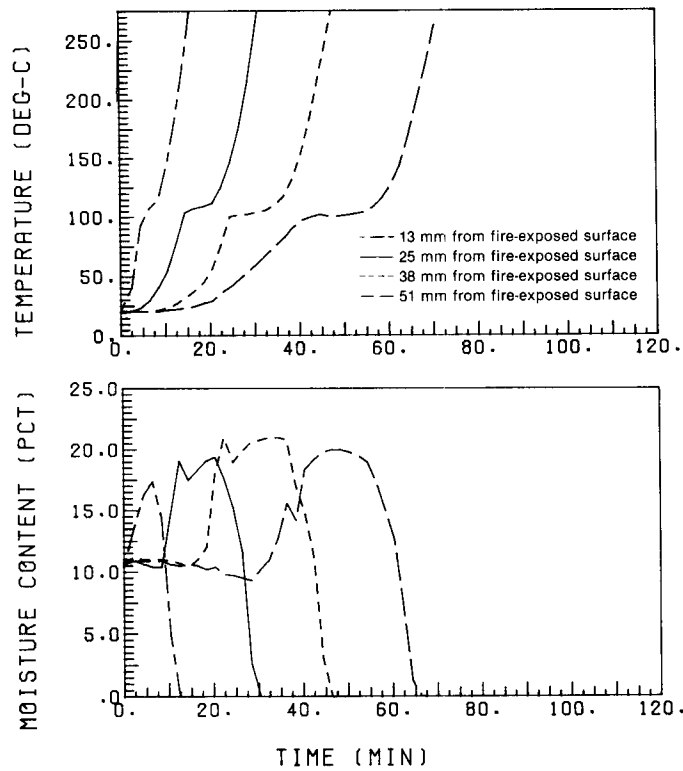


FIG. 3. Time-temperature and time-moisture content curves of Standard E 119 fire-exposed southern pine wood slab (test No. 1). Initial equilibrium moisture content established by conditioning in 27 C, 65% RH room.

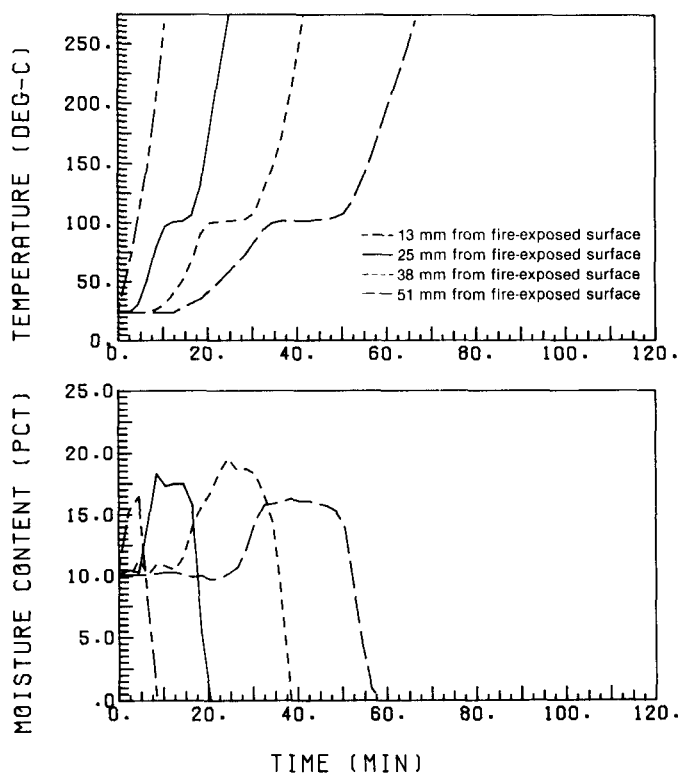


FIG. 4. Time-temperature and time-moisture content curves of southern pine wood slab (test No. 2) subjected to a more severe fire exposure than Standard E 119 (a temperature of 927 C). Slab conditioned to moisture equilibrium in 27 C, 65% RH room.

was obtained from a single iron-capped thermocouple which was 51 mm (2 in.) from the original surface of the slab, 100 mm (4 in.) above the bottom of the slab, and equal distance from each side of the slab.

Moisture content and temperature measurements

Moisture content and temperature measurements were taken within the middle section of the Douglas-fir and southern pine slabs, and the fourth section from the top of the white oak slab. These sections were opposite the iron-capped control thermocouple inside the furnace. Moisture content and temperature measurements were also taken within other sections of the slabs. The electrodes (Fig. 2) for moisture content measurements and thermocouples for temperature measurements were 13, 25, 38, and 51 mm (0.5, 1, 1.5, and 2 in.) on center from the original fire-exposed surface of the slab and within the central 200 mm (8 in.) of the 508-mm (20 in.) long section.

Moisture content readings were obtained with a moisture meter that measures the resistance between electrodes. The electrodes (Fig. 2) at the different locations were silver conductive paint coated on the bottom of a pair of 6.4-mm (0.25-in.) diameter, 38-mm (1.5 in.) (20 mm [0.8 in.] for white oak slab) deep, flat-bottomed holes. The holes were drilled from the top of the section before the slab

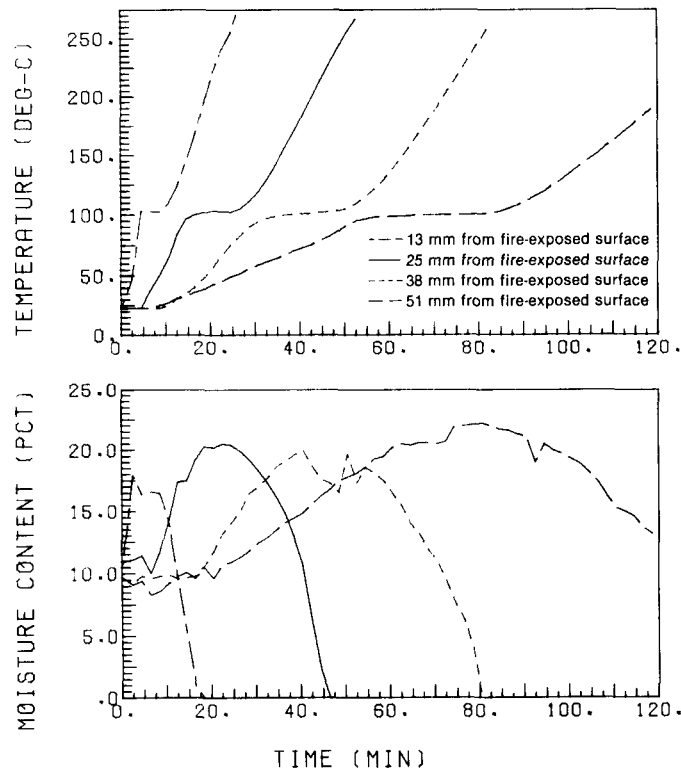


FIG. 5. Time-temperature and time-moisture content curves of southern pine wood slab (test No. 3) subjected to a less severe fire exposure than Standard E 119 (temperature 538 C). Conditioned to moisture equilibrium in 27 C, 65% RH room.

was glued together. Thus, the length of the hole was perpendicular to the direction of flow of heat and moisture. The electrodes in each pair were 25 mm (1 in.) on center from each other so that resistance parallel to the grain was measured. Cotton insulated copper wires (30 gage) were attached to the electrodes with a second layer of silver paint and a layer of rubber cement. A 30-gage thermocouple was placed in each of the holes. The holes were filled with sawdust to minimize interference to moisture flow and reduce the void volume.

