PREDICTING AVERAGE MOISTURE CONTENT OF WOOD IN A CHANGING ENVIRONMENT

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ABSTRACT

In the past, predicting the behavior of wood exposed to a variable temperature and humidity environment was based on experience. However, with recent advances in solving complicated heat and mass transfer problems with the digital computer, prediction of the behavior of wood exposed to a variable temperature and humidity environment has become possible.

This report examines several of the factors that influence wood's behavior and gives some simplifications necessary to formulate an adequate model of moisture movement in wood. A series of experiments was conducted to measure moisture content of wood in a changing temperature and humidity environment. These measurements were compared with the results predicted from the model using a digital computer. The model was adequate for predicting the moisture response of the samples used in these experiments.

Additional keywords: *Picea engelmannii, Tsuga heterophylla, Populus grandidentata, P. deltoides, Prunas serotina, Acer rubrum, Ulmus americana, Quercus alba, Q. rubra*, moisture gradients, diffusion coefficients, equilibrium moisture content, relative vapor pressure, vapor diffusion, vapor pressure.

INTRODUCTION

The equilibrium moisture content (EMC) is the moisture content wood will attain at equilibrium when exposed to a given humidity and temperature. These values for various temperatures and humidities, first published at Forest Products Laboratory by Koehler (1919), have been successfully applied to most North American species. But, because moisture moves in wood very slowly, the EMC values are useful for predicting the moisture content only for small samples, 1 cm or less thick in the flow direction. Larger samples, when exposed to dynamic environments, may never reach equilibrium but will continually have internal moisture gradients. As a result, in order to predict accurately the moisture content for many wood products, a dynamic situation of moisture flow must be considered.

The specific objectives of this work have been: (a) to develop a model for easily predicting the moisture content and moisture gradients of wood in a dynamic environment using as input certain wood properties and environmental data, (b) to show how well the method works for several different circumstances, and (c) to provide a useful and practical computer program to predict moisture content in wood that incorporates the results of this work.

Specifically, the reseach and model were confined to predicting the dynamic moisture content of wood in a dry condition (0% moisture content to fiber saturation) with a temperature range from 32 F to 212 F, simulating the response of kiln-dried wood to environments normally encountered in industrial or construction uses. It considers only one- and two-dimensional flows; it is not restricted to uniform initial moisture content.

MODELING MOISTURE MOVEMENT

Fick's Second Law is the governing equation used in this model. The one-dimensional expression from Bird et al. (1960) is:

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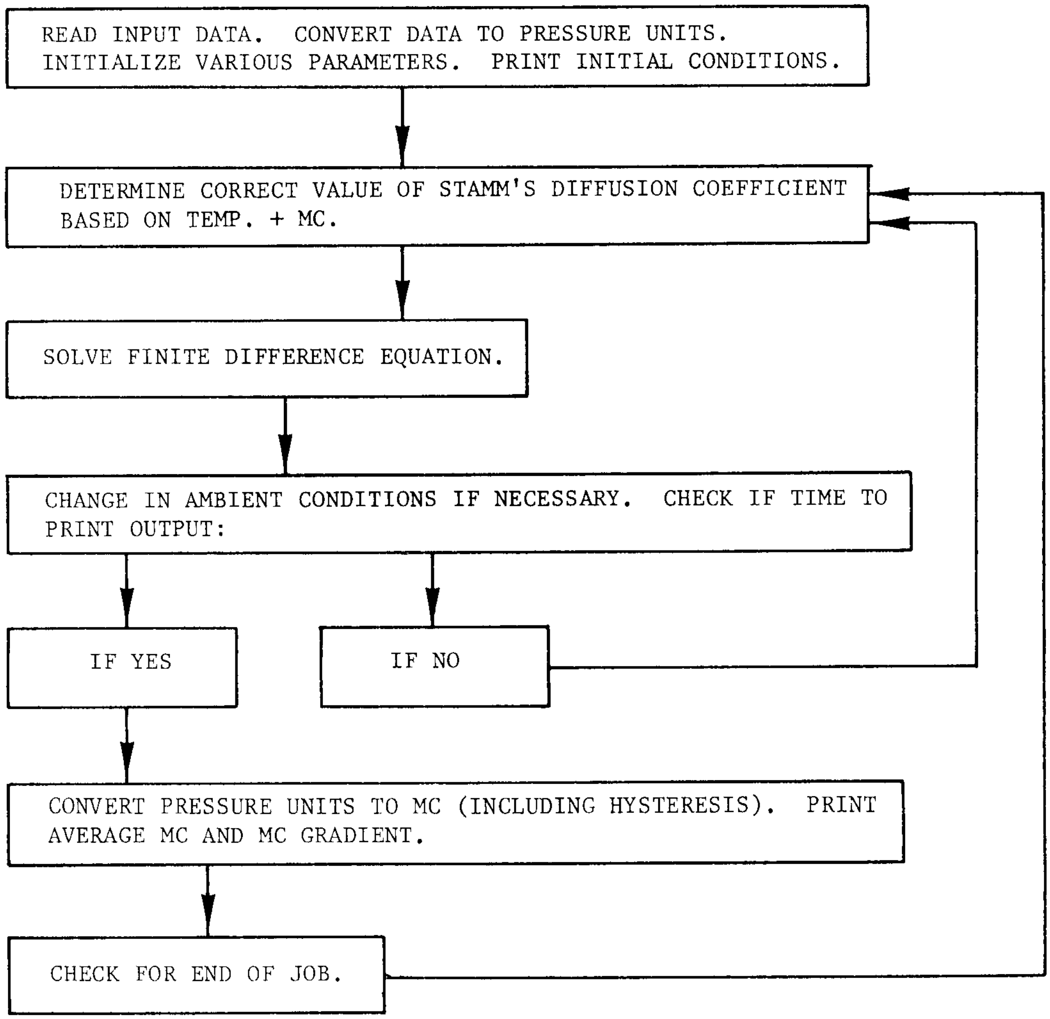

