MOISTURE ADSORPTION AND TRANSPORT BY WOOD DUE TO A THERMAL GRADIENT CAUSED BY AIR-TO-AIR THERMAL DIFFERENCES[1]

Robert W. Erickson, Robert T. Seavey, and Stephen L. Quarles

Professor and Graduate Students, respectively
Department of Forest Products, University of Minnesota, St. Paul, MN 55108

(Received 4 August 1980)

ABSTRACT

An experiment was conducted in which a thermal gradient was established in wood by air-to-air temperature differences. A walnut board and a redwood board, each ¾ inch thick and approximately 4 inches wide, were installed in a 1-inch-thick sheet of wood fiber insulation board employed as the lid of a chest-type freezer. The narrow edges of the boards were exposed to room air and freezer air, respectively. The MC profiles were periodically determined by removing cross sections from the boards and reducing them to thin slices. Moisture moved down the temperature gradient and against the concentration gradient. The average MC of the walnut and redwood boards increased 21% and 2%, respectively, during the 53-day test. The results showed that when wood is used as a thermal barrier, water vapor will enter the wood from the warm air and can be condensed in the wood if the necessary temperature profile exists. In certain applications of wood, this raises the possibility for free water accumulation in wood and the associated hazards. Moisture movement down a temperature gradient in wood is hypothesized to be a causative factor in the ceiling/partition separation problem with trusses in residential housing.

Keywords: Moisture movement, moisture profile, temperature gradient, concentration gradient, ceiling/partition separation.

INTRODUCTION

In recent years a problem has been encountered in the use of wood roof trusses in residential houses wherein the ceiling, which is fastened to the tension chord of the truss, separates from the interior partition walls. The separation is usually less than ½ inch, but openings up to 1.5 inches have been reported. This phenomenon has been given the name of ceiling/partition separation (CPS).

A significant feature of CPS is its cyclic nature, i.e. the separation will appear and disappear, respectively, with the cold and warm seasons of the northern regions of the United States. This suggests some relationship of the thermal properties of the construction to its behavior.

Coefficients of thermal expansion and contraction for wood are quite low, especially parallel to the grain. For example, in a 16-foot-long Douglas-fir member, the parallel-to-grain change in length for a change in temperature of 100 F is about 0.03 inch. By comparison, total normal shrinkage parallel to the grain would amount to perhaps 0.25 inch to 0.30 inch. It seems unlikely that even the most extreme differences in winter and summertime temperatures could cause sufficient thermal dimensional changes to account for the movements observed. There is the possibility, however, that temperature differences are responsible

[1] Published as Scientific Journal Series, Paper No. 11,351 of the University of Minnesota Agricultural Experiment Station. This research was partially supported by McIntire-Stennis funds.

for changes in moisture content that result in deflection due to longitudinal shrinkage.

MacLean (1941) has obtained data showing moisture redistribution due to heat flow. His experiments consisted of placing a wood slab between two hot plates maintained at a steady-state temperature differential. Moisture flowed from the warm toward the cold face of the wood slab. In one test he used southern yellow pine with an average moisture content (MC) of 14.9% and a temperature differential of 54 F with the average temperature of the wood being about 85 F. After 144 hours the wood adjacent to the cold plate was at 37.8% and that adjacent to the hot plate was 6.9%, even though the moisture distribution was approximately uniform before the test.

MacLean concluded that the redistribution of moisture was due to differences in vapor pressure resulting from temperature differences. MacLean points out that in any structure where a temperature gradient exists between the faces of the wood, a moisture gradient will be produced and whether drying occurs from the cold face will depend upon a variety of factors.

During winter months in cold climates, the bottom tension chord of a truss is subjected to a temperature differential. The bottom edge of the chord is in contact with a surface, normally sheetrock, that is at 70 F or higher. The top edge of the chord is at a lower temperature, the level of which probably depends upon the amount of insulation and the degree of attic ventilation. If only the top edge of the chord is exposed to attic air because the sides are covered with insulation, the differential might be the greatest. If the insulation covers the chord, the respective k factors of the chord and the insulation come into play. In any event, it seems imperative that heat flow would occur from the warm to the cold face. In accordance with MacLean's finding, this could conceivably cause a movement of chord moisture from the warm to the cold face. It is then possible to visualize compression wood or pith wood lying along the top or bottom edge of the chord, or possibly even both edges. The longitudinal dimensional changes of the bottom and top edges, i.e. their respective shrinking and swelling, would complement each other in producing an upward arching of the chord. In the spring and summer months, the temperature gradient in the chord would essentially disappear, leading once again to a more or less uniform distribution of moisture in the chord. As a consequence, the chord would tend to return to its installed position.

