THERMAL EXPANSION OF MOIST WOOD[1]

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ABSTRACT

Linear thermal expansion of wood, as measured with sealed cylindrical specimens at constant moisture content, generally increased with the amount of bound water. This could be expected on the basis of the low stiffness of moist wood. Near the fiber saturation point and above, shrinkage from internal drying was superimposed on true thermal expansion. At temperatures above 0 C during heating, water migrated out of fiber-saturated cell walls; the resulting shrinkage reduced the expansion significantly and between 20 and 70 C even led to contraction. At freezing temperatures during cooling, moisture diffused out of the saturated cell walls and condensed as ice crystals in the cell cavities; the resulting shrinkage supplemented true thermal contraction and caused large coefficients of thermal expansion in a broad sense.

Thermal expansion was largest tangentially and smallest in the longitudinal direction. Tangential coefficients of thermal expansion at 12% moisture content and room temperature averaged 53×10^{-6} mm/(mm C) for redwood, 70×10^{-6} mm/(mm C) for northern red oak, 38×10^{-6} mm/(mm C) for Douglas-fir and yellow birch. Coefficients in the longitudinal direction and for plywood were below 10×10^{-6} mm/(mm C) on the average.

Additional keywords: Betula alleghaniensis, Quercus rubra, Pseudotsuga menziesii, Sequoia sempervirens, plywood, thermal expansion coefficients, internal drying, shrinkage.

INTRODUCTION

When the temperature of a substance is raised, the substance generally expands. Solids expand in each direction. Their change in length is expressed as the coefficient of linear thermal expansion, which represents the expansion per unit length per degree change in temperature.

According to earlier measurements (Weatherwax and Stamm 1946), the thermal expansion of wood is of the same order of magnitude as the expansion of metals. Yet engineers pay much less attention to thermal expansion of wood than to expansion of steel. The reason is that the reaction of wood to moisture overshadows its reaction to temperature. Oven-dry wood, for example, swells from 10% adsorbed moisture 10 times more than it expands from a 50 C rise in temperature. Changes in temperature usually cause changes in moisture content, and the resulting swelling and shrinkage may conceal thermal expansion, but even then thermal expansion contributes to the dimensional change. Under some circumstances wood does not swell and shrink when its temperature changes—above fiber saturation, in the oven-dry state, deep inside timbers, and when the material is encased as in the core of "metal" skis. For such cases coefficients of linear expansion of wood are needed; the "metal" skis' stiffness, for example, depends on the coefficient.

Thermal expansion of oven-dry wood was measured by Hendershot (1924), Nikolov and Rajčev (1967), Stevens (1960), Weatherwax and Stamm (1946). Others obtained the coefficients for a few wet wood samples in water (Kübler 1959; Perkitny and Heliński-Raczkowska 1966; Schirp and Kübler 1968; Yokota and Tarkow 1962).

In the hygroscopic moisture range, between oven-dry and fiber saturation, shrink-

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age could affect the observed dimensional changes. In thermal expansion tests with such wood, Struve (1855) paid no attention to possible variations in moisture content; Glatzel (1877) noticed some drying of his samples but disregarded the corresponding shrinkage; and Villari (1868) used oil-soaked samples apparently assuming that the oil prevented or at least reduced changes in moisture content. Hendershot (1924) and Ogarkova (1961) corrected observed expansions and contractions for measured changes in moisture content, a method that is inaccurate because swelling and shrinkage vary much. Kübler (1959) as well as Schirp and Kübler (1968) maintained constant moisture contents by wrapping samples in aluminum foil, but their experiments were restricted to low temperatures.

It seemed desirable to measure accurately and report the coefficients of thermal expansion of wood in the hygroscopic moisture range at temperatures to which wood is exposed under normal circumstances. Besides being needed by engineers, knowledge of the thermal expansion of moist wood helps scientists understand the wood-water system and sheds light on the structure of wood cell walls. Measurements of oven-dry and wet specimens are included as extremes and for comparison with previous investigations.

MATERIALS AND METHODS

Wood specimens

Wood species chosen for the measurements were redwood (*Sequoia sempervirens*, specific gravity 0.42), Douglas-fir (*Pseudotsuga menziesii*, 0.46), yellow birch (*Betula alleghaniensis*, 0.58), northern red oak (*Quercus rubra*, 0.62), and yellow birch plywood (0.67). The specific gravities are measured averages of the specimens used, based on weight and volume when oven-dry. The plywood consisted of 11 rotary-cut veneers, each 2 mm thick, and bonded with phenolic resin at 160 C under a pressure of 10 kg/cm^2.

