TOKUO YOKOTA and
HAROLD TARKOW
U. S. Forest Products Laboratory[2]
Madison, Wisconsin

Changes in Dimension on Heating Green Wood[1]

The dimension change that green wood undergoes when heated in water is the net effect of a normal, reversible thermal expansion, a normal reversible reduction in fiber saturation point, and an irreversible expansion due to the recovery of growth strains. The factor responsible for the latter may be reintroduced into wood during drying, and gives rise, in very thin sections, to a slight dependency of the equilibrum moisture content on the rate with which the ambient relative humidity reaches its final value.

THE ADSORPTION OF MOISTURE BY cellulosic materials is an exothermic process. Consequently, moisture adsorption at constant relative humidity should decrease with temperature. This agrees with experience under "usual" conditions.

Urquhart (8), however, reported that above a certain relative humidity, the moisture adsorption-temperature curve of cotton (constant relative humidity) reaches a minimum, then rises again (Figure 1). Below 80 percent relative humidity, only the normal effect of temperature is observed. Above 80 percent relative humidity, the minimum adsorption is observed to occur at a lower temperature with increasing relative humidity. Figure 2 shows this relationship.

Extrapolation of the curve in Figure 2 indicates that a minimum adsorption at 100 percent relative humidity would occur at about 38° C. It is difficult to determine moisture adsorption of cotton at 100 percent relative humidity, however, because of excessive condensation unrelated to the true adsorption process. Since that part of the total sorbed moisture which is related to the true adsorption process causes swelling, one should be able to make observations similar to those of Urquhart simply by measuring some dimension at 100 percent relative humidity as a function of temperature. One would expect a minimum in the dimension at about 38° C. Accurate swelling measurements cannot be made with cotton. They can be made with wood. In this paper, the dimension changes in water-submerged wood are reported as a function of temperature in order to determine whether the prediction based on the behavior of cotton is applicable to wood.

Experimental Procedure

Preparation of Specimens: Cross sections, 5 by 5 by 0.3 centimeter in size, were cut from a bolt of green Sitka spruce and kept in water until ready for use. Serially cut sections assured excellent matching.

Equipment and Technique: Figure 3 is a schematic view of the equipment. The wood section is mounted on a metal framework, which in turn is submerged in a constant-temperature bath (± 0.1° C.). One end of a rod 3/16 inch in diameter is in contact with the upper edge of the specimen. The other end is in contact with dielectric constant-type gauge (designed by U. S. Forest Products Laboratory) (7). The water temperature is raised to some fixed value and held there until the dimension of the specimen becomes sensibly constant. The resulting change in dimension is transmitted to the gauge, where the corresponding change in dielectric constant is transformed to an equivalent direct current voltage. A calibration curve was established by means of the mounted micrometer. Suitable experimentally determined corrections were made for the thermal expansion of the metal framework. The smallest observable change in dimension of the green wood was 0.0001 centimeter, or 0.002 percent.

Results and Discussion

Results of one typical experiment in which the temperature was raised to 80° C. and the tangential dimension of the submerged specimen was measured continuously are shown in Figure 4. The dashed curve (right ordinate) describes the temperature. The curve marked "first heating" is a record of the dimension change. Initially, a slight decrease in dimension occurred, but this was soon followed by a rapid increase that continued over the first 3 hours, after which very little change occurred. After 51/2 hours, the temperature was dropped to 30° C. The dimension thereupon increased, as shown by the curve labeled "first cooling."

Without removing the wet specimen, the treatment was repeated to give the curve labeled "second heating." A "third heating" curve essentially coincided with the second. During the first heating, a pronounced increase in tangential dimension occurs. During succeeding beatings, this is not observed; instead, the dimension decreases. Thus, during the first heating, an irreversible tangential expansion or swelling occurs. Although previously reported by Koehler (4) and MacLean (6), Kübler (5) was the first to make systematic studies of this phenomenon.

The dimensional decrease during the second heating is reversible; on cooling, the specimen increases in dimension by about the same amount. Since reversible swelling and shrinking of wood are associated with reversible adsorption and desorption of moisture, the phenomenon occuring after the first heating is related to the normal effect of temperature on adsorption at constant relative humidity and is a requirement of the exothermic nature of the adsorption process.