Compression or pith wood along the narrow edges of the piece may not be required to produce the arching. Southern yellow pine has an inherent tendency for high and nonuniform longitudinal shrinkage irrespective of these two factors. There are considerable data on the longitudinal dimensional properties of SYP in Koch's book (1972) *Utilization of the Southern Pines*. A scatter diagram of Longitudinal Shrinkage vs. Rings Per Inch of Radius for loblolly pine shows a shrinkage value for two rings per inch of over 2%. A graph of Longitudinal Shrinkage vs. Growth Ring Number for slash pine shows an average shrinkage for growth ring number four of approximately 0.6%, with a range of 1.3% to −0.5%. At eight growth rings per inch, the range is 0.5% to −0.4%. Obviously the potential for high longitudinal dimensional change does exist in the southern pines.

Against this hypothetical background, it was decided to conduct a cursory experiment on the question of what happens to the moisture in wood as a result of a thermal gradient through it due to an air-to-air temperature differential.

EXPERIMENTAL OBJECTIVE

The objective was to determine if the moisture contained in a piece of wood will migrate from the surface of the wood in contact with warm air toward the surface in contact with cold air.

EXPERIMENTAL PROCEDURES

Stored in a coldroom (34 F) and considered suitable for this experiment were two heartwood boards, one of walnut and the other of redwood. Each was about ¾ inch thick, 4 inches wide and 24 inches long. A phenolic end-coating plus aluminum foil were applied to the end-grain and the wide surfaces. The edges were left unsealed.

The cover of a chest-type freezer was replaced with a 1-inch-thick piece of wood fiber insulation board. Two slots were cut into the insulation board, each ¾ inch wide and 24 inches long. The test pieces were inserted into these slots. For each piece, approximately the same volume was exposed to freezer air as to room air. The air temperature in the freezer near to the test piece was determined by a thermocouple and was found to remain at about +10 F. The temperature of the unconditioned room air fluctuated within the range of about 70 to 85 F. The test was conducted during July and August 1979.

The edge-to-edge MC profile was determined for both test pieces just prior to the test and several times additionally during its 53-day duration. This procedure consisted of removing the piece, cutting a 1-inch cross section about 1 inch from the end of the piece, resealing the end-grain, and replacing the piece in the slot. Insulation plugs were used to seal the open slot area generated by shortening the test piece.

The walnut cross section was subdivided into eleven slices, each slice being about ¼ inch thick. The redwood cross section, having a slightly larger edge-to-edge dimension, was subdivided into fourteen thin slices. The standard oven-dry procedure was used for determining the MC of the individual slices. A thin-kerf bandsaw was used for producing the slices.

RESULTS AND DISCUSSION

The MC profiles for the walnut board and the redwood board are shown in Figs. 1 and 2, respectively. Let us first examine the profiles obtained with the walnut board.

On 20 June, just prior to the start of the test, the surface slices had comparable MC's of about 22%. The profile was of a parabolic nature, which is to be expected for a board that has undergone partial drying. The skewed distribution of moisture was possibly due to unequal drying conditions for the board surfaces during storage in the coldroom or unequal distrubution of moisture in the green material. The highest average MC in this profile was 37% for slice No. 4.

By 29 June, the average MC of the eleven slices had increased from 26.9 to 33.6%. Slice No. 11, facing the freezer air, had an average MC of about 21%.