Cylindrical specimens were prepared from the dry raw material. Each specimen was 120 mm long and 20 mm in diameter. The axis of the solid wood specimens was oriented in either the tangential, radial, or longitudinal direction of the wood structure. The specimens consisted of three plugs, which had been cut from lumber with a plug cutter and bonded together lengthwise with epoxy resin. The plywood specimens were turned on a lathe from plywood sticks 120 mm long, their lengthwise orientation coinciding with the longitudinal direction of every second sheet of veneer. Brass plates 0.7 mm thick, were bonded with epoxy adhesive to the ends of all specimens to provide a hard reference surface for measurements. Excessive adhesive was squeezed out of the joints under a pressure of 5 kg/cm^2 to minimize the effect of the adhesive on thermal expansion.

Before the thermal expansion trials, the specimens were soaked in water for 24 hr, then heated in vapor-tight brass tubes at 95 C in an oven for an additional 24 hr to release irreversible changes in dimension (Kübler 1959). Next the specimens were dried slowly at room temperature to approximately 10% moisture content, and finally conditioned to various moisture contents in 27 C conditioning rooms with different constant relative humidities. The wet condition was achieved by soaking in water, the oven-dry condition by final drying for 48 hr at 103 C.

In the trials with redwood, each specimen was used at one moisture content only. The specimens of the three other wood species were tested in several consecutive trials at various moisture contents; one series began oven-dry and progressed stepwise toward wet wood, while the other series started wet and ended oven-dry. In each series there were two replicates except for redwood, where three or more specimens were measured under most conditions. Specimen weight was determined before and after each trial to obtain the moisture contents.

Apparatus and procedure

In the trials, the specimens were enclosed in a brass tube, which was sealed vapor-

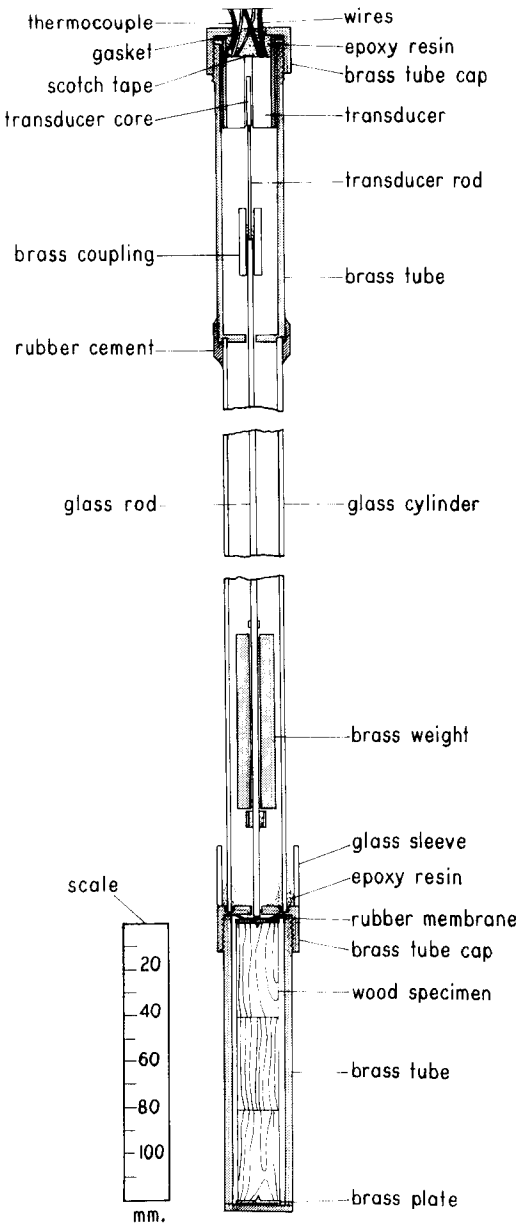

FIG. 1. Apparatus for measurement of linear thermal expansion.

tight by a rubber membrane under the screw cap (Fig. 1). A long glass rod projected into the tube through a hole in the cap and pressed the membrane against the specimen surface. In this way, the rod transferred changes in length of the specimen to an electrical DC-DC displacement transducer at the other end of the rod. The transducer, held in a second tube 40 cm above the specimen tube, controlled a millivolt strip chart recorder (type Hewlett-Packard 7128A/17500A). A constant temperature circulator pumped heat exchange liquid through a copper coil around the specimen tube to achieve the desired temperature condition. A thermocouple, inserted into a dummy specimen along the specimen axis in another specimen tube, registered the wood temperatures over a multipoint strip chart recorder (type Honeywell Electronik 15).