FIG. 1. A computer program can provide generalized methods of predicting moisture movement in wood, based upon heat transfer methods.

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x} D \frac{\partial c}{\partial x}$$

where c = concentration,
t = time,
x = distance in the flow direction, and
D = diffusion coefficient (or coefficient of moisture diffusivity).[3]

[3] In steady-state flow, the flux, F, is related to D by

$$F = -D\ (\partial c/\partial x)$$

In the model developed here, moisture movement is attributed to a partial water-vapor pressure gradient rather than to a moisture content gradient, as previous reports have done. There are several advantages to this approach:

(a) Moisture movement due to a vapor pressure gradient is realistic. For example, consider wood exposed to 80 F and 80% RH (15.9% EMC and a partial pressure of 17.8 mm Hg) on one side and to 120 F and 21% RH (4.0% EMC and 17.8 mm Hg) on the other side. There is a moisture content gradient (15.9 to 4.0%) but no flow or partial pressure gradient. With pressure units, Fick's Law can be used directly.

(b) The surface resistance, primarily a boundary layer phenomenon, is not dependent on the vapor pressure level for slow flow rates, but only on temperature and other external factors (Bird et al. 1960).

(c) When calculating unsteady-state flow using Fick's Law, partial pressure units will provide usable results regardless of the EMC *vs.* partial pressure relationship (hysteresis) that wood has. That is, the hysteresis effect only affects the conversion from partial pressure to moisture content and does not influence the calculated value of flux.

A great deal of progress has been made in the last decade in solving complicated dynamic heat transfer problems with a digital computer. Because of the mathematical and phenomenological similarity between heat transfer and moisture movement, generalized methods of predicting moisture movement in wood based upon heat transfer methods can be obtained.

The solution of the model equation with suitable boundary conditions here is based on a finite difference approach. See, for example, Crank (1956). (The wood sample is modeled with many small pieces and the flux within each small piece is analyzed repetitively at successive small time steps.) An outline of the computer program is given in Fig. 1.

It would be easy to utilize these heat transfer methods for moisture flow if moisture movement adhered to Fick's Law. However, past attempts by McNamara (1969) and Moschler and Martin (1968) to use Fick's Law have not been too successful, possibly because other factors besides the moisture concentration gradient play a role and/or because D has not been correctly determined.

DETERMINING VALUE OF D

When looking at the various diffusion coefficient versus moisture content curves from experimental results of past studies,

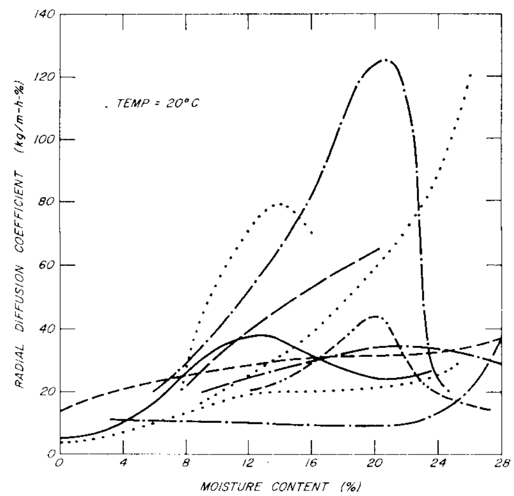

FIG. 2. A diverse collection of experimentally determined values of the diffusion coefficient versus moisture content, assembled from Kubler (1957).

such as compiled by Kubler (1957) (Fig. 2), the problem arises of which value to use in analysis. These published curves can be confusing; they are frequently based on only a few points through which a smooth line was drawn.