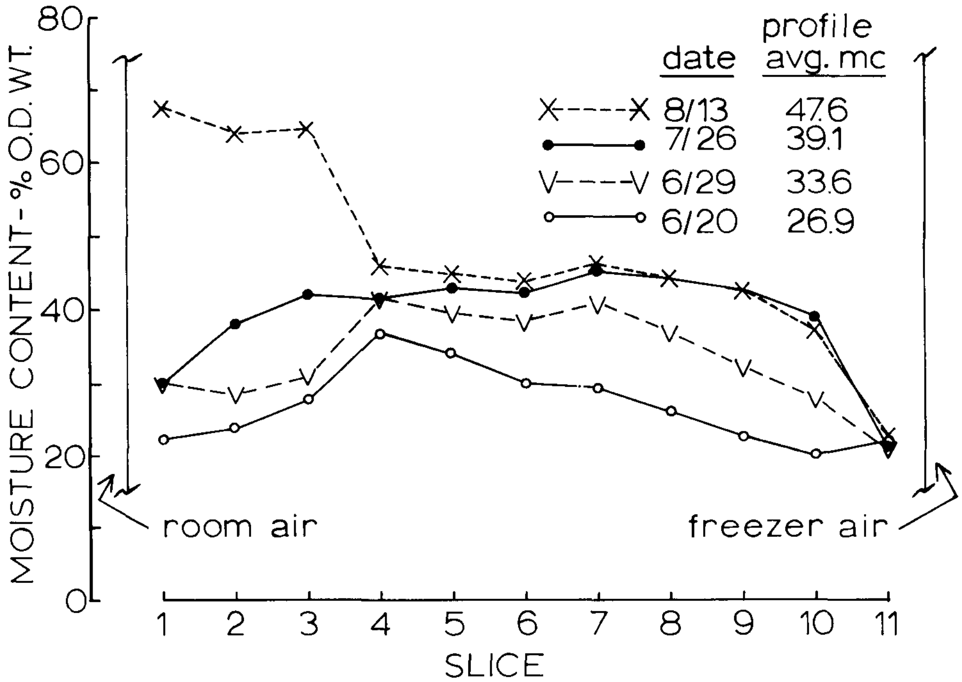

FIG. 1. Moisture content profiles for the walnut board.

This was very close to its original MC. The remaining slices all increased in MC, with the largest increases occurring in slices 6 through 10.

The next profile is for approximately one month later on 26 July. Slice 11 remained essentially the same, which is indicative of an equilibrium condition with the freezer air. The remaining slices, with the exceptions of 1 and 4, all increased appreciably. The failure of 1 and 4 to increase might be explained on the basis of variation in MC along the grain, as the profiles came from individual cross sections that were serially cut along the length of the board.

The final profile was determined on 13 August. Again there was no appreciable change in the MC of slice No. 11. The dramatic increases in MC occurred in slices 1 through 3. The average MC for this profile was 47.6%, almost 21% greater than for the profile of 20 June.

What was the source of the moisture responsible for a 21% increase in MC? There are apparently only two possibilities, the edge exposed to the warm air or the edge exposed to the cold air. All other surfaces were covered with phenolic end-coating plus aluminum foil.

If the moisture originated from the cold air, it would have needed to move inward against a steep concentration gradient, especially between slices 11 and 10, and also against the thermal gradient. It is, therefore, more logical to conclude that the vapor originated from the warm air, with the thermal gradient as the driving force. This is similar to the familiar problem of water vapor movement into the insulation of a house wall. Moisture is driven from the warm toward the cold side down the thermal gradient, with the potential for condensation in the