The resistance measurement of moisture content required the conversion of electrical resistance to moisture content. The conversion is based on the nearly linear inverse relationship between the logarithm of the electrical resistance and the logarithm of the moisture content between oven-dry and fiber saturation. Because of the high resistance involved at room temperature, the lower limit for moisture meter measurements is 5%. The fiber saturation point is about 30% at room temperature. For a variety of reasons, resistance measurement of moisture content above the fiber saturation point is not considered reliable.

The manufacturer's calibration of the moisture meter was based on Douglas-fir at 21 C. Since the electrical resistance of wood decreases as the temperature increases, the meter readings must be corrected for temperature. The meter read-

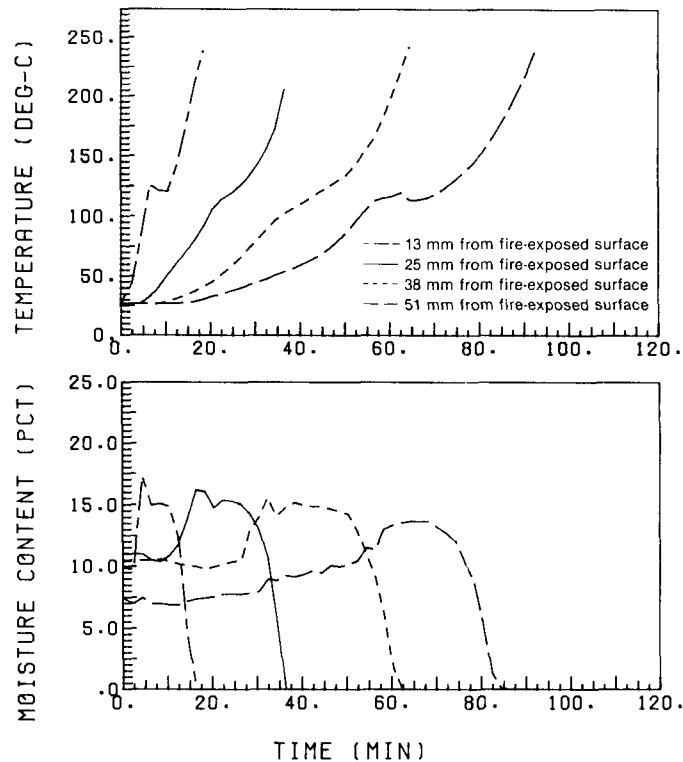


FIG. 6. Time-temperature and time-moisture content curves of slab (test No. 4) of Douglas-fir, a species less permeable than southern pine. Specimen conditioned to moisture equilibrium in 27 C, 65% RH room prior to fire exposure (E 119).

ings were corrected for temperatures up to 100 C by using the correction curves of James (1975) for meter readings below 28%, and the curves of Keylwerth and Noack (Kollmann and Côté 1968) for meter readings at or above 28%. These curves were extrapolated to 250 C in order to obtain corrections for temperatures above 100 C. The corrections provided by the manufacturer of the meter were used to correct for species.

During the fire exposure of the slabs, moisture meter readings were taken at 2-min intervals. A different meter was used to take the readings for each of the two sections of the slab with electrodes in them. It took 1 min to read the four pairs of electrodes in a section of the slab.

Verification of methodology

Two types of tests were conducted to partially verify the results obtained using the resistance moisture meter. Methodology tests involving moisture contents of 7 to 17% and temperatures of 20 to 100 C generally supported the temperature corrections used in this study. These tests consisted of putting a pair of electrodes, and thermocouples in the center of a coated block (rock tar) of southern pine and slowly heating the block in an oven. As moisture content remained

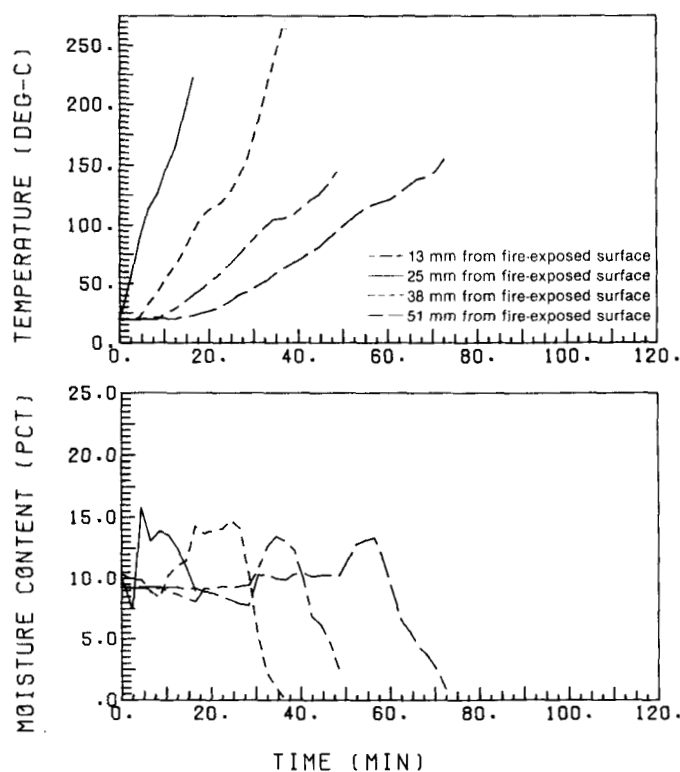


FIG. 7. Time-temperature and time-moisture content curves of slab (test No. 5) of white oak, a species less permeable than Douglas-fir. Specimen conditioned to moisture equilibrium in 27 C, 65% RH room prior to fire exposure (E 119).

constant during the test, any change in the meter reading was due to temperature. An oven-dry moisture content determination was made at the end of the test.