The temperature was raised first from 25 to 50 C until the specimen's temperature and dimension reached constancy. Next, temperature levels of 65, 75, and 95 C were attained, followed by cooling to 25 C in the same steps. Then the tubes were cooled to 0 and –16 C, and finally reheated to 0 and 25 C. With moist wood the nominal temperature level of 0 C was slightly higher to make sure that no ice existed in the specimens. When the transducer-controlled recorder did not return to the starting point, the respective cycles had to be repeated; only cycles in which starting and ending dimensions coincided were evaluated.

In the cooling steps from 95 to 25 C, lengths indicated were generally identical with those of the heating steps at same temperature; the cooling steps were therefore skipped in many trials to save time. Correspondingly, in quite a few of the cooling cycles the tubes were reheated directly from –16 to 25 C without taking readings. In the experiments with redwood, low temperature levels were 0, –25, and –35 C.

Sensitivity and accuracy

The transducer was calibrated against a micrometer screw over a linear range of 5 mm; the screw had 0.01-mm divisions on the vernier scale. With an error in the micrometer reading of 0.01 mm at each end of the 5-mm range, the corresponding maximum error in the slope of the calibration line was 0.02 mm/5 mm or 0.4%.

The millivolt recorder had 10 different sensitivities. In each trial the sensitivity selected was such that the recorder indicator approximately moved over the full width of the chart, 25.4 cm, in each temperature step. The apparatus multiplied tangential expansion by a factor of roughly 1,000, and the longitudinal expansions by a factor of 10,000. The error in reading the recorder chart was below 1% of the indicated change in dimension. The indicator very slightly vibrated and reached identical positions for certain positions of the transducer core.

The specimen brass tube elongated with temperature and caused an experimental error. To determine it, a solid cylinder from fused quartz was used as a specimen in one heating and cooling cycle. As thermal expansion of fused quartz varies little and is extremely small (International Critical Tables 1928), the difference between the indicated expansion and the calculated expansion could be considered as the experimental error. A control trial with a brass cylinder resulted in a coefficient which was within the range given for various kinds of brass (International Critical Tables 1927).

Evaporation of wood moisture into the empty space of the brass tube was another possible source of error. This space, necessary for free expansion of the specimen, amounted to less than one tenth of specimen volume. Under conditions of maximum evaporation, with fiber-saturated wood in the temperature step from 75 to 95 C, the corresponding theoretical tangential shrinkage was less than 0.002% or two hundredths of thermal expansion. The cell cavity space exceeded the empty space of the tube, especially in the light redwood; therefore, the cell cavities could take up more moisture than the tube, but the corresponding "internal drying" is not considered as an error—it rather represents a negligible part of thermal expansion in a broad sense.

In the vapor-tight tube, heating raised the pressure of the air-vapor mixture. Under extreme conditions, at 95 C with wet wood, the pressure increased by about 1 kg/cm^2; the corresponding force in the 3.2-mm-diameter hole of the cap amounted to 80 g. This pressure tended to lift the rubber membrane with the glass rod off the specimen. A 280-g brass weight, bonded to the glass rod, counterbalanced the lifting force and kept the rod in its indirect contact with the specimen. The membrane, 0.4 mm thick, was very flexible; the gas pressure forced it against the cap around the end of the glass rod to a much greater extent than shown in Fig. 1.

The total of potential errors in the single trials under a combination of most unfavorable circumstances was within ± 4%. Accordingly, the measured coefficients of the single specimens were fairly accurate.

RESULTS

When the temperature of the heat exchange liquid was raised or lowered, specimen temperature reached the desired level within about 40 min. Specimen dimension immediately responded to the temperature change and generally became constant as fast as temperature. Wet specimens took longer to expand or contract, up to 2 hr above, and a full day below, 0 C. In the lowest cooling step, from –25 to –35 C, wet redwood contracted for two days.

The dimensional changes depended on the wood's structural direction, on its moisture content, and on the temperature level. The dimensions changed most in the tangential direction, and the least longitudinally (Table 1). The four wood species expanded by different amounts, but the effects of direction, moisture, and temperature level seemed similar for all.