During the first heating, the change in dimension is the net effect of the irreversible increase in dimension and the smaller but reversible component made apparent during the second heating. This latter in turn is the net effect of a normal thermal expansion and a contraction due to loss in moisture from wood substance. The true irreversible change is thus the total observed dimension increase during the first heating minus (algebraically) the contraction during the second heating. This true irreversible dimension change is given by the curve marked "true tangential recovery." It amounts here to about 0.022 centimeters or 0.45 percent at 80° C. In contrast, the reversible change is about 0.15 percent and with opposite sign. The tangential recovery is very probably due to the breaking of strained hydrogen bonds,

Presented at the American Chemical Society meeting, St. Louis, Mo., 1961. Approved for publication October, 1961.

Maintained in cooperation with the University of Wisconsin, Madison, Wis.

The Authors: H. Tarkow is a chemist at the U. S. Forest Products Laboratory; T. Yokota was formerly an FAO collaborator at the Laboratory, and is presently a research associate at the Forest Experiment Station, Tokyo, Japan.

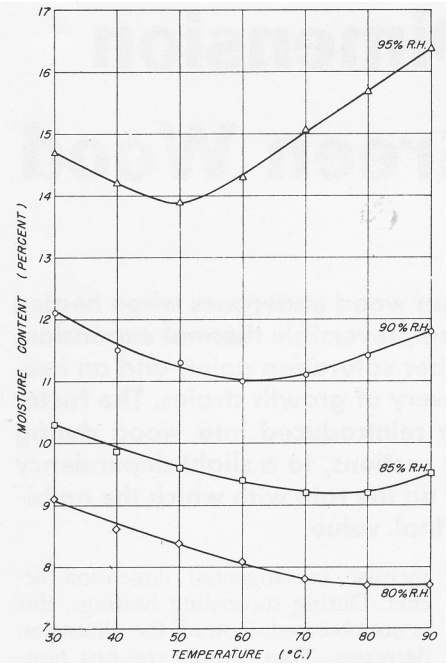

Fig. 1.—Relationship between moisture content of wood and temperature at constant **relative humidity.**

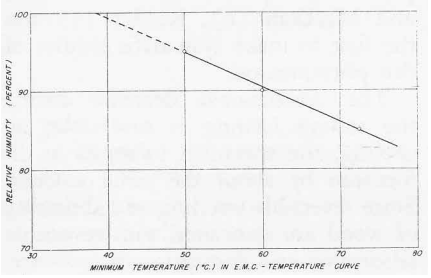

Fig. 2.—Relationship between relative humidity and the temperature at which a occurs in the moisture content-temperature curve.

which are present even in freshly felled green wood. Jacobs (2) has demonstrated the presence of compressive stresses in the tangential direction of growing trees. The thermal recovery of the corresponding strains constitutes the "true tangential recovery."

Corresponding changes in the radial direction are shown in Figure 5. Here too, an irreversible change in dimension occurs during the first heating; it is, however, in the opposite direction from that in the tangential direction. To obtain the true radial recovery at 80° C., the diinension change during the first heating must be reduced by the dimension change during the second heating. The radial recovery at 80° C. is —0.2 percent. The reversible change between 30° and 80° C. is —0.05 percent. Volumetrically, (considering the sum of the tangential and radial effects) there is an irreversible increase during the first heating. During subsequent heating, however, the volume decreases on heating and increases reversibly on cooling.

True tangential recoveries were also measured at other temperatures on separate specimens for each temperature (Figure 6). The magnitude of the recovery decreases with decreasing temperature and extrapolates to zero recovery at about 35° C. Thus, if a green cross section at 20° C, is heated in water, its tangential dimension would decrease initially as a result of the exothermic nature of the interaction. Beyond about 35° C., however, an inflection would occur because of the onset and superposition of the irreversible change on the normal reversible change. In other words, at 100 percent relative humidity, the tangential dimension-temperature curve would show a minimum at about 35° C. If the dimension change is accompanied by a change in moisture content of the wood substance (not the wood), the curve relating moisture adsorption to temperature at 100 percent relative humidity very probably would show a minimum at about 35° C. This would appear to be in excellent agreement with the prediction made previously from Urquhart's work and would indicate that the minima he observed were also due to the onset of an irreversible change, such as the breaking of hydrogen bonds (3). If this is so, then with cotton, as with the wood at a fixed high relative humidity, the peculiar curves of moisture regain versus temperature shown in Figure 1 would not be reversible. Instead, during a second heating, the amount of moisture regained would decrease continuously with increasing temperature. Unfortunately, there are no known experimental data for examining this prediction for cotton.