Tests were also conducted in which the specimen was removed from the furnace after fire exposure for oven-dry moisture content measurement using a sectioning procedure. In two of these tests, a single 86- × 86- × 508-mm (3.4- × 3.4- × 20-in.) block of southern pine (27 C, 65% RH conditioning) was placed between concrete blocks in the opening on the side of the furnace and opposite the iron-capped thermocouple. Thermocouples were inserted in 3-mm (0.125-in.) diameter holes drilled down from the top of the specimen at locations 13 to 70 mm (0.5 to 2.75 in.) from the original fire-exposed surface. The specimen was subjected to fire exposure (ASTM E 119 or constant 538 C) until the thermocouple 25 mm (1 in.) from the original fire-exposed surface recorded a temperature just below 150 C. After the specimen had been removed from the furnace, about 175 mm (6.9 in.) was cut from each end of the specimen and about 30 mm (1.2 in.) was cut from the top and bottom of the specimen. A bandsaw was used to cut 1.8-mm (0.07-in.) thick slices out of the 48- × 86- × 152-mm (1.9- × 3.4- × 6-in.) block remaining. The slices were cut from the part of the block which was 25 to

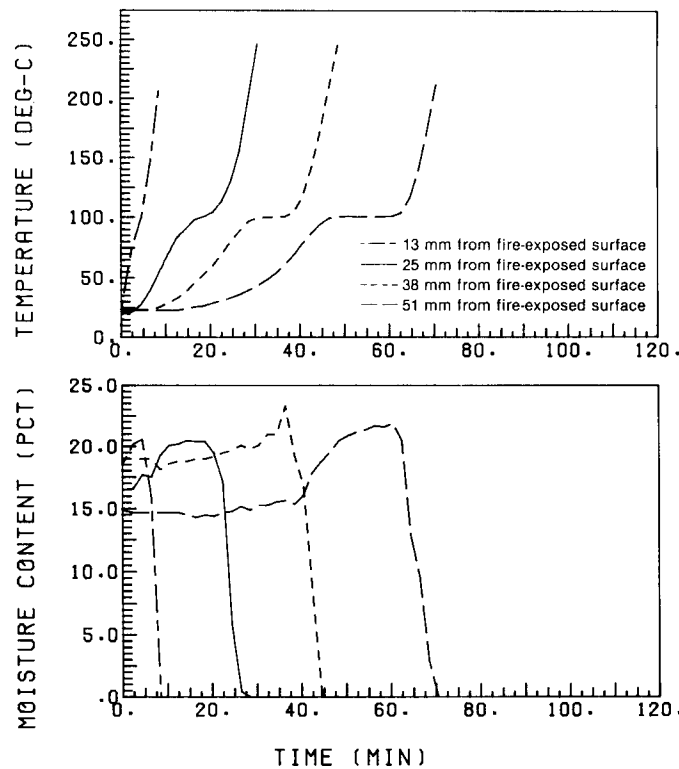


FIG. 8. Time-temperature and time-moisture content curves of southern pine slab (test No. 6) with a higher initial moisture content than the other slabs. Specimen conditioned to moisture equilibrium in 27 C, 90% RH room prior to E 119 standard fire exposure.

70 mm (1 to 2.75 in.) from the original fire-exposed surface. The weighing of the slices was completed about 15 min after the specimen was removed from the furnace. The oven-dry-sectioning results are given in the section on results and discussion.

RESULTS AND DISCUSSION

The basic results of this study are the time-moisture content curves for the different locations within the fire-exposed wood slabs. For each time-moisture content curve, there is a peak in the moisture content. Associated with the peak moisture content, there was a dwell in the time-temperature curves obtained with thermocouples at the different locations in the slab. To partially verify the results obtained with the resistance measurement of moisture content, some oven-dry measurements of the moisture content were made. The validity of the time-moisture content curves is dependent on the accuracy of resistance measurement of the transient moisture content. Each of the above items is discussed in this section. The section is concluded with a discussion of the possible driving forces causing the moisture transfer associated with the transient moisture content gradient and a review of a possible analytical model.

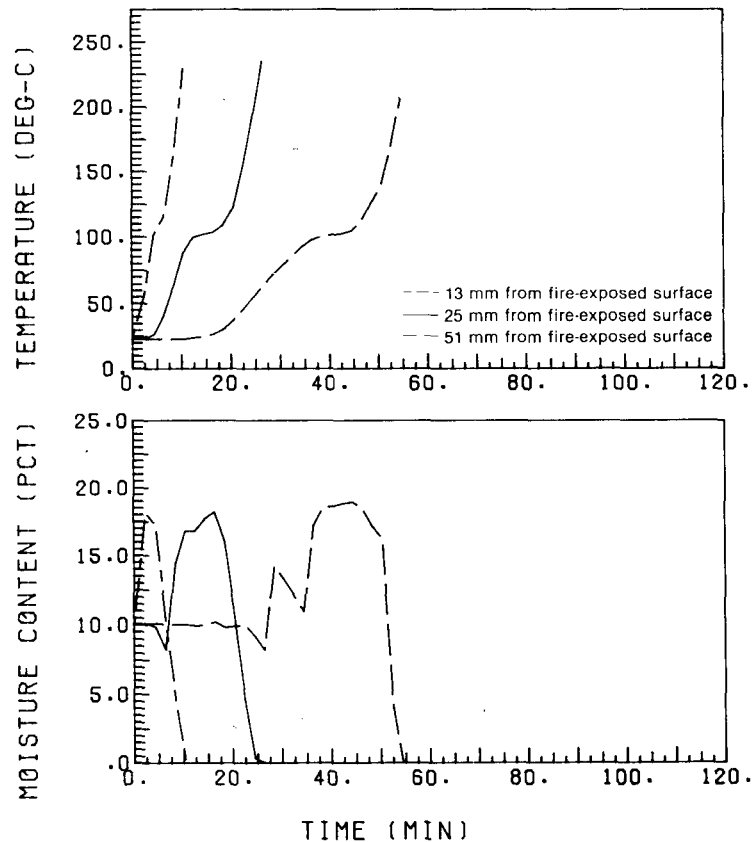


FIG. 9. Time-temperature and time-moisture content curves of southern pine slab (test No. 8) with annual rings parallel to the fire-exposed surface instead of perpendicular to the surface. Specimen conditioned to moisture equilibrium at 27 C, 65% RH prior to E 119 fire exposure.

Time-moisture content curves

The results are presented as time-moisture content curves and time-temperature curves at 13, 25, 38, and 51 mm (0.5, 1, 1.5, and 2 in.) from the original fire-exposed surface (Figs. 3-9). In the middle section of the oven-dry slab, the temperature-corrected moisture content did not exceed 1% moisture content. Measurements in the top section of the slab did indicate moisture at the 25-, 38-, and 51-mm (1-, 1.5-, and 2-in.) locations.

In the constant high-temperature (927 C) exposure, considered more severe than the ASTM E 119 exposure test (test No. 2), the final exposure temperature was not attained as rapidly as desired. Furnace temperature development was 538, 732, 860, 916, and 927 C at 3, 5, 10, 15, and 17 min, respectively. The standard ASTM E 119 time-temperature exposure is 538, 704, 760, and 927 C at 5, 10, 15, and 60 min, respectively.

Earlier research at the Forest Products Laboratory on moisture gradients produced during the Standard ASTM E 119 fire exposure of wood slabs was conducted by Schaffer and Duff in 1965 (Schaffer 1977). The change in electrical resistance of small wood probes (Duff 1966) embedded within Douglas-fir slabs was recorded. Typical curves obtained in this earlier work are shown in Fig. 10.