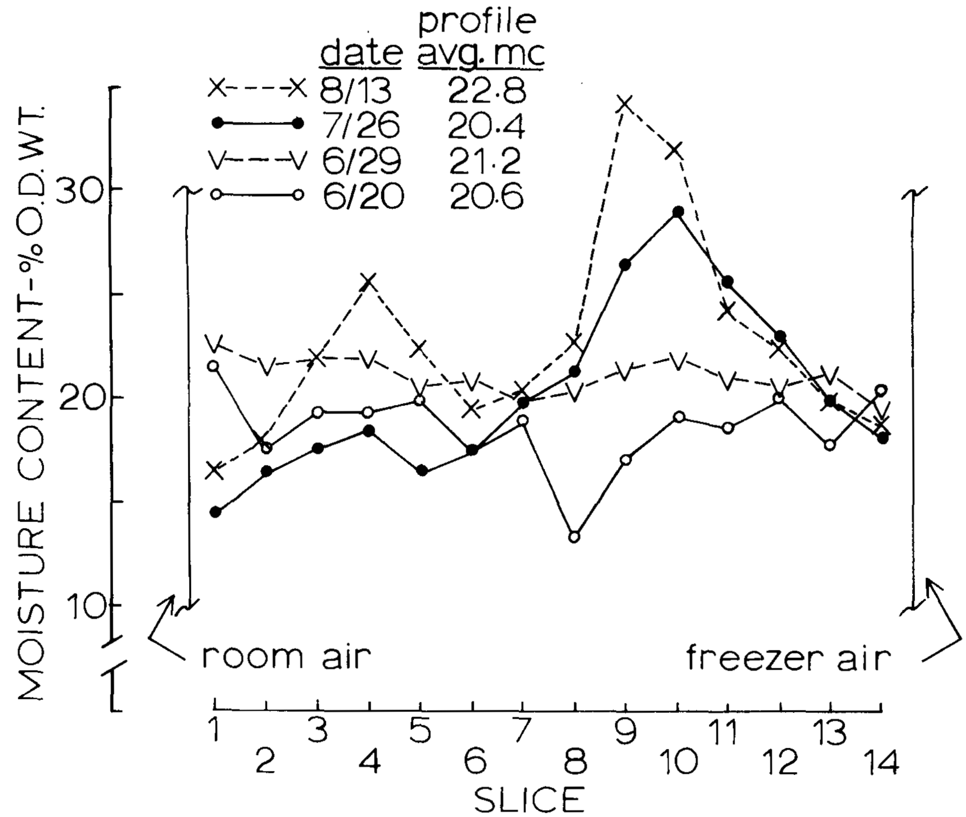

FIG. 2. Moisture content profiles for the redwood board.

body of the insulation. In our experiment, the wood can be thought of as a thermal barrier analogous to the insulation.

The room air-conditions were not controlled. The temperature ranged between 70 and 85 F and the equilibrium moisture content (EMC) condition of the air, as periodically established by temperature measurements with a sling psychrometer, remained close to 10% throughout the test.

Since the MC of the wood at the warm face was considerably above 10%, one might have expected it to lose moisture and reach an equilibrium with the surrounding air. Instead, slice No. 1 increased from 22% to 30% MC during the first 9 days of the test. Obviously there was a driving force moving moisture from the warm air into the wood, namely the thermal gradient between the air and the wood surface. When the water vapor molecules in the air came in contact with the wood, their energy level was reduced and they were "captured" by bonding sites in the wood. Evidently the driving force due to the thermal gradient exceeded the driving force in the opposite direction due to the concentration gradient.

Once the moisture was adsorbed, it moved from the warm towards the cold face down the temperature gradient and against the concentration gradient. The movement inward against the concentration gradient is quite evident for slices 1 through 4 for the profiles of 29 June and 26 July.

Initially there was no free water at the warm surface of the wood as the MC of slice No. 1 was 22%. Consequently, water molecules obtained from the room air were adsorbed by the cell walls. Inward migration then had to occur as molecular diffusion from bonding site to bonding site against a concentration gradient below the fiber saturation point (FSP). Eventually, as shown by the profile for slices 1 through 4 for 29 June and 26 July, the migration had to occur against a concentration gradient totally above the FSP. This migration could not occur as liquid water. The thermal gradient must have produced a vapor pressure differential sufficient to exceed the driving force in the opposite direction due to the concentration gradient, thus moving the water down the temperature gradient toward the cold face.

What will eventually happen to the water molecules as they diffuse toward the cold face, whether their diffusion be taking place above or below the FSP? At some point along the thermal gradient, they will encounter the dewpoint temperature. If the dewpoint is along a line situated in wood below the FSP, the condensation will be adsorbed by the wood substance. If it is situated in wood above the FSP, the condensation will appear as additional free water.

The rapid accumulation of free water creates the possibility of mass flow due to capillary forces. The mass flow could presumably occur towards both the warm and cold faces of the wood, with its rate determined by the amount of free water and the wood permeability. The movement toward the cold face would eventually be stopped by the fact that the free water reaches a location where the temperature is below freezing.

As the wood increases in MC, its thermal conductivity (k value) increases. This shifts the dewpoint towards the warm face. This was partially responsible for the dramatic MC increase of slice 1, 2 and 3 between 26 July and 13 August. Drops of water were observed on the "warm" face, indicating that the surface temperature had reached the dewpoint temperature. Reaching of the dewpoint temperature was probably also due to an increase in the relative humidity of the room air. If the experiment had been continued beyond 13 August, the MC of the wood should have rapidly increased to a level approaching saturation because of a mass flow of liquid water from the warm face to the ice line. Because the solubility of air in water is inversely related to water temperature, air blockage would be decreased and the mass flow of water through the capillary structure enhanced. Superimposed on the mass flow would be molecular diffusion due to the combined effects of the thermal and concentration gradients. The maximum MC achievable would be influenced by the location of the ice line, which would shift toward the warm face as the k value of the wood continued to increase.