Following a first heating to 80° C., the sections of wood were removed from the water, oven-dried, resubmerged in water, and again heated. The object was to determine whether drying reintroduced weak hydrogen bonds that are unstable at some elevated temperature. If so, curves to those of Figure 3 should be obtained.

No evidence of such bond instability was found. During heating, the dimension decreased at all temperatures with no indication of an inflection or irreversible change. If weak bonds had been created during drying, they seemed to resist the subsequent moist, high-temperature treatment. Urquhart's cotton (8) had been kier-boiled and dried before he measured the adsorption. Such cotton, unlike the once-dried wood, did show behavior that was interpreted above in terms of the occurrence of an irreversible change. There is thus the problem of rationalizing the divergent behavior of our once-dried, wet-heated wood cross sections and Urquhart's once-dried, wet-heated cotton. Bonds sensitive to moisture and heat are present in cotton, but apparently not in wood.

Bonds sensitive to moist heat are probably created during the drying of

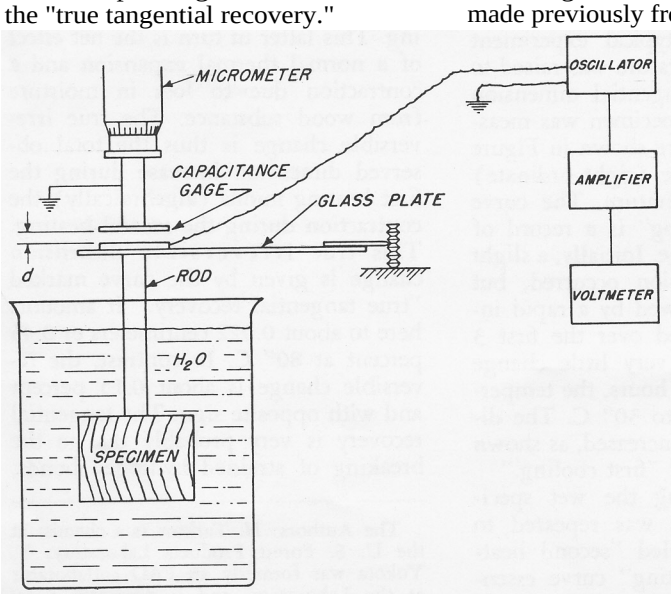

Fig. 3.--Schematic drawing of equipment for measuring change in dimension of green wood with temperature.

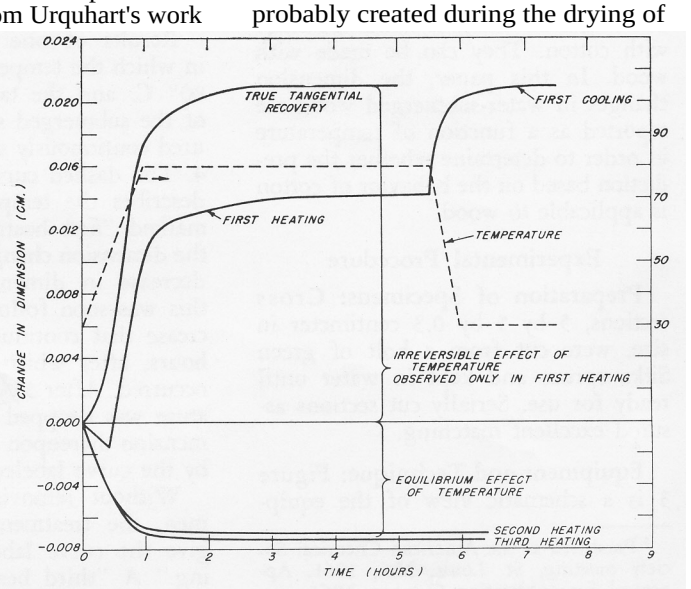

Fig. 4.—Tangential dimension change when **green wood is heated** and cooled in water.