The coefficients of linear thermal expansion, as calculated from the changes in dimension and temperature, varied within each group from specimen to specimen. Variation was greatest in the tangential direction; for oven-dry wood between 25 and 50 C the standard deviation averaged 7×10^{-6} mm/(mm C) and the coefficient of variation was 25% for the four species. The deviations increased with increasing moisture content as shown for radial speci-

TABLE 1. Average coefficients of thermal expansion between 0 and 50 C.

WOOD SPECIES	COEFFICIENT OF LINEAR THERMAL EXPANSION $\alpha \times 10^6$ mm/(mm °C)								
	Tangential			Radial			Longitudinal		
	% Moisture Content			% Moisture Content			% Moisture Content		
	0	12	>60	0	12	>60	0	12	>60
Redwood	28	53	-12	21	31	-5	6	7	-4
Douglas-fir	29	38	9	24	38	9	6	10	10
Yellow birch	28	37	12	26	41	4	9	10	9.6
Red oak	32	70	0	26	44	0	9	8	0.3
Plywood	--	--	--	--	--	--	5.5	9.5	4.5

mens in Fig. 2; they reached highest values with wet specimens at freezing temperatures and in the 75 to 95 C heating step. Figure 3 illustrates the nature of the deviations; some specimens expanded more than others in each consecutive temperature step; in plots of coefficients over moisture content the situation appeared similar though not as distinct; here the coefficients of single specimens at consecutive moisture contents were more often than not higher than coefficients of other specimens. Because of the large deviations, the mean coefficients cannot be considered to represent the species with the accuracy calculated above for single specimens.

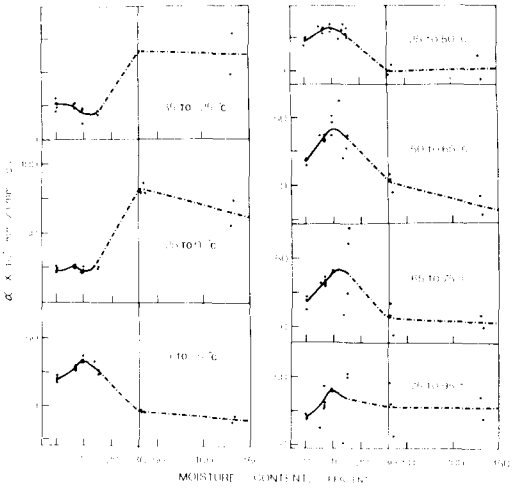

FIG. 2. Effect of moisture on radial coefficients of linear thermal expansion in various temperature ranges for redwood.

Moisture and heat affected tangential and radial expansions in very similar ways, whereas the effect on longitudinal expansion differed to some extent. Transverse and longitudinal thermal expansions are therefore separated.

Effect of moisture in transverse directions

At high moisture contents, the few coefficients obtained for a wood species varied so much that, in some temperature ranges, no distinct relationship between thermal expansion and moisture content could be recognized. For this reason, the tangential

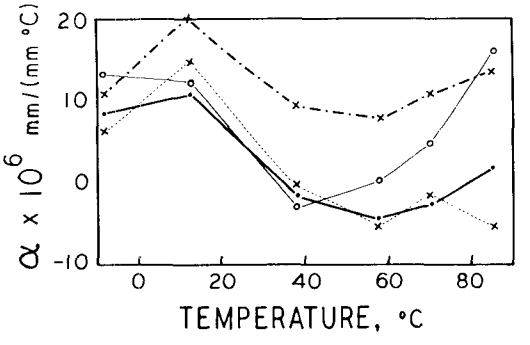

FIG. 3. Linear thermal expansions of four birch plywood samples at 23% moisture content.

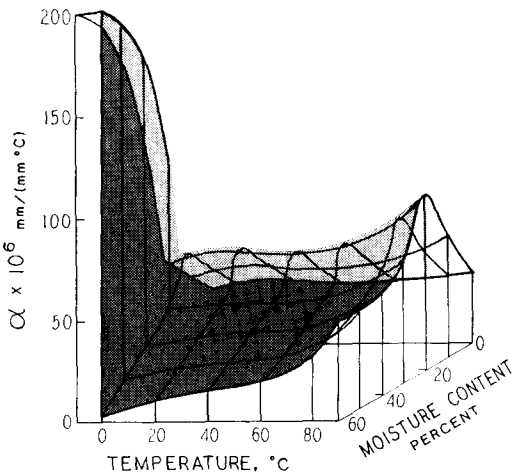

FIG. 4. Average tangential coefficients of linear thermal expansion for Douglas-fir, red oak, and yellow birch.