For this analysis, the diffusion coefficient of Stamm (1962) was used for all species as his values agreed well with the theoretical analyses by Wirakusumach (1962). In order to use these values, they were first converted to (1/D) *vs.* vapor pressure.[4] The data then showed a linear relationship (Fig. 3), the slope of the line being negative, decreasing with increasing temperature.

Two conclusions can be drawn from these curves:

(a) The lower the temperature and the lower the vapor concentration, the slower moisture moves (i.e., the higher the resistance); the higher the temperature, the less effect different moisture levels have on the rate of movement.

(b) At very high vapor pressure levels, temperature has little effect on the rate; at low levels, temperature has a tremendous effect.

[4] The value (1/D) can be considered as the resistance to moisture flow.

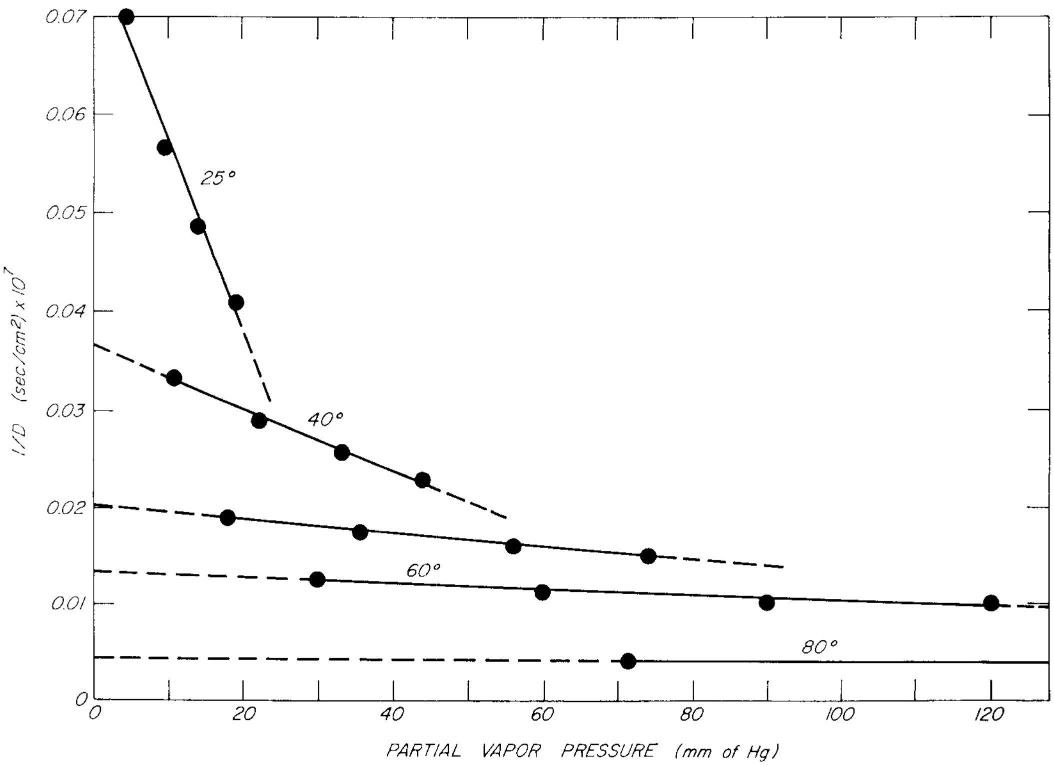

FIG. 3. Reciprocal of the diffusion coefficient *vs.* vapor pressure from data of Stamm (1962). Dashed lines are projections beyond original data.

INCORPORATING VARIABLES

Temperature changes

The changes that occur with a change in ambient temperature are complex. The procedure in this analysis is a simplified approch: When the temperature changes, it is assumed that the moisture content remains constant throughout the sample. This is not true because the temperature change in wood is not instantaneous, but occurs over a period of time. Further, in the analysis, it is assumed that an immediate temperature change to the new ambient temperature occurs throughout the sample. Because heat moves 10^3 times faster than moisture—the Lewis number is 10^{-3} or smaller—and because the sorption isotherm is not extremely sensitive to temperature, the error introduced by this procedure is small for small temperature changes and for high moisture contents or high levels of temperature.