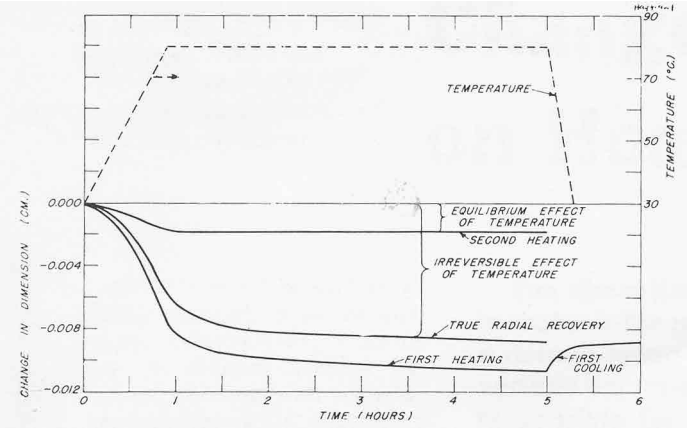

Fig. 5.-Radial dimension change when green wood is heated and cooled in water.

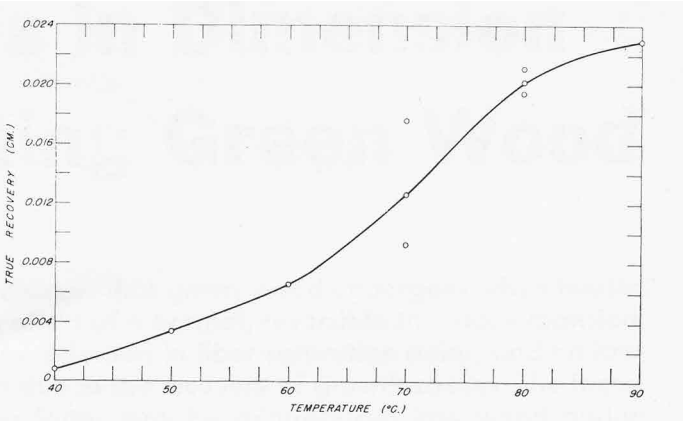

Fig. 6.-Relationship between true tangential recovery of green wood and temperature.

wood, but the subsequent difference in behavior between the cotton and the wood may be due to the different conditioning procedures following drying. The wood was conditioned at 100 percent relative humidity by plunging the dry specimens directly into water. Swelling stresses must have been high; in fact, under such conditions, one can "hear" wood swell. Owing to such high stresses, hydrogen bonds are broken that remain unbroken if rehumidification is carried out slowly.

Figure 7 which was prepared from a recent paper by Christensen and Kelsey (1), shows the "equilibrium" moisture regain of very thin wood sections at 88 percent relative humidity as a function of the number of intervening relative humidity steps. With decreasing rate of humidification, the adsorption decreases. Fewer bonds are broken by slow humidification. The wood conditioned at 100 percent relative humidity by direct contact with liquid water had most of its weaker bonds broken; hence no thermal recovery was subsequently observed. Urquhart's cotton, on the other hand, had been humidified very slowly following drying. Under such conditions, severe swelling stresses could not develop. Very weak bonds were therefore present when the cotton was tested. Their breaking is responsible for the minima in Figure 1. Precisely speaking, then, the term equilibrium moisture content is ambiguous since the adsorption is dependent on the manner in which humidification is carried out. This ambiguity, it should be emphasized, becomes significant only with thin sections of wood. One wonders if such ambiguity in moisture content exists at the immediate surface of wood. That is, although the average moisture content of a block of wood is predictable from the adsorption isotherm, is the moisture content of the immediate surface layer dependent on the rate of humidification?