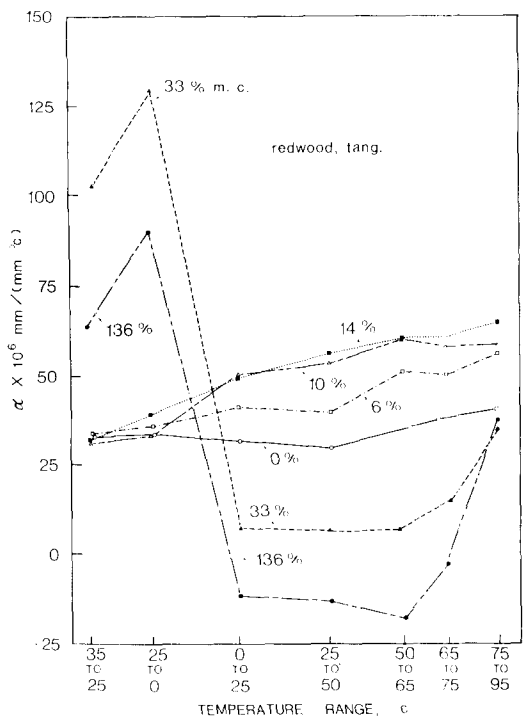

FIG. 5. Effect of the temperature range on tangential coefficients of linear thermal expansion at various moisture contents for redwood.

coefficients of red oak, yellow birch, and Douglas-fir have been averaged together (Fig. 4). The results of redwood (Figs. 2 and 5) with its high extractives content are not included in Fig. 4 because the effect of moisture on thermal expansion differed quantitatively in redwood.

The expansions of oak, birch, and Douglas-fir peaked above 20% moisture content. Beyond the peak, at temperatures above 0 C, the coefficients decreased with increasing moisture contents, especially in the 0 to 25 C step (Fig. 4). Redwood, because of its low fiber saturation point (Wangaard 1957), had a peak between 10 and 15% moisture content; most of the wet redwood specimens contracted when heated between 0 and 65 C (Fig. 2).

In the freezing process, wet wood contracted substantially as indicated by large coefficients of linear thermal expansion below 0 C (Fig. 4). The sharp rise at 0 C in Fig. 4 was not measured; the average coefficient between 0 and 16 C could be obtained only in the cooling step; however the recorder indicated large contractions from 0 C wood temperature down. In the small range of free moisture tried with Douglas-fir, red oak, and yellow birch at the low temperatures, the coefficients increased with the amount of free water. At extremely high moisture contents, which were applied in redwood only, the contraction during the freezing process was generally smaller than occurred near fiber saturation, with low contents of free water (Fig. 2, range –25 to 0 C).

Conditioning in atmospheres with various relative humidities led to moisture contents lower in the adsorption series than in desorption, as expected. The coefficients of thermal expansion differed correspondingly. Above 20% moisture content, another difference between adsorption and desorption series existed in transverse specimens of yellow birch and Douglas-fir: in the first heating above 25 C after conditioning, the adsorption series expanded much more than the desorption series shrank, so the specimens did not return to their original dimension at the end of the cycle; heat apparently removed swelling hysteresis (Kubler 1973). Data obtained in such trials of the adsorption series had to be disregarded.

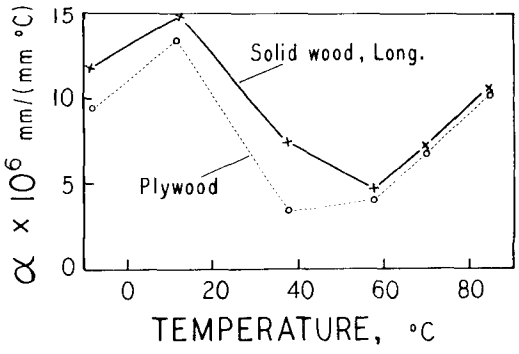

FIG. 6. Average coefficients of linear thermal expansion in the hygroscopic moisture range for yellow birch longitudinally and for yellow birch plywood.

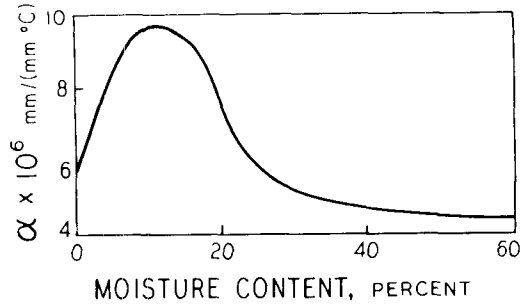

FIG. 7. Average linear thermal expansion of plywood between −16 and 95 C, exclusive of wet plywood below 0 C.