Surface resistance

The determination of surface resistance is quite complex, depending on many factors. Mathematically, the flux of moisture, F, is related to surface resistance, R, by

$$F = R\Delta c$$

where c = concentration.

Order of magnitude estimates are provided in the computer program analysis to accommodate various situations,[5] based on the similarity between heat and mass trans-

[5] The computer program incorporating this model, written in FORTRAN IV, is available from the author. The program requires only minimal input data—sample size, initial moisture content gradients, and the temperature and humidity of the environment as a function of time.

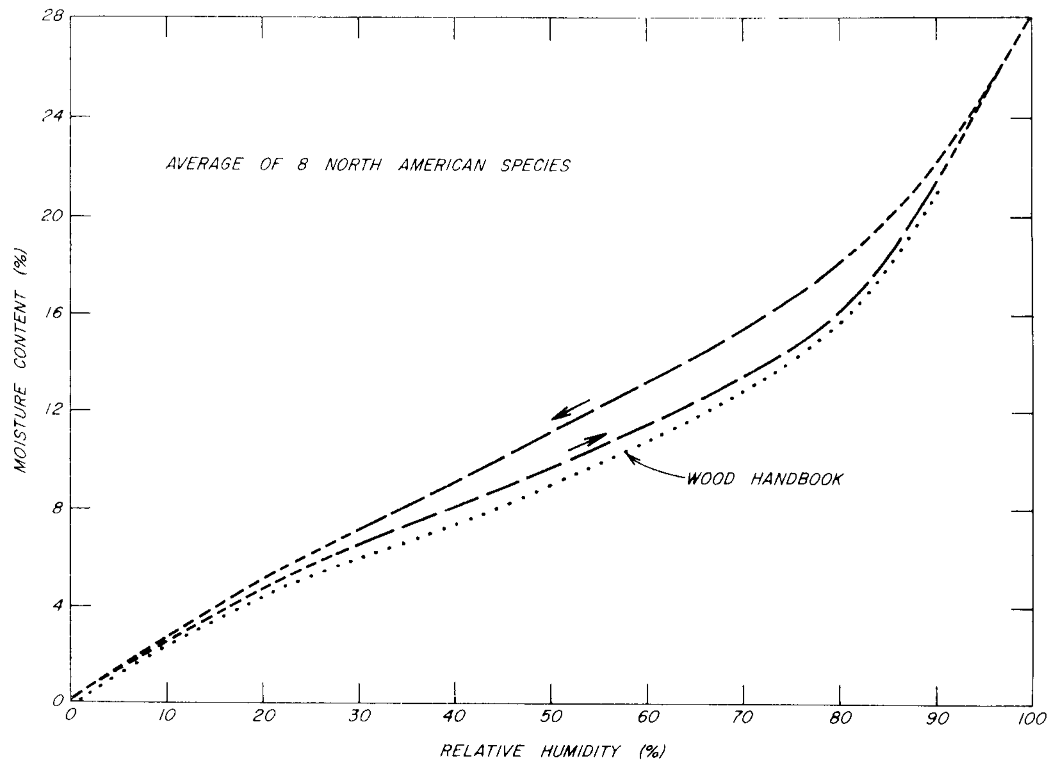

FIG. 4. Average sorption isotherm for eight North American species compared with *Wood Handbook* (U.S. Forest Products Laboratory 1974), Table 3-4, at 80 F. Short dashed lines are projections beyond available data.

fer. (See, for example, Chapter 21 of Bird et al. 1960.) For wood samples over 2 inches long in the flow direction, the surface resistance is negligible in many cases, so that it can be set equal to zero.

Equilibrium moisture content

One point of some uncertainty in the model is the EMC values. A review of unpublished documents at the U.S. Forest Products Laboratory in Madison, Wisconsin, indicated that the published and widely used EMC table, Table 3-4 of the *Wood Handbook* from the U.S. Forest Products Laboratory (1974), was based on a few measurements, primarily on Sitka spruce, subjected to oscillating desorption. Therefore, additional data were collected for this study, using 3 adsorption-desorption cycles with 8 species of wood and 10 samples for each species. (See Fig. 5 for species used.) The results at 80 F are summarized in Figs. 4 and 5. Deviations from "Table 3-4" values are noted. Similar deviations were noted by Spalt (1958), Hedlin (1969), and Djolani (1970).