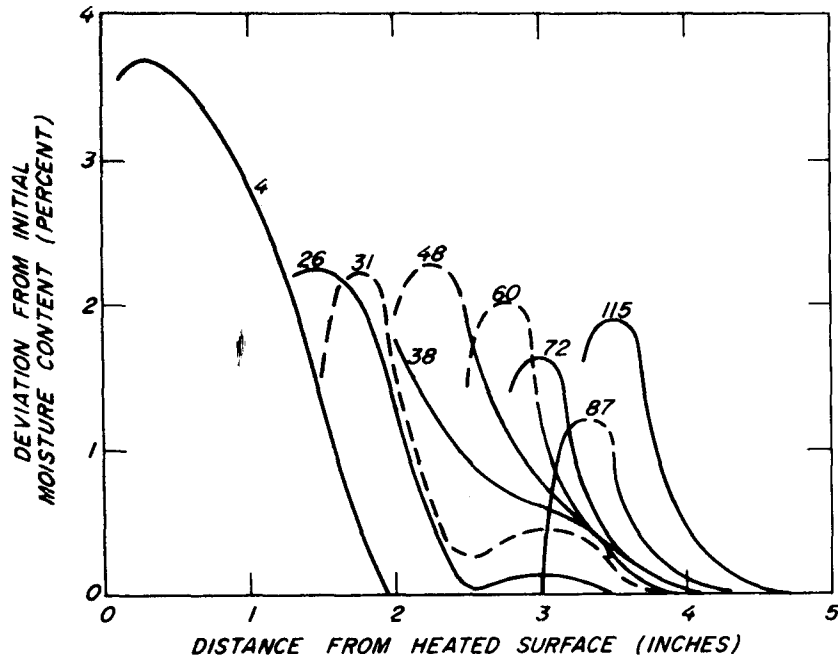


FIG. 10. Moisture gradients in charring Douglas-fir slab (190 mm [7.5 in.] thick) having initial moisture content of 16% exposed to Standard ASTM E 119 fire on one surface (time in minutes is indicated at each peak) (Schaffer 1977).

Initial moisture content was 16%. The current study was conducted because of uncertainties in the accuracy of the previous work. Current results are in general agreement with the earlier work.

At a location behind the char layer, there is an increase in moisture content. The magnitude of the maximum increase in moisture content can be expressed as the peak moisture content.

Peak moisture content

The time of peak moisture content versus location and time of char/wood interface (288 C) versus location for test Nos. 2 and 3 are shown in Fig. 11. The data for the rest of the tests are between the data for these two tests. The char rate (Table 2) is based on least-square analysis of times from ignition that the thermocouples at the four locations recorded 288 C, and the distance from the original fire-exposed surface. The peak moisture content rate (Table 2) is based on least-square analysis of times of the peak moisture content at the four locations and the distance from the original fire-exposed surface. In the cases in which there was a plateau (less than 1% moisture content change) in the time-moisture content curve, the midpoint in the plateau was recorded as the time of peak moisture content. The linear correlation coefficients, r , for the peak moisture content time—location and char base time—location data are extremely high (0.98+).

TABLE 2. *Experimental results.*

Test no.	Species	Average initial moisture content	Average peak moisture content	Fractional increase	Char rate	Peak moisture content rate	Fraction of moisture driven
		%	%			mm/hr	
1	S.P.	11	19	0.81	41	53	0.57
2	S.P.	10	18	0.74	40	61	0.39
3	S.P.	10	20	1.00	25	29	0.61
4	D.F.	10	16	0.62	29	37	0.23
5	W.O.	10	14	0.47	35	46	0.09
6	S.P.	17	22	0.26	40	43	0.05
7 ¹	S.P.	—	—	—	52	—	—
8	S.P.	10	18	0.86	51	58	— ²

¹ Moisture content measurements within middle section of oven-dry slab indicated no moisture.

² Fraction of moisture driven was not computed due to lack of data at the 38-mm location.

The peak moisture content can be described as a front that moves through a fire-exposed section in a fashion that is correlated with the location of the char/wood interface. A graph of time of peak moisture content versus time of char/wood interface is given in Fig. 12. The data have a correlation coefficient of 0.94 and are consistent with those reported previously (Schaffer 1977). The data indicated no correlation between the magnitude of the peak moisture content and the distance from the original fire-exposed surface.

For each slab, the initial moisture content reading of the four pairs of electrodes was averaged (Table 2). The average of the peak moisture contents recorded by the four pairs of electrodes and the fractional increase of the average peak mois-

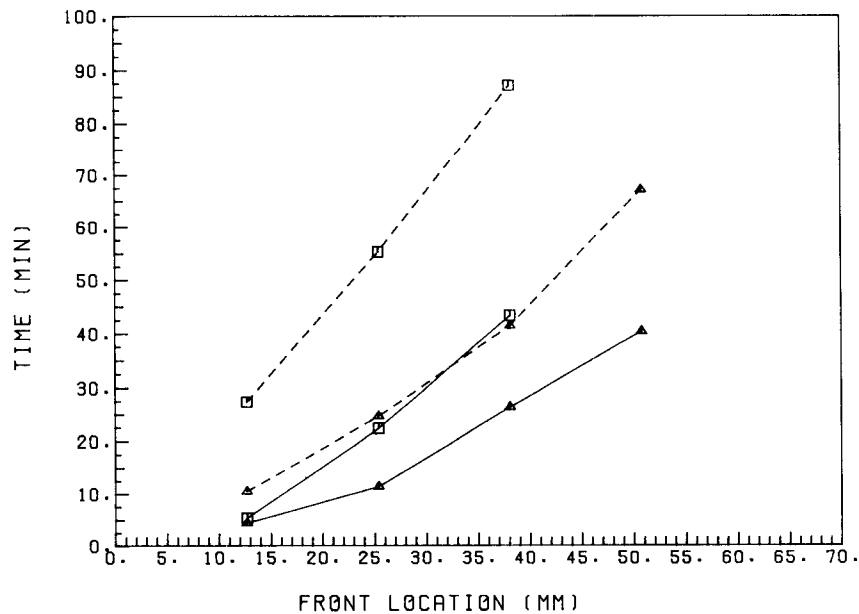


FIG. 11. Curves of time of peak moisture content front versus location (—) and time of char/wood front versus location (- -) for test Nos. 2 (Δ) and 3 (\square).