The redwood board (Fig. 2) increased in average MC from 20.6 to 22.8% between 20 June and 13 August. This was about only one-tenth of the increase demonstrated by the walnut. The differences in behavior for the walnut and redwood are believed to be directly attributable to their different thermal properties.

The walnut board had a higher initial average MC. Walnut also has a higher specific gravity than redwood. Both of these factors would contribute to a higher k value. Consequently, there was undoubtedly a significantly different temperature profile in the two boards, and we did not observe condensation droplets on the warm face of the redwood board. Apparently its k value and resulting temperature profile were such that the warm face never reached the dewpoint temperature of the room air. However, slices 9 and 10 in Fig. 2 illustrate the general location of the dewpoint temperature. Slice No. 9 went from about 17 to 34% during the test. Slice No. 10 increased from about 19 to 32%. At some point along the profile between slices 8 and 11, the dewpoint temperature was reached for the water molecules diffusing through the cell lumens. As long as the MC of the wood was below the FSP, the condensation was adsorbed by the cell walls and by 26 July the MC of slices 9 and 10 was at or above the FSP for redwood. As additional water vapor diffused into this region, it was condensed and then appeared as free water. This quickly raised the MC of slices 9 and 10 to 34 and 32%, respectively, by 13 August.

It is predicted that if the experiment had been continued for a sufficient length of time under the same conditions, the redwood profiles would have approximated those for the walnut. The migration of water vapor from the warm air into the wood, and through the wood, would have continued in response to the thermal gradient. The dewpoint would have shifted toward the warm face as the k value increased with increasing MC. Eventually condensation would have occurred on the warm face, with a dramatic decrease in the rate of transfer across that boundary. The rate of mass flow in redwood would probably be lower than that in walnut due to its lower permeability.

SUMMARY

The results of this experiment demonstrate that a thermal gradient through wood due to air temperature differences will serve as the driving force for the movement of moisture. The moisture movement is from the warm toward the cold surface and will occur against a moisture content gradient. This seems to confirm the earlier hypothesis that the moisture in the bottom tension chord of a house truss could move from the bottom edge toward the top edge, i.e. in the direction of decreasing wood temperature.

We believe that the phenomenon depicted in Figs. 1 and 2 has additional practical significance plus fundamental significance.

There are numerous applications of wood in which it is subjected to substantial temperature differentials. The 2 by 4 stud in a well-insulated house wall is one example. The surface temperature of the inside edge of the stud may be close to 70 F while the exterior could be well below freezing. Such a temperature differential could be in effect for weeks or even months in the colder regions of North America. Is there a moisture pickup and migration in such members under certain types of installation? If so, what does this mean with respect to dimensional stability, k value, and other performance criteria of the stud and the wall?

A more extreme example is wood structural members in the exterior walls of well-insulated buildings used for animal housing and crop storage. Quite often the inside air is of extremely high relative humidity and coupled with a severe temperature gradient through the wood member. Under such conditions, the results depicted in Fig. 1 indicate the possibility for the wood members to accumulate free water. The presence of free water has serious implications with regard to decay, strength, corrosion of connectors, etc.

The demonstration of moisture movement through wood against a concentration gradient, with a thermal gradient as the driving force, would appear to have a fundamental significance. There are several researchers who have addressed the question of thermal diffusion. Siau (1980) states that for steady-state isothermal vapor movement, approximately the same flux can be calculated using either partial vapor pressure, moisture content, concentration or chemical potential, but that under nonisothermal conditions the use of any of these potentials will give different results when applied to the same data. He indicates that there is a definite need for experimentation in order to quantify the significance of the Soret effect (thermal diffusion) in moisture transport through wood and that calculations show a significant Soret effect if high temperature gradients are present. Siau proposes an unsteady-state equation that incorporates a thermal diffusion term. Bramhall (1978) concludes that both isothermal and nonisothermal sorption diffusion are due to a spreading pressure whose saturated value at any temperature is determined from use of the Clausius-Clapeyron equation. Bramhall used experimental data from the literature to demonstrate validity of spreading pressure as the driving force under nonisothermal conditions. Wengert (1975) states than when temperature gradients are large, thermal diffusion can occasionally cause a flux in wood and that the flux results primarily from the effect of temperature upon the hygroscopicity. He portrays a possible experiment in which there exists, in the absence of a vapor pressure gradient, a moisture content gradient through the wood due to a thermal gradient. He concludes that at steady-state conditions there is no flux and that diffusion due to a thermal gradient is only of importance in transient circumstances. With refinements and improvements in the type of experiment being reported in this paper, it should be possible to answer more precisely the contribution of thermal diffusion to moisture flux through wood.