Effect of temperature level in transverse directions

Below fiber saturation at all temperatures and with wet wood above 0 C, thermal expansion generally increased with the level of temperature (Figs. 4 and 5). The slight bump between 0 and 20 C in the hygroscopic range of Fig. 4 may be incidental; the level of significance between the coefficients obtained in the 0 to 25 C and in the 25 to 50 C steps was beyond 0.05. Wet specimens had expansion minima at 0 C (Fig. 4).

The coefficients of wet wood also seemed to increase with temperature below 0 C. In wet redwood the −25 to 0 C step caused larger thermal expansions than the −35 to −25 C step (Fig. 5), but the difference between the two levels of temperature was statistically insignificant.

Longitudinal expansions

The longitudinal coefficients depended on moisture content in the hygroscopic range in the same way as transverse coefficients, peaking above 20%. Above fiber saturation, longitudinal expansion varied considerably from specimen to specimen within the same species, so calculated averages may be very incidental; above 0 C the averages of wet wood were higher than at 25% moisture content but lower than at 20%. By far the greatest variations occurred below 0 C with wet wood, whose longitudinal coefficients ranged from -40×10^{-6} to 126×10^{-6}, with an average near 10×10^{-6} mm/(mm C).

The longitudinal coefficients of birch, oak, and Douglas-fir depended on the temperature level at all moisture contents below fiber saturation as shown in Fig. 6 for yellow birch. Longitudinal expansion of redwood rose with the temperature level up to the 25 to 50 C step; then the values dropped off to a minimum in the 65 to 75 C step. The longitudinal expansions of wet specimens changed with the temperature level like transverse expansions (Fig. 4).

Expansion of plywood

Surprisingly, yellow birch plywood expanded not more than solid yellow birch in the fiber direction (Fig. 6). Except for freezing temperatures in wet material, moisture affected expansion of plywood in a similar way in all temperature ranges, so that the coefficients of the various temperature ranges could be averaged (Fig. 7). As with solid wood, expansion peaked within the hygroscopic moisture range, though the peak appeared at a lower moisture content.

Figure 3 shows the coefficients of four plywood specimens with 23% moisture content in the various temperature ranges. The relationship between thermal expansion and temperature was similar at other hygroscopic moisture contents. The expansion maximum in the 0 to 25 C step was much more distinct for plywood than

for solid wood in the transverse direction (Fig. 4). Plywood specimens with 50 to 60% moisture content had the highest coefficients at the freezing temperature, on the average 31×10^{-6} mm/(mm C); above 0 C, expansion of wet plywood averaged 4.5×10^{-6} mm/(mm C), with insignificant differences between the various temperatures.

DISCUSSION

Thermal expansion of gases, liquids, and solids generally increases with increasing temperature. Above 0 C the wood specimens reacted correspondingly, but wet samples expanded much more below the freezing point than above it. Similarly, moisture increased thermal expansion in some moisture ranges, while in others the more moist specimens expanded less.

The maxima and minima of the coefficients at certain temperatures and moisture contents indicate that more than one process contributed to the observed changes in dimension. Besides thermal expansion per se or true thermal expansion, dimensions changed from shrinkage and swelling because of internal drying and readsorption of moisture. Moisture-related shrinkage and swelling were superimposed on the true thermal expansion, and, being restricted to certain temperature and moisture ranges, explain the maxima and minima in Figs. 2 to 7. Another process that may have contributed to the dimensional changes is expansion of freezing water. Contraction from thermal decomposition was negligibly small; otherwise the dimensional changes would not have been reversible; significant decomposition may have occurred before the expansion trials when the specimens were heated at 95 C for 24 hr.

Internal drying between 0 and 95 C

The fiber saturation point of wood decreases with rising temperature, as is well known. Therefore when fiber-saturated wood is heated, water must migrate out of the cell wall and wood shrinks. This phenomenon explains the low coefficients for wet wood above 0 C (Fig. 4). In redwood, the shrinkage was numerically larger than thermal expansion per se so that the material even contracted when its temperature was raised (Fig. 5). Contraction during heating had been observed before on beech wood in water (Kübler 1959). Yokota and Tarkow (1962), who had expected internal drying on the basis of wood's equilibrium moisture content, observed it with Sitka spruce samples in water.