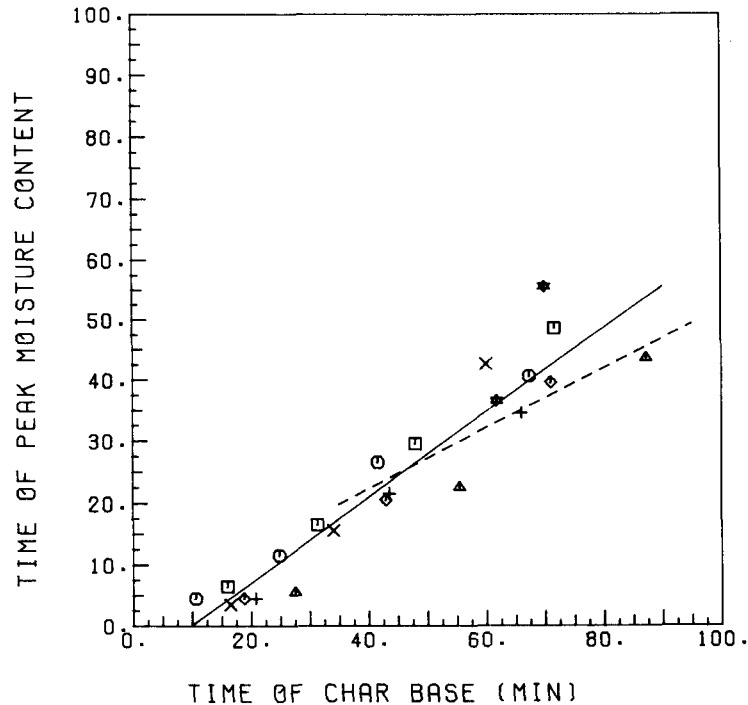


FIG. 12. Correlation between the time of peak moisture content and time of char base. The symbols □, ○, △, ◇, +, *, and × are for test Nos. 1, 2, 3, 4, 5, 6, and 7, respectively. Dashed line from results of Schaffer and Duff (Schaffer 1977).

ture content over the initial moisture content are also given in Table 2. The largest increase in moisture content occurred in the low heat exposure of a southern pine slab (test No. 3). A more severe fire exposure (test Nos. 1, 2, and 8) resulted in a slightly lower peak moisture content and a reduction in the duration of the peak moisture content. The white oak and Douglas-fir slabs (test Nos. 4 and 5) had a lower peak moisture content than the southern pine slabs (test Nos. 1 and 8).

There was a small increase of moisture content in the slab with the high initial moisture content (test No. 6). This test, along with the others, suggests that the highest peak moisture content possible is about 24%. This may be because the equilibrium moisture content for 100% relative humidity and 100 C is 23% (Stamm and Loughborough 1935). The existence of free liquid water above the fiber saturation point was not indicated in any of the tests.

This transient pulse-type moisture gradient is associated with a dwell in the rise in temperature within the fire-exposed slab. The increase in moisture content occurred as the temperature increased to 100 C. On the average, the peak moisture content occurred at a temperature of 98 C. At or above 100 C, the moisture content decreased to zero.

Temperature dwell

At temperatures around 100 C, there was a dwell in the temperature rise (Figs. 3-9). This thermostatic effect, much like that seen in wood drying experiments,

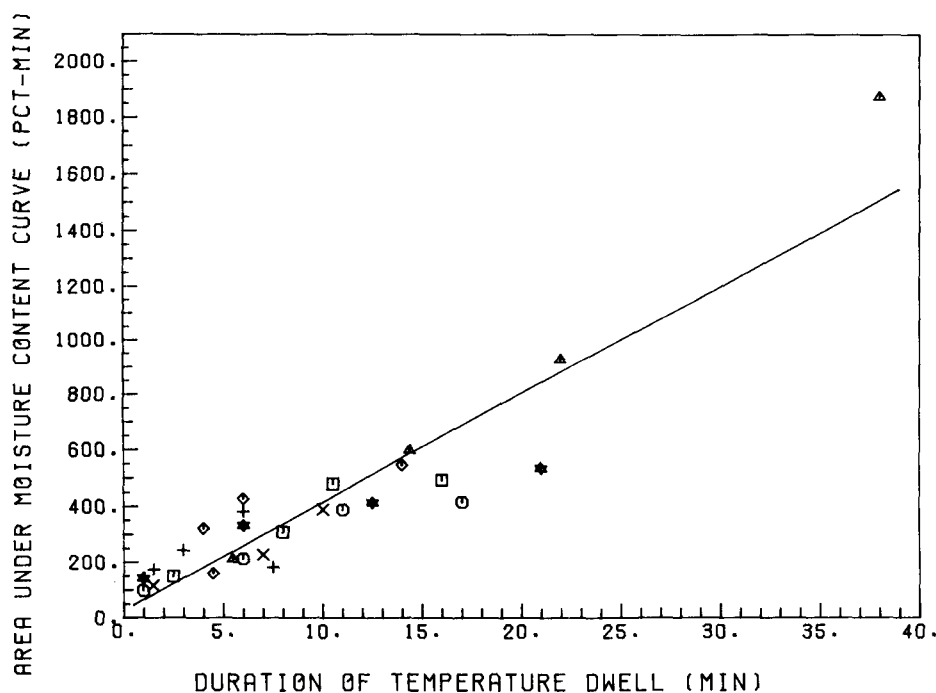


FIG. 13. Area under time-moisture curve from time of initial increase in moisture content correlated to the duration of the dwell in temperature rise. The symbols \square , \circ , \triangle , \diamond , $+$, $*$, and \times are for test Nos. 1, 2, 3, 4, 5, 6, and 8, respectively.

in temperature rise within fire-exposed wood slabs has been previously reported (Schaffer 1967). The thermostatic periods, at temperatures of 90 to 140 C, was reported as being proportional to distance from the fire-exposed surface, initial specimen moisture content, and fire exposure temperature.

In tests of cylinders pressed from filter clipping of α -cellulose, Blackshear and Murty (1965) obtained a pronounced thermostatic effect at 100 C in the temperature rise near the center of the cylinders. Since the cylinders had been dehumidified by placing them in ovens at 105 C, Blackshear and Murty concluded that the water vapor produced by the decomposition process had diffused and condensed within the solid. Because of their method of preparation, the cellulose cylinders would have a relatively high radial permeability. Therefore, products from the pyrolysis of the surface layers would be able to diffuse toward the center of the specimen without difficulty (Roberts 1970).

In the oven-dry slab (test No. 7), the measurements in the middle section indicated zero moisture content and no temperature dwell. The measurements in the top section of the slab indicated a positive moisture content at 25, 38, and 51 mm (1, 1.5, and 2 in.) and a slight dwell in the temperature rise at the 38- and 51-mm (1.5- and 2-in.) locations. The dwell in temperature rise occurred at a temperature of 120 C. It is possible that the top section had not been completely dried.

For moist southern pine slabs, the temperature dwell occurred at about 100 C.

The temperature dwell occurred at about 110 to 120 C in the Douglas-fir and white oak slabs.

For all the moist slabs, the duration of the temperature dwell was linearly correlated with various areas under the time-moisture content curves, the peak moisture content ($r = 0.47$), and the distance from the original fire-exposed surface ($r = 0.71$). The different areas were the total area (base of zero percent) under the time-moisture curve ($r = 0.95$), the total area after the time of the initial rise in moisture content ($r = 0.92$), and the area above a base of the initial moisture content ($r = 0.89$). The data for the duration of temperature dwell, and the area between zero percent and the time-moisture content curve after the time of initial rise in moisture content are given in Fig. 13.

The dwell in temperature rise generally corresponded with the time duration of the existence of the plateau in the time-moisture content curve. The recorded drop in moisture content generally occurred during the temperature rise after the dwell. As will be explained later, this probably reflects a defect in the experimental method. The vaporization of the moisture probably does occur during the temperature dwell. If the vaporization of the moisture results in increased pressure, it is possible that there is a rise in temperature during the vaporization process. The duration of the temperature dwell could reflect the delay caused by the moisture vaporization in the region closer to the fire-exposed surface. This is possibly why better correlations were obtained with the areas under the time-moisture content curves than with the peak moisture contents.