In retrospect, it is realized that the determination of the MC profiles in this experiment should have been over a longer period of time and should have been accompanied by the determination of the temperature profiles. In the absence of temperature data, the explanations given for Figs. 1 and 2 are based largely on deductive reasoning. It is also recognized that the shape of the thermal profile through the wood is dependent upon the area of the wood in direct contact with air at both the warm and cold surfaces plus the air conditions. As a result of these considerations, we currently have underway an experiment that is designed to correlate the MC and temperature profiles under more precisely defined and controlled experimental conditions.

ACKNOWLEDGEMENTS

The authors are indebted to Donald H. Percival, University of Illinois Small Homes Council; Dr. Stanley Suddarth, University of Purdue; and Gerald Sherwood, U.S. Forest Products Laboratory for historical data on CPS.

Thanks are also due to Dr. Ralph Hossfeld, Department of Forest Products, University of Minnesota, and Dr. John Siau, Wood Products Engineering Department, State University of New York, Syracuse Campus, for their contributions to the interpretation of the data.

ADDENDUM

Subsequent to submission of this paper to *Wood and Fiber*, an additional experiment on monisothermal moisture movement was completed. Samples of green ash (*Fraxinus lanceolata*) were subjected to a thermal gradient by installation in slots provided in a 4-inch-thick sheet of styrofoam insulation used to replace the cover of a chest-type deep-freeze. All surfaces of the samples, except the narrow edges that were exposed to the room and freezer air, were covered with aluminum foil. The samples were ¾ inch thick, 4 inches wide and 2 inches along the grain. The room and freezer temperatures were held constant at 80 F and −40 F, respectively. The relative humidity in the environment room used to house the deep-freeze was maintained at close to 40%.

A matching sample of green ash (from one of the parent boards used for the freezer samples) was placed on a rod-type shelf in the environment room. None of the surfaces of this sample were covered with aluminum foil. It soon equilibrated to room temperature and was thereafter free of a thermal gradient.

Every three days a sample was removed from the styrofoam freezer cover and sliced into moisture content sections about ¼ inch thick. The experiment continued for three months.

Near the end of the experiment, a more precise determination was made of the moisture content of wood interfacing directly with air. The objective was to make a comparison of the interfacial moisture content for freezer samples and the sample stored on the environment room shelf. A microtome was used to remove slices about $^1/_{32}$ inch thick from the narrow edges of the samples.

The first slices off the shelf sample had a moisture content of 8%, which is equivalent to what one would expect from an EMC table. The comparable slices from the freezer samples had an average moisture content of about 14%, or 6% above the predicted EMC for the room conditions. The temperature drop from room air to the first thermocouple embedded in the thermal gradient sample, a distance of $^1/_8$ inch from the wood surface, was 80 F to 60 F. The elevated moisture content is believed to be due to the reduction in vapor pressure coincidental with the temperature drop.

A more detailed report on this latest experiment will be published as early as possible.

REFERENCES

Bramhall, G. 1978. Sorption diffusion in the drying of solids. Fiber Sci. Technol. (11).

Koch, Peter. 1972. Utilization of the southern pines. Vol. 1. Agricultural Handbook No. 420.

MacLean, J. D. 1941. Thermal conductivity of wood. American Society of Heating and Ventilation Engineers. Journal Section, Heat, Piping and Air Conditioning.

Siau, John F. Nonisothermal moisture movement in wood. (Unpublished manuscript provided to the authors by Dr. Siau in July 1980.)

Wengert, E. M. 1975. Prediction of moisture content in wood. Ph.D. Thesis. University of Wisconsin, Madison, WI.