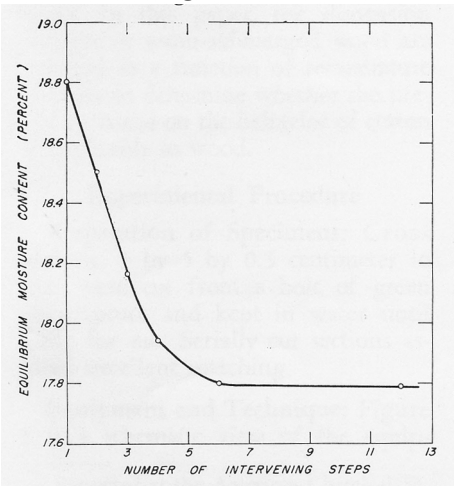

Fig. 7.—Relationship between "equilibrium" moisture content of wood at 88 percent relative humidity and the number of intervening relative humidity steps.

Curve A in Figure 8 shows the percentage decrease in tangential dimension when the green Sitka spruce is heated in water following a first heating to remove the irreversible component. This decrease, as mentioned previously, is the net effect of a normal thermal expansion and a contraction due to a reduction in the amount of moisture in the wood substance (reduction in fiber saturation point). If it is assumed that the first effect is the same as the thermal expansion of dry wood, then available data (9) can be used to compute it. This contribution is given by curve B. Curve C, obtained by adding B and A (algebraic subtraction) then represents the change in dimension due only to the reduction in fiber saturation point. The change is reversible and is a requirement of the exothermic nature of the adsorption process. Green wood in a growing tree is seldom subjected to temperatures above 30° C. In temperate climates, it may be subjected to low temperatures of -10° or -20° C. If supercooling occurs here, then curve A is an indication of the tangential (and related cross sectional area) change that may accompany variations in ambient temperatures (winter and summer) if no other ambient changes (relative humidity) occur. This point is introduced here to emphasize the fact that dimension changes can occur in a growing tree as a result of changes, with temperature, of the amount of moisture associated with the wood substance.

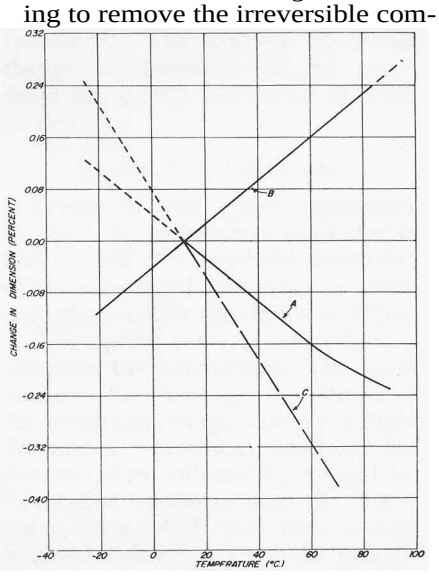

Fig. 8.-Effect of heating strain-recovered green wood in 20 ter: A,100sTEMPERATURE i gential dimension (the green wood was previously heated in water to recover growth strains); B, computed expansion of wood, assuming same coefficient as Act of dry wood; and C, computed change in tangential dimension caused only by change in mo ture associated with wood substance at 100 percent relative humidity (fiber saturation point).

Literature Cited

1. Christensen, C. N., and Kelsey, K. E. 1959. Holz als Roh-u. Werkstoff 17:178.
2. Jacobs, M. A. 1945. The Growth Stresses of Wood Stems. Commonwealth of Australia Forestry Bureau Bull. 28.
3. Kawai, T. 1959. Jour. Pol. Science 37: 185.
4. Koehler, A. 1933. AWPA Proceedings 29:376-388.
5. Kiibler, H. 1959. Holz als Roh-u. Werkstoff 17:77.
6. MacLean, J. D. 1952. AWPA Proceedings Kübler 154.
7. Norris, C. B., James, W. L., and Drow, J. T. 1956. ASTM Bull. 218, pp. 40-48.
8. Urquhart, A. R. 1924. Jour. Text. Inst. 15:T138, T433, T559.
9. Weatherwax, R. C., and Stamm, A. J. 1947. Trans. Am. Soc. Mech. Eng. 69: 421.

**Purchased by the Forest Products Laboratory,
U. S. Department of Agriculture, for official use.**