Oven-dry measurement of moisture

The oven-dry measurement of the moisture content gradient employing a sectioning technique was done to verify the resistance measurement of moisture-content gradient. The oven-dry results are shown as a distance-temperature curve and a distance-moisture content curve (Fig. 14). The curves are for the test with a constant 538 C furnace temperature. The temperature data are the temperatures recorded just before the specimen was removed from the furnace after 30 min of fire exposure. Using the temperature curve of this test and the moisture meter-measured moisture contents of test No. 3 (electrodes in middle section and electrodes in top section of slab) that correspond with the temperatures, distance-moisture content curves were obtained (Fig. 14). In the test with ASTM E 119 furnace temperatures, the peak moisture content obtained by oven-drying the slices was 17%. In the tests using the resistance moisture meter to obtain the moisture content (tests Nos. 1 and 8), the average peak moisture content was 19%.

The curves based on the moisture meter indicate higher moisture contents than the sectioning-oven-dry results for temperatures above 40 C (Fig. 14). Some of this difference, particularly in the peak moisture content, is probably due to the loss of moisture during the process of cutting the specimen and obtaining the weights for the oven-dry moisture content.

Dorn and Egner (1961) examined the distribution of moisture over the cross sections of two fire-exposed pine-fir timber beams having initial moisture contents of 13%; one after 30 min of fire exposure and the other after 60 min. A slicing and weighing technique was employed. Slices 1 cm (0.4 in.) thick were extracted

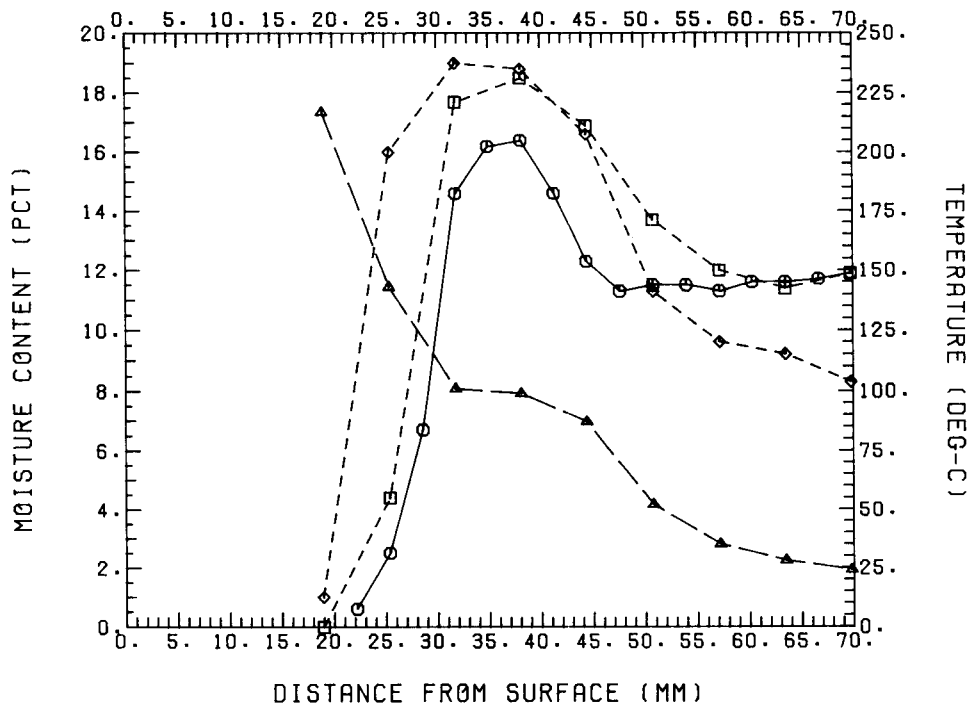


FIG. 14. Temperature (Δ) and oven-dry determined moisture content (\circ) gradients within slab exposed on one face to furnace temperature of 538 C. Other two moisture content curves are based on temperature-moisture content data derived by resistance probe measurements in middle section (\square) and top section (\diamond) of test No. 3.

and dried. The results are shown in Fig. 15. No indication of the period of time exhausted following the end of the fire exposure and slicing is given. It is seen that the wood dries in a zone 1 cm (0.4 in.) below the char/wood interface and increases before decreasing to initial moisture content levels at deeper depths. The peak moisture content was about 16% at 30 min and about 15% at 60 min. Temperature levels at the occurrence of these peaks was about 100 C (range 90 to 120 C).

Resistance measurement of moisture content

The existence of a finite moisture content gradient and temperature gradient across the 6.4-mm (0.25-in.) diameter electrode influences the accuracy in results in using this technique of resistance measurement of moisture content in a fire-exposed wood slab. The difference between sectioning oven-dry and moisture meter results can also be partially attributed to the moisture meter responding to the wettest wood in contact with the two electrodes (path of least resistance). The moisture meter apparently records the moisture content at different points across the width of the electrode as the moisture peak progresses across the electrode. The thermocouple used to compensate resistance measurements to determine moisture content was recording the temperature at a single point within

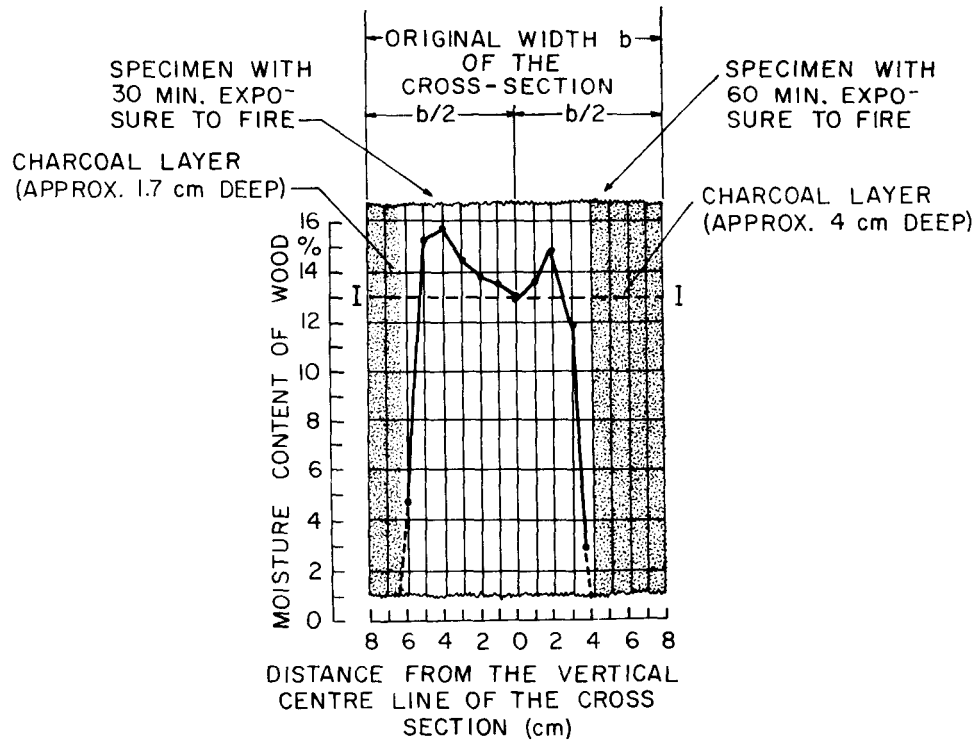


FIG. 15. Distribution of moisture in wood over the cross section after 30 and 60 min exposure to fire from several oven-dry measurements (Dorn and Egner 1961).