Wet redwood contracted by heat up to 75 C only; between 75 and 95 C it expanded. The reversal at 75 C agrees with earlier observations made on beech (Kübler 1959). The coefficients of oak, birch, and Douglas-fir were not negative below 75 C, but as in the case of redwood the expansion increased substantially in the 75 to 95 C step. Apparently, thermal expansion per se increased at the higher temperature levels and became more and more dominating over shrinkage from internal drying.

Migration of water out of the cell walls and into the cell walls took some time; therefore the dimension changes lagged behind the changes in temperature.

In connection with the internal drying process the question arises of how relative humidities in the specimen tube responded to changing temperatures. As equilibrium moisture content of wood at constant relative humidity decreases when temperature rises, relative humidity must have increased at constant moisture contents. Relative humidity was not measured in these experiments, but Hedlin (1969) found it indeed to increase when he heated sealed moist wood samples.

Internal drying at freezing temperatures

As explained elsewhere (Kübler 1962), during cooling below 0 C, moisture diffuses out of wet cell walls and condenses on ice crystals in cell cavities. This represents a kind of internal drying that caused the very high coefficients of moist wood below 0 C. The process is again reversible; during reheating, moisture diffused from the ice back into the cell walls and reswelled the wood.

Some may question why in Fig. 4 the

coefficients have been assumed to change so abruptly at 0 C and then gradually decrease toward lower temperatures. The explanation is that, when wet wood was cooled, water diffused out of cell walls as soon as free water froze in the cell cavities at 0 C. How much moisture migrated out depended on temperature. At each temperature, ice has a certain vapor pressure, which is lower than the vapor pressure of supercooled water and of moisture in saturated cell walls (Hedlin 1967). The difference in vapor pressure between ice and moisture in saturated cell walls increases with decreasing temperature. At each temperature, the diffusion of moisture to the ice in the cell cavities ended when the vapor pressure of the remaining cell-wall moisture sank to the vapor pressure of ice. It took some time until this equilibrium was reached, especially at very low temperatures; and for this reason the specimen dimensions stabilized long after the temperature had become constant. At equilibrium conditions, a certain amount of moisture remained in the cell wall. Conversely, in fiber-saturated wood, a certain amount of water froze out and the wood shrank correspondingly. The shrinkage gradually decreased with decreasing temperatures (Kübler 1962). Cooling from 0 to –1 C, for example, caused slightly more water to migrate into the cell cavity than cooling from –9 to –10 C. Correspondingly, the coefficients have been assumed to decrease with lower temperatures as observed on wet redwood (Fig. 5).

Expansion of freezing water

When water freezes, it expands in volume by 9%. One might expect that water freezing in wood inflates the material correspondingly. Bound wood moisture, located in the cell walls, seems to cause no such expansion; otherwise the moist wood specimens would not have contracted but expanded when their temperature was lowered from 0 to –16 C. The measured large positive coefficients of moist wood indicate that no water freezes within the cell walls, that cell-wall moisture cannot freeze, and that no cell-wall moisture is in a liquid stage as some assume (Kollmann 1968).

The situation is different with so-called free water in cell cavities. This water does freeze and expands like water in any container of macroscopic size. Whether its freezing affects the dimension of wood depends on the extent to which the cavities are filled. In cells partly filled with air, the freezing water expands into the air space without enlarging the cavity and without changing outside dimensions of the wood. Water-saturated wood, in which the cavities are filled entirely, does expand by several percent during freezing (Schirp and Kübler 1968).

In this investigation, no water-saturated wood has been tested. The wet specimens still contained some air and therefore generally did not increase in size during freezing. A few specimens only, especially some longitudinal ones from red oak, expanded; this resulted in large negative coefficients. Other longitudinal specimens contracted from internal drying when they froze and this caused large positive coefficients. Therefore, the longitudinal coefficients of wet wood appeared to vary widely below 0 C.

The free water in the specimens was distributed unevenly; some cell cavities may have been filled entirely, whereas others contained air only. Water-saturated pockets expanded during freezing, but the expansion was restrained or offset by adjoining zones that contracted because their moisture content was much lower. Of course the size and number of water-saturated pockets increased with the average moisture content. Radial redwood in the –25 to 0 C temperature step therefore had lower coefficients at 135% than at 35% moisture content (Fig. 2). In the tangential redwood specimens, the difference in expansion between the two moisture contents was much larger.