The incorporation of these data and the hysteresis effect is not without problems. There is the question of how to get from the desorption to adsorption isotherm. An abrupt jump from one to the other in the calculation procedure can result in an immediate change in moisture content of as much as 2% on the graph. The transition from adsorption to desorption has not been well studied, but the jump is not in agreement with observed behavior. Therefore, in the analysis here, transfer is made from one isotherm to the other by a horizontal line on a plot such as Fig. 3 (i.e., as relative hu-

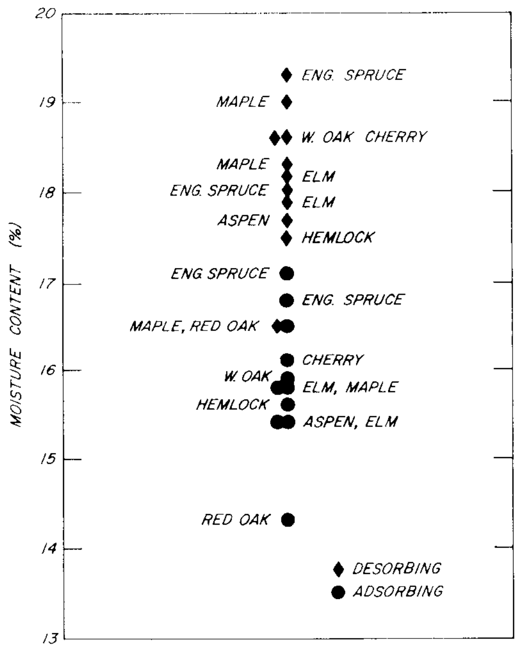

FIG. 5. Measured equilibrium moisture contents of eight North American woods at 80 F, 80% RH.

midity changes, the EMC is considered constant until the new isotherm is reached). An example is:

> Assume a cube of wood has reached a moisture content of 12% throughout by adsorption. Ambient conditions are then changed to 6% EMC. As soon as the vapor pressure in the block begins to drop, the desorption isotherm is used. However, to prevent a sudden increase in moisture content, the analysis holds the moisture content at 12% until the moisture content from the desorption isotherm falls below this value.

Flow direction

In this analysis, no distinction is made for the radial or tangential direction, as most diffusion properties are similar or nearly so (Stamm 1962; Wirakusumach 1962). However, the diffusion coefficient is several orders of magnitude different in the longitudinal direction.

EXPERIMENTAL

In order to evaluate with actual data the analytical procedure and parameters employed, three representative experiments are described.

All lumber for these experiments was sawn from freshly felled trees and was stored at 36 F until used. This storage condition was chosen to reduce the rate of drying and to reduce the risk of stain, fungus, and mold formation. When samples were needed, they were air-dried at 80 F, 80% RH and then band-sawn to the required size. In order to restrict flow to one or two dimensions as required, three coats of aluminum paint sealer were applied. The samples were then exposed to the desired ambient conditions. Moisture content measurements were made at least every 48 h. Temperatures were controlled to within ± 0.5 F. Following exposure, standard oven-drying was done to obtain oven-dry weight for calculation of moisture contents.

In the first experiment, the objective was to evaluate the moisture gradient in 2-inch cubes of Engelmann spruce (*Picea engelmannii*) in a desorption experiment. The cubes were conditioned initially at 80 F and 80% RH. At 0 h, ambient conditions were changed to 80 F, 58% RH, and then at 296 h to 56% RH. This condition was held until 600 h when the experiment was stopped.[6] Gradients were determined throughout the 600 h by slicing a specimen into small sections and measuring the moisture content of these sections by standard oven-drying.

A second experiment studied the behavior in a changing humidity and temperature condition. The entire block was weighed to obtain the average moisture content of the 2-inch Engelmann spruce cubes. The direction of flow varied: In some blocks flow was restricted to radial flow, in some to tangential, in some to longitudinal, and in some to radial and tangential (i.e., the longitudinal ends were painted).

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[6] The experiments were stopped due to either equipment failure or malfunction.

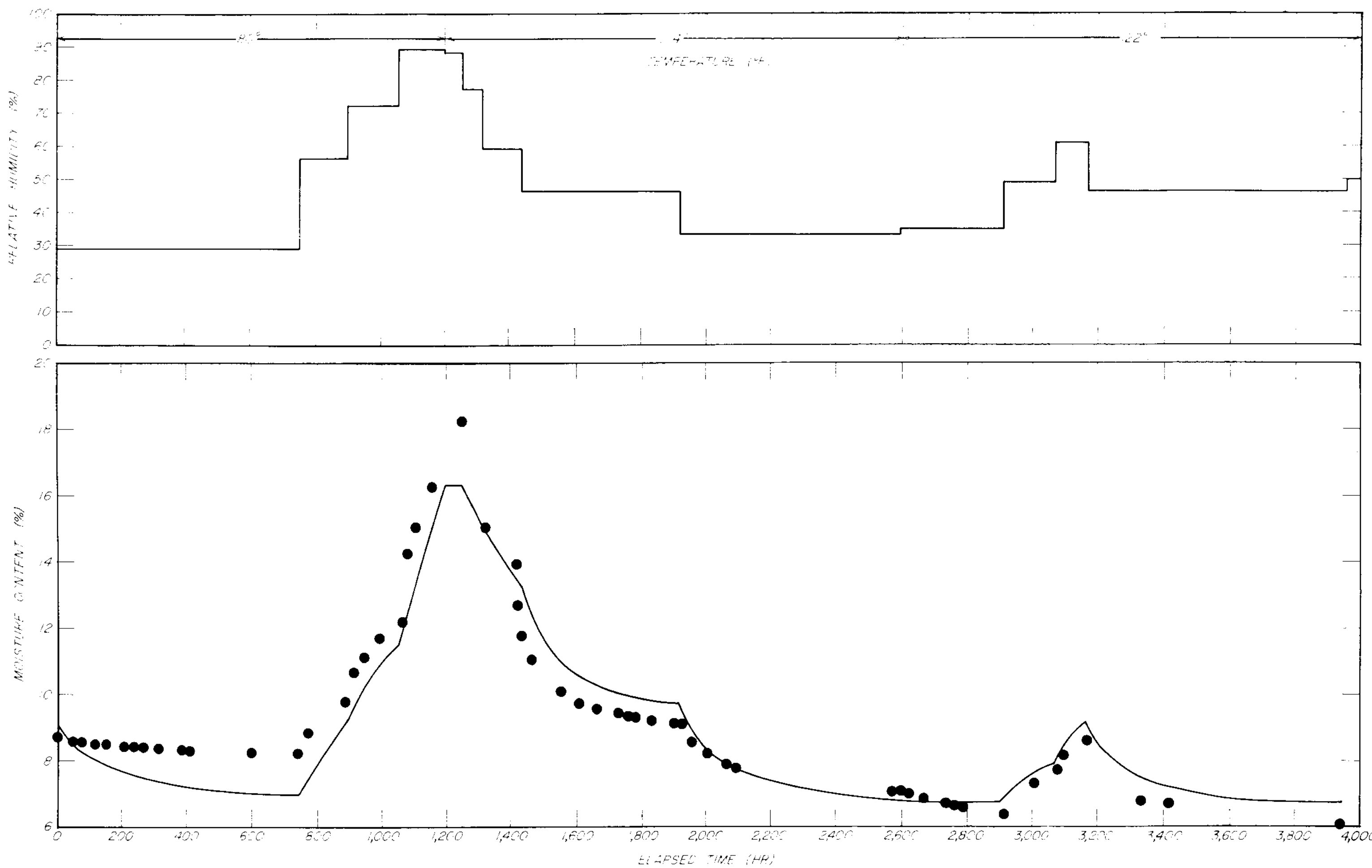

FIG. 6. Upper: Relative humidity and temperature schedule for Experiment 2. Lower: Moisture content (solid circles) of Engelmann spruce 2-inch cubes determined by weighing the entire cube, two-dimensional flow, Experiment 2. Solid line shows predicted moisture content.

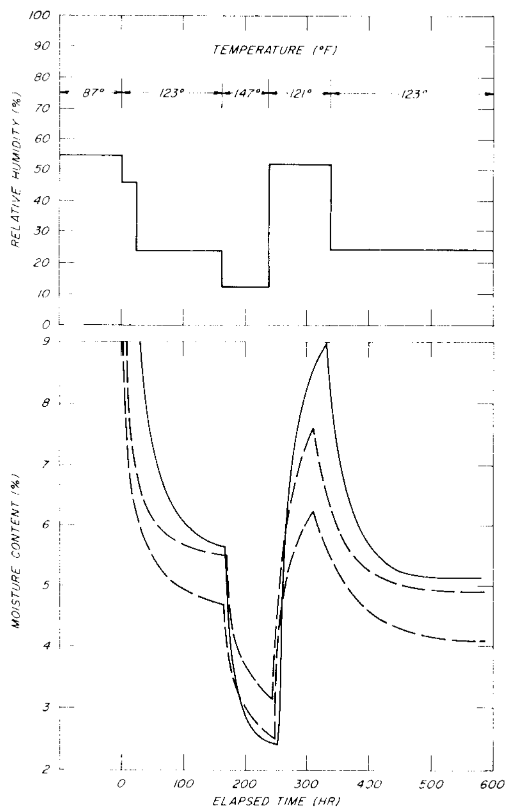

FIG. 7. Upper: Relative humidity and temperature schedule for Experiment 3. Lower: Minimum (lower dashed line), maximum (upper dashed line), and predicted (solid line) moisture contents for all nine species of Experiment 3.

The time and temperature schedule is shown in Fig. 6.

The final experiment was run with samples from nine species[7] to study their various behavior in a changing temperature and humidity environment. Moisture contents were determined by weighing the entire sample. Samples varied in cross-section from ¾- by ¾-inch to ¾- by 1½-inch; all were 2 feet long. The schedule is illustrated in Fig. 7.

[7] Engelmann spruce (*Picea engelmannii*, 3 trees), western hemlock (*Tsuga heterophylla*), bigtooth aspen (*Populus grandidentata*), cottonwood (*P. deltoides*), cherry (*Prunus serotina*), soft maple (*Acer rubrum*), American elm (*Ulmus americana*, 2 trees), white oak (*Quercus alba*), and red oak (*Q. rubra*).

RESULTS AND DISCUSSION

EMC

The fact that the EMC data collected here (Fig. 4) do not coincide with the *Wood Handbook* "Table 3-4" (1974) is understandable; the *Wood Handbook* data are based only on Sitka spruce in initial desorption. Somewhat unexpected was the wide range of EMCs encountered at a given condition (Fig. 5) for the eight species tested. At 80 F and 80% RH, the average for the desorbing samples was 16.5 to 19.3% MC depending on the species; for adsorbing, 14.3 to 17.1% MC. The variation between samples from different trees of the same species (Engelmann spruce, maple, and elm were replicated) was also larger than expected, averaging about ½% MC. A more extensive evaluation of Table 3-4 EMC *vs.* RH data is in order.

Experiment 1

As could be expected, the average moisture content measured while the cubes were drying varied little (Fig. 8). The gradients were all quite uniformly shaped without large variations from slice to slice (Figs. 9 and 10). The agreement between the actual and the predicted moisture contents is very good for this drying experiment.

The scatter of the data (solid circles in Fig. 8) is attributable to the variation in EMC behavior noted above, to small errors in the slicing procedure used to obtain the gradients, and to variation in the grain angle in the samples. This grain angle effect was controlled in later experiments by more careful sample selection.

Experiment 2

In this trial, in which moisture content was determined by weighing the entire cube, the measured results again agreed well with predicted values. The comparison for two-dimensional flow is given in Fig. 6. Comparisons for one-dimensional flow in the radial or tangential direction were as good as the two-dimensional comparisons given.