the area of the electrode. The current is not confined to the regions between electrodes but also spreads into regions behind the electrodes (Skaar 1964). In one test, thermocouples were inserted into 3-mm (0.125-in.) holes drilled from the back so that a thermocouple was at the fire-exposed edge, the middle, and the unexposed edge of the electrode. The data from that test indicated that the wood near the side of the electrode opposite the fire-exposed surface was still close to 100 C when the drop in temperature-corrected moisture content reading occurred.

The temperature gradient creates a problem in measuring the temperature to correct the moisture meter readings, and the correction for temperature can be substantial. For the peak temperature-corrected moisture content, the average meter reading was 35%. On the average, the temperature correction for the peak moisture content was 47% of the meter reading and the species correction was 3% of the meter reading. Also, because of the logarithmic relationship between the actual moisture content and electrical resistance, the high meter readings are somewhat less accurate than low meter readings. Between 10 and 13% moisture content, a 3% actual moisture content difference, indicated by a 570-megohm change at 27 C, is indicated by a 1-megohm difference at 100 C.

Any artificial accumulation of moisture near the holes drilled for the electrodes

can induce an error since electrical resistance readings apparently reflect resistance concentrated near the electrodes. The concentration of resistance in the vicinity of the electrodes is greater for electrodes with large electrode spacing to electrode diameter ratio (Skaar 1964). The electrodes used in this study have a relatively small spacing to diameter ratio. On occasion, there was erratic behavior of the meter, which was attributed to static charges.

Because the moisture meter probably responded to the wettest wood in contact with the electrodes, the duration of the increased moisture content is probably less than the resistance moisture meter results (Figs. 3–9) indicate. In particular, the drop of moisture content likely does occur during the 100 C dwell in temperature rise. Since the moisture meter is reading the highest moisture content, and the temperature gradient around 100 C is negligible, the peak moisture contents are expected to be accurate within 1 to 2% moisture content.

Flow of moisture

Three driving forces may be involved in the flow of moisture in a fire-exposed wood slab. Moisture flow can be caused by a moisture concentration gradient, a temperature gradient, and a total pressure gradient.

In most circumstances, the movement of moisture in wood is by diffusion due to a gradient in moisture concentration (partial vapor pressure). This random motion to reduce the moisture gradient is normally expressed as Fick's law.

Moisture movement induced by a temperature gradient will occur in wood. In thermal conductivity tests of moist wood, even though the moisture distribution is approximately uniform before the test, there is often a marked increase in the moisture content of the wood near the cold plate during the test. Results obtained during conductivity testing (MacLean 1941) indicated that when the average moisture content was about 10% or less, the change in moisture distribution was comparatively small, but when the initial moisture content was in the range of about 20 to 30%, there was from 20 to 40% moisture content difference between the moisture content of the wood near the cold plate and that near the hot plate side.

The generation of water vapor within a wood slab can result in a total pressure gradient and a corresponding moisture flow. Darcy's law is often used to express this movement of a fluid due to a pressure gradient. With the low cross-grain permeability and limited void volume of wood, any rapid generation of gases will result in an increase in the total pressure. Tinney (1965), for example, obtained internal-pressure histories of oven-dry $\frac{3}{8}$ -inch dowels that were exposed to a constant temperature between 300 and 650 C. With a furnace exposure temperature of 550 C, the maximum center gage pressure resulting was 30 kilopascal (4.3 lb/in.²) (center temperature of 280 C). At a lower furnace temperature (350 C), the maximum center gage pressure was 14 kilopascal (2 lb/in.²) (center temperature of 330 C). Tinney noted that the pressure dropped when surface cracks and interior longitudinal channels developed. Other experiments have shown a rapid decrease in resistance to flow at a mean temperature of 308 C (standard deviation of 30 C) (Roberts 1970).

The generation of water vapor within a wood slab can be due to the vaporization of the bound water, or the thermal degradation of the wood. When wood is heated

TABLE 3. *Permeability and diffusion coefficient (Choong and Fogg 1968).*

Species	Specific permeability			Diffusion coefficient adsorption (7-14% EMC)		
	L	T	R	L	T	R
	cc/sec-cm-atm/centipoise			10 ⁻⁶ cm ² /sec		
Southern pine (sapwood)	2.150	0.0003	0.0113	4.2	0.16	0.66
White oak (heartwood)	0.202	0.0010	0.0000	1.9	0.15	0.26

L = longitudinal direction.
T = tangential direction.
R = radial direction.

for prolonged periods of time at 105 C or for shorter periods of time at considerably higher temperatures, some water of constitution is lost (Stamm 1964). An oven-dry slab has no initial bound moisture. In the middle section of the oven-dry slab (test No. 7), the moisture content during fire exposure did not exceed 1%. Therefore, the local increase in moisture content observed in the other tests is likely due to the redistribution of the bound water. Assuming that the local increase in moisture content is due to movement of the bound water, it is clear that diffusion cannot be the major mode of movement because diffusion due to moisture concentration tends to reduce the moisture gradient. This means that it cannot be the cause of the peak moisture contents. Diffusion due to a temperature gradient results in a moisture increase on the cold side of a material. Here the peak moisture content occurred near 100 C, which is the hot side of the liquid (bound) water region within the wood slab.

If the generation of water vapor is due to thermal degradation, diffusion due to temperature gradient could be the cause of moisture movement to the cold side (100 C) of the water vapor region of the wood slab. But the differences in published diffusion coefficients of white oak and southern pine (Table 3) do not appear to be significant enough to explain the difference in the test results for the southern pine and white oak slabs (test Nos. 1 and 5). Moisture content gradients in thermal conductivity specimens (Table 4) indicate little difference between Douglas-fir and southern pine. But there is an observed difference in the fire test results for the southern pine and Douglas-fir slabs (test Nos. 1 and 4).

The penetration into the slab and away from the peak moisture content may

TABLE 4. *Comparison of moisture content in wood near hot and cold plate surfaces after 1 day (MacLean 1941).*

Species	Average moisture content	Moisture content near hot plate	Moisture content near cold plate	Thickness of specimen	Average specific gravity	Temperature difference between plates
	%	%	%	Mm		°C
Southern pine	11.8	7.6	14.8	17.96	0.53	28
Southern pine	13.1	9.0	15.7	16.56	0.49	24
Southern pine	18.2	12.6	31.8	20.42	0.50	28 (48-19)
Douglas-fir	10.2	8.6	10.8	16.76	0.47	29 (40-11)
Douglas-fir	14.3	10.8	18.0	12.70	0.43	24 (35-11)
Douglas-fir	20.4	10.8	33.0	17.96	0.44	26

be due to the moisture content and temperature gradients. This movement away from the peak moisture content may account for slightly more moisture being driven in during the low exposure test (test No. 3), and less during the high fire exposure test (test No. 2).