Thermal expansion per se

It is assumed that shrinkage from internal drying occurred only near the fiber satu-

ration point and in wet specimens. Then the dimension changes in the lower four-fifths of the hygroscopic moisture range represented thermal expansions per se. According to Figs. 2 and 4, the expansions per se increased with increasing moisture content. An attempt is made to explain why the more moist wood samples had higher true thermal expansions.

According to the kinetic theory of matter, atoms in solids vibrate about positions of equilibrium. Heat increases the amplitude of the anharmonic vibrations so that the distance between the atoms becomes larger and the solid expands (Yates 1972). Mechanical tension stress increases the distance between the atoms and expands or extends solid bodies, too. Both heat and tension stress raise the internal energy of the system.

For wood the analogy between thermal expansion and mechanical extension does not end here. It is known from moduli of elasticity, a measure of stiffness, how much wood extends under tension stress. A certain stress causes much more extension in the transverse direction than longitudinally—just as heat causes more transverse than longitudinal expansion. Stiffness is defined as resistance against dimensional change. It this definition "dimensional change" can include thermal expansion and even swelling, besides mechanical extension; wood "resists" all these changes in dimension longitudinally more than transversely. Thermal expansion and mechanical extension are very similar and appear to be closely related. It is then possible to draw conclusions on thermal expansion from measurements of stiffness. Adsorbed water makes wood less stiff and could therefore be expected to increase thermal expansion.

This brings up the question of what mechanism on the molecular level increases true thermal expansion of moist wood. The similar anisotropies of stiffness, thermal expansion, and swelling must have their common cause in the structure of wood.

The bonds between atoms of a molecule are much stronger than bonds between molecules. Consequently, intramolecular bonds may be assumed to be more stiff and to permit less thermal vibration than bonds between adjoining molecules. Thermal expansion of substances like wood is then caused mainly by increased distances between molecules and not by increased distances between atoms within the molecule. Wood consists mainly of chainlike cellulose molecules, most of which are arranged parallel to each other approximately in fiber direction. In such a structure exist many more "variable" intermolecular joints per unit of specimen length in the transverse direction than longitudinally. This explains the large transverse expansion.

In dry wood, cellulose-cellulose hydrogen bonds represent the variable links between adjoining molecules. When wood swells, entering water splits cellulose-cellulose hydrogen bonds and forms cellulose-water-cellulose hydrogen bonds. With the water molecule intruding, the links in the swollen moist wood become not only longer but also weaker and less stiff than in dry wood. The water links permit more thermal vibration and allow greater thermal expansion.

The hypothesis may be modified. It seems possible that not links between molecules but links between aggregates of molecules such as microfibrils in the cell wall account for the expansions. The difference is without consequences, because the cellulose aggregates have the same orientation as the chainlike molecules of which the aggregates consist.

Forsaith (1946) speculated that the atomic vibrations in the elongated slender cellulose molecule develop "sufficient disturbance to cause the chain to vibrate in a plane perpendicular to its long axis." This leads to transverse thermal expansion, which is much larger than thermal expansion of most materials. Applying Forsaith's hypothesis to the swollen state, the weakened bonds between molecules can be assumed to result in even larger transverse vibrations and thus increased expansions of moist wood.

Comparison with published results

Thermal expansions measured in this investigation fairly well agree with expansions reported in literature on similar wood species. For oven-dry longitudinal wood, some coefficients of other investigators are lower (Hendershot 1924; Villari 1868; Weatherwax and Stamm 1946); others appear to be higher (Glatzel 1877; Hendershot 1924; Nikolov and Rajčev 1967; Stevens 1960; Struve 1855; Villari 1868; Weatherwax and Stamm 1946). The averages of oven-dry longitudinal coefficients obtained in this study are comparable to published values.

In contrast, the measured transverse coefficients of oven-dry wood averaged 30% lower than the coefficients measured by Glatzel (1877), Hendershot (1924), Nikolov and Rajčev (1967), Schirp and Kübler (1968), Stevens (1960), Villari (1868), Weatherwax and Stamm (1946). No explanation is available for this difference.

Contractions of wet wood during freezing in this research were as large as the ones observed by Kübler (1962) as well as Schirp and Kübler (1968) on several wood species. The negative coefficients obtained with wet redwood between 0 and 75 C had the same magnitude as coefficients measured by Kübler (1959), Perkitny and Helińska-Raczkowska (1966), and Schirp and Kübler (1968) on beech wood; only Yokota and Tarkow's (1962) negative coefficients of Sitka spruce were numerically much higher.

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