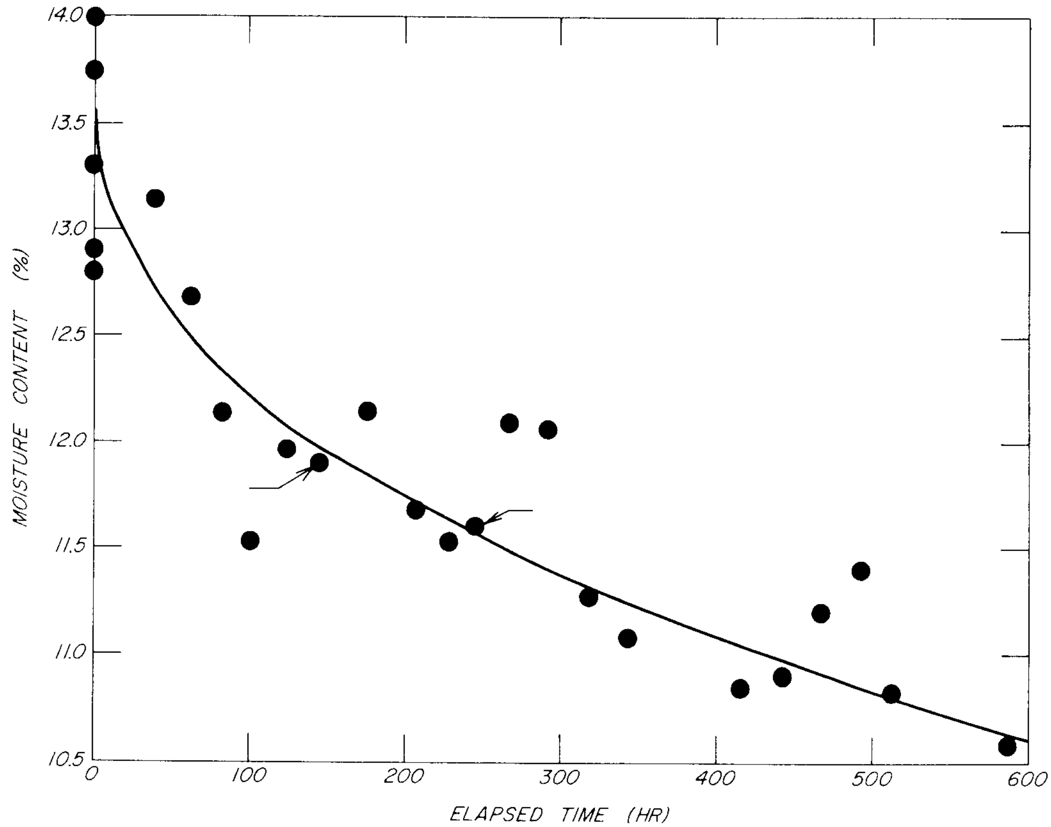

FIG. 8. Measured moisture content (solid circles) of 2-inch Engelmann spruce cubes as determined by slicing (Experiment 1). Solid line is predicted moisture content using Stamm's (1962) diffusion coefficient. Points identified by arrows, left and right, are taken from the following Figs. 9 and 10, respectively.

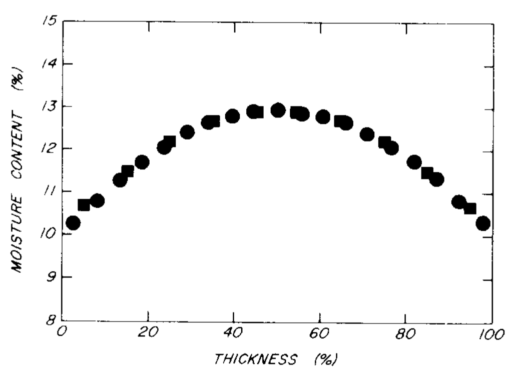

FIG. 9. Moisture content gradient in Engelmann spruce 2-inch cube at 146 h elapsed time and 11.9% mean MC. Actual data are solid circles; data predicted from Stamm's (1962) diffusion coefficient are shown as squares.

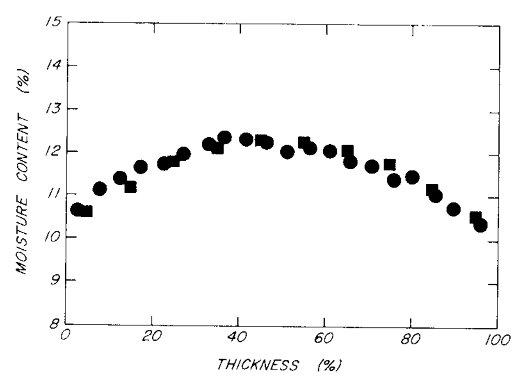

FIG. 10. Moisture content gradient in Engelmann spruce 2-inch cube at 240 h elapsed time and 11.6% mean MC. Actual data are solid circles; data predicted from Stamm's (1962) diffusion coefficient are shown as squares.

Experiment 3

This experiment compared species. It was expected that these species, having different specific gravities and anatomical characteristics, would behave quite differently when the same diffusion coefficient was used for all. Again, the overall agreement between measured and predicted values was good.

The variation between the various species was not as large as expected; the maximum variation is illustrated in Fig. 7, in which the upper dashed curve is Engelmann spruce and the lower dashed curve is red oak. The other species were between these extremes, but were omitted for clarity.

It is likely that this maximum variation between species here is reflecting the differences in the sorption isotherms for the various species, as discussed earlier and illustrated in Fig. 5. This is further supported by the fact that the data from white oak (the densest species used in this study) were almost identical to the data from Engelmann spruce (the lightest species), which are the upper dashed line. These two species were also two of the uppermost data points in Fig. 5.

CONCLUSIONS

1. The slicing method of determining moisture content is satisfactory when moisture content accuracy of better than ½% is not required.

2. Stamm's diffusion coefficient is satisfactory when used with the model developed here to predict moisture content of wood in dynamic environments within the range evaluated—80 to 147 F, and approximately 10 to 90% RH.

3. The hysteresis effect is a very important factor to consider when predicting moisture content. The isotherm values obtained here are considerably higher than the widely used *Wood Handbook* values. The sorption isotherms varied significantly from species to species, although the general shape was similar.

4. A large practical variation in average moisture content for nine different species in a changing environmental condition was not noted. Variations were attributed to variations in the isotherms.

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