The major mode of moisture movement in the fire-exposed wood slab appears, therefore, to be water vapor transfer due to a total pressure gradient resulting from vaporization of water within the wood slab. As vapors penetrated into the slab, the air in the void volume of the wood became saturated and the moisture content of the cell walls increased. The increased moisture content was governed by the sorption isotherm of wood.

An attempt was made to determine the fraction of the moisture that is driven toward the cool side of the slab. Accuracy in doing so was limited because measurements were taken only at four widely spaced locations. Assuming a linear gradient between the four locations, the areas under the moisture content gradient above and below the initial moisture content gradient were computed. At each time interval, the ratio of the area above and the area below the initial moisture content was computed for the cross section. The difference was assumed to represent the fraction of moisture that had been driven into the wood. Using the values from the time the moisture content at 13 mm (0.5 in.) was zero to the time there was an increase in moisture content at 51 mm (2 in.), the ratios were averaged (Table 2).

Permeability is used to define the ease of movement of a fluid in a material when subjected to a pressure gradient. The relative permeability of the three species appears to be a major factor in the results obtained. More moisture was apparently driven into the slab if the permeability of the wood was high. The fraction of moisture driven in and the increase in moisture content were higher for southern pine sapwood, which is considerably more permeable than white oak heartwood (Table 3). Douglas-fir (coast) heartwood is considered moderately difficult to penetrate while white oak heartwood is considered very difficult to penetrate (MacLean 1952). This difference is also reflected in the fire test results. Low permeability limits the moisture transfer into the slab. Moisture that could not penetrate further into the slab escaped from the slab by passing through the fire-exposed surface. In a previous study (Schaffer 1967), it was concluded that moisture in slabs having an equilibrium moisture content at or above 10% in white oak, 14% in Douglas-fir, and 16% in southern pine caused char to spall in areas of the exposed surface, increased the occurrence of specimen checking along the grain at the fire-exposed face, and caused deformation of the specimen. As with the results of this study, these levels of moisture content reflect the correlative effect of the permeability of the species.

The permeability of wood is also reflected in the charring rates of wood. Specimens of a highly permeable wood, Abura, and a very impermeable wood, Makore, both having similar densities have markedly differing charring rates (Great Britain 1965). In this study, southern pine and Douglas-fir both having similar densities also had different charring rates.

Analytical model

For this study, efforts to obtain an analytical solution were limited to a literature review. The review indicated that there were systems of differential equations of

heat and mass transfer that may help explain the results of this study. Because of the complexity of the phenomena being examined, the solution of these equations was beyond the time available and scope of the study.

Wood has been recognized as a capillary-porous material for some time (Luikov 1966). A material of this type is hygroscopic and has a void volume interconnected only by capillaries formed by its geometrical structure. The presence of such capillaries affects moisture movement within the material. A system of differential equations of heat and mass transfer has been developed for capillary-porous materials (Lykov and Mikhaylov 1961; Luikov 1964, 1966, and 1975).

The capillary-porous system consists of the capillary-porous body and the material bounded within it. The bounded material consists of moisture (water, vapor, and ice) and dry air. The transfer of moisture takes place due to a temperature gradient, moisture gradient, or a total pressure gradient. Since the mass of vapor and dry air in the body is negligibly small, the moisture content is assumed to be the mass of water and ice. For many situations (e.g., relatively low temperature fields), there is no total pressure gradient. For this case, the differential heat and mass transfer equations are (Luikov 1975):

$$\frac{\partial T}{\partial t} = a \nabla^2 T + \frac{\epsilon r}{c} \frac{\partial u}{\partial t} \quad (1)$$

$$\frac{\partial u}{\partial t} = a_m \nabla^2 u + a_m \delta \nabla^2 T \quad (2)$$

where

- a: thermal diffusivity of a moist body
- a_m : diffusion coefficient of moisture
- c: specific heat of moist body
- r: specific evaporation heat
- t: time
- T: temperature
- u: moisture content
- δ : thermogradient coefficient based on the moisture content difference
- ϵ : phase conversion factor of liquid into vapor.

Intense moisture evaporation in higher temperature fields for a capillary-porous body additionally results in a total pressure gradient that induces filtration movement of vapor. For this case, the differential equations must be expanded to (Luikov 1975):

$$\frac{\partial T}{\partial t} = \left[a + \frac{\epsilon r a_m \delta}{c} \right] \nabla^2 T + a_m \frac{\epsilon r}{c} \nabla^2 u + a_m \delta_p \frac{\epsilon r}{c} \nabla^2 P \quad (3)$$

$$\frac{\partial u}{\partial t} = a_m \delta \nabla^2 T + a_m \nabla^2 u + a_m \delta_p \nabla^2 P \quad (4)$$

$$\begin{aligned} \frac{\partial P}{\partial t} = & a_m \delta \left[\frac{\epsilon r P}{c T} + \beta - \frac{\epsilon}{C_B} \right] \nabla^2 T + a_m \left[\frac{\epsilon r P}{c T} + \beta - \frac{\epsilon}{C_B} \right] \nabla^2 u \\ & + \left\{ a_p + a_m \delta_p \left[\frac{\epsilon r P}{c T} + \beta - \frac{\epsilon}{C_B} \right] \right\} \nabla^2 P \end{aligned} \quad (5)$$

where

- a_p : convective diffusion coefficient
- C_B : specific capacity of vapor moisture
- β : coefficient dependent on porosity and moisture content
- δ_p : relative coefficient of filtration flow of vapor moisture

The solution of these equations for dynamic situations, such as the intense drying of wood or wood charring with significant moisture present, is difficult. Wood charring would require the solution of the equations including total pressure for moving boundaries. Solutions of these equations usually involve numerical methods such as finite difference or finite elements. A finite-element approach has been used recently, for example, to solve the equations for constant total pressure (Eqs. 1 and 2) for the case of drying of porous materials such as wood (Comini and Lewis 1976; Lewis et al. 1979).

CONCLUSIONS

Time-moisture content curves indicated an increase in moisture content that appeared to be associated with the vaporization of the hygroscopic water in wood slabs exposed to fire on one face. The peak moisture content occurs when the temperature of the wood is about 100 C. For the wood sections tested, the average peak moisture content was 1.26 to 2.0 times greater than the initial moisture content. The location of the peak was strongly correlated to the location of the char/wood interface. The increase in moisture content was likely due to a redistribution of the existing moisture within the wood slab. The movement of moisture was concluded to be largely due to the total pressure gradient created by the rapid vaporization of hygroscopic water at about 100 C. The fraction of moisture driven into or generated within the wood slabs versus the total amount initially present varied from essentially none in oven-dry sections to as high as 60